

Where do solar eruptions come from?

Anthony Yeates

Durham University, UK



Durham
University

Karen Harvey Prize Lecture, June 2019

Thanks!

Duncan Mackay, Eric Priest (St Andrews)



Aad van Ballegooijen (formerly CFA)



**Dibyendu Nandy
(IISERKOL)**



Piet Martens (Georgia State)

**Gunnar Hornig
(Dundee)**



Chris Lowder (now SwRI)



**Tim Whitbread
(Durham)**



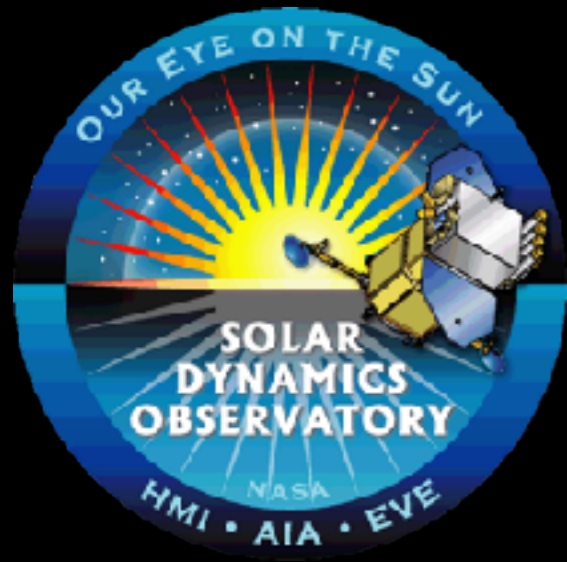
**Gareth Hawkes
(Exeter)**



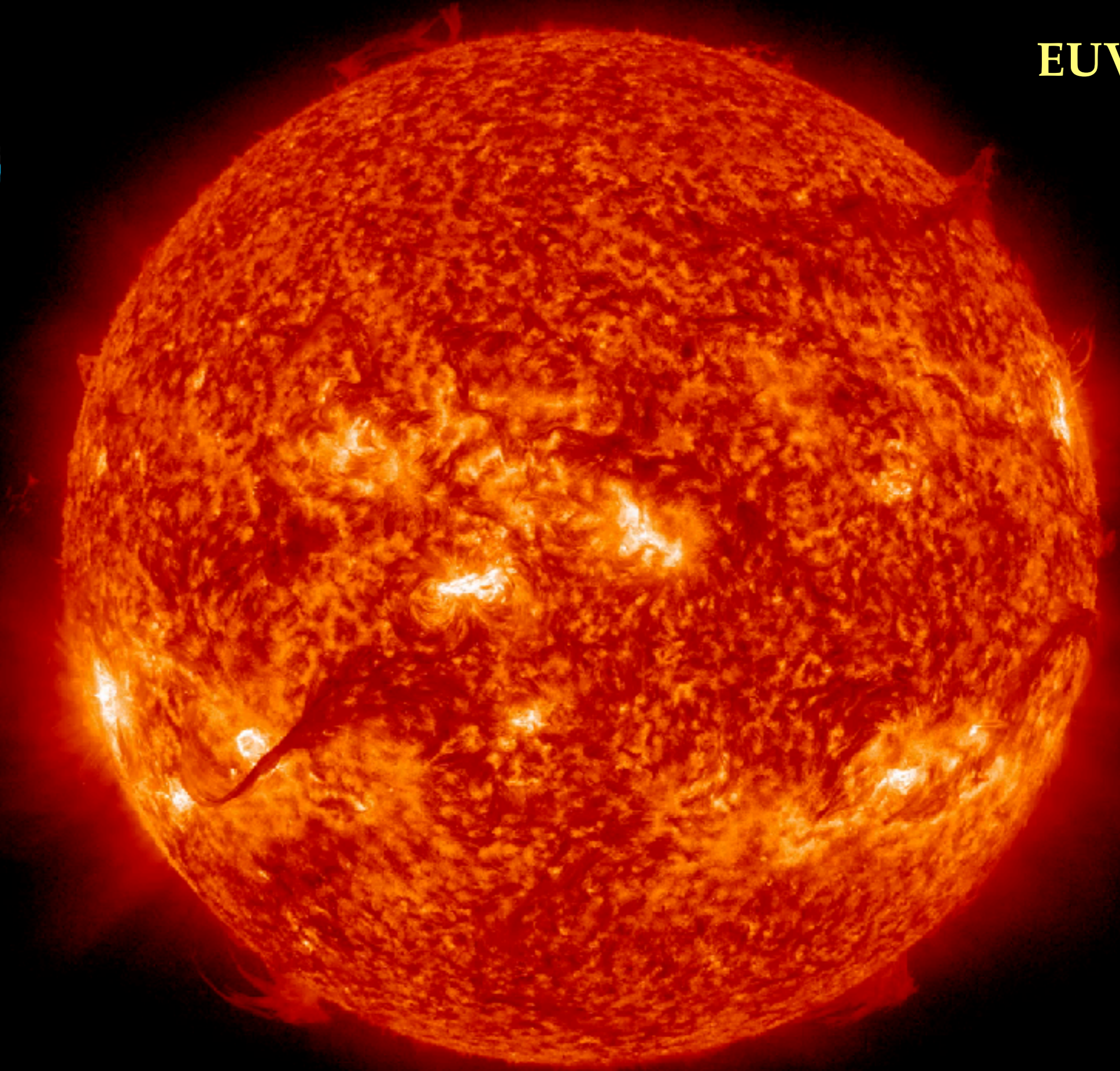
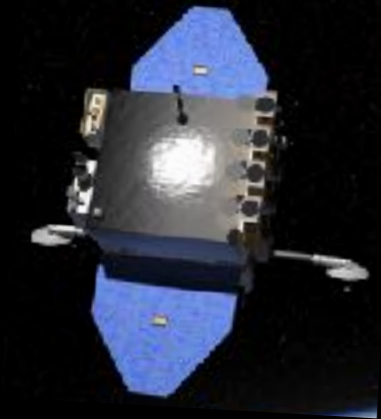
**Chris Prior
(Durham)**



*and many
more...*

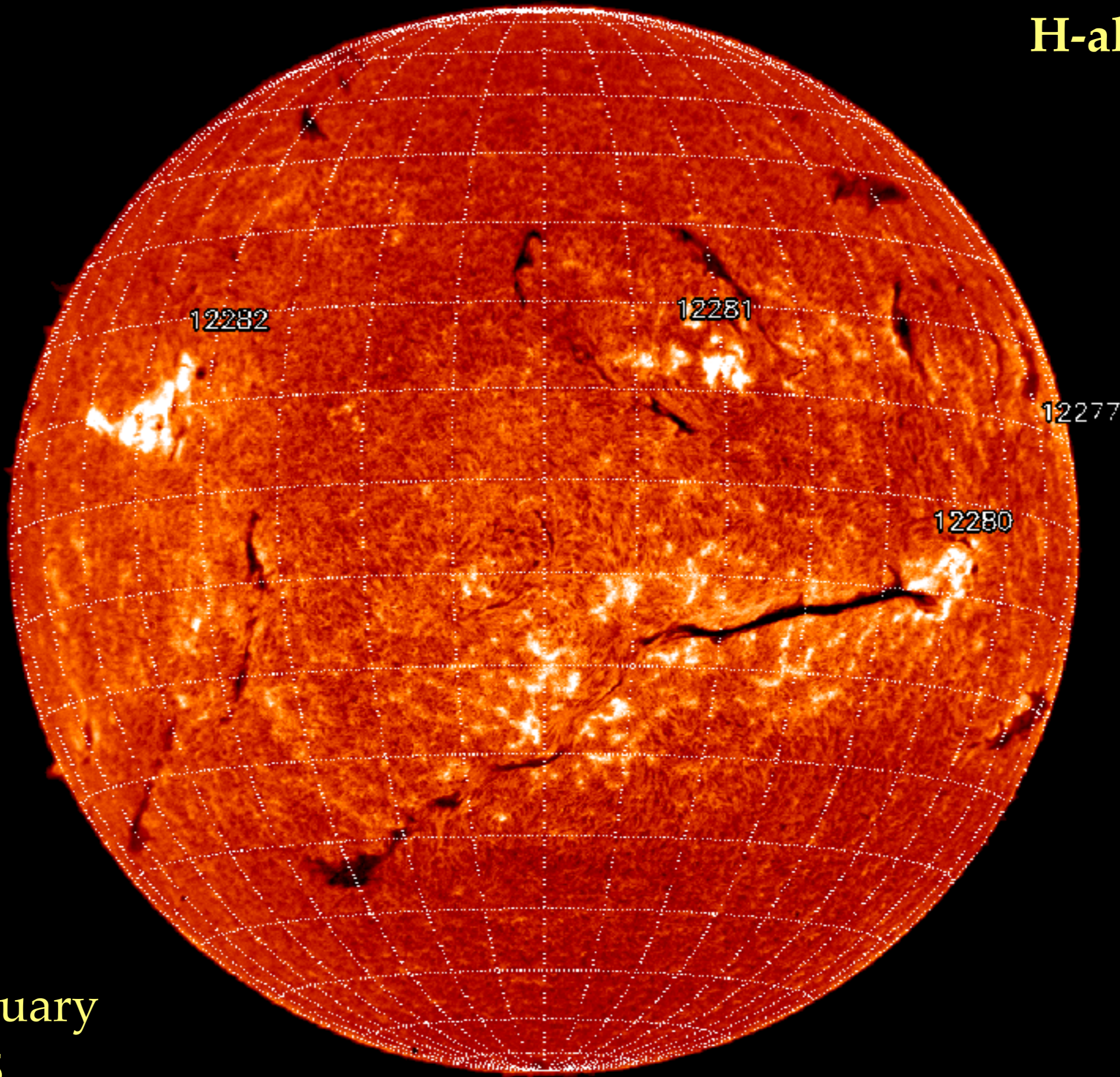


EUV



August
2012

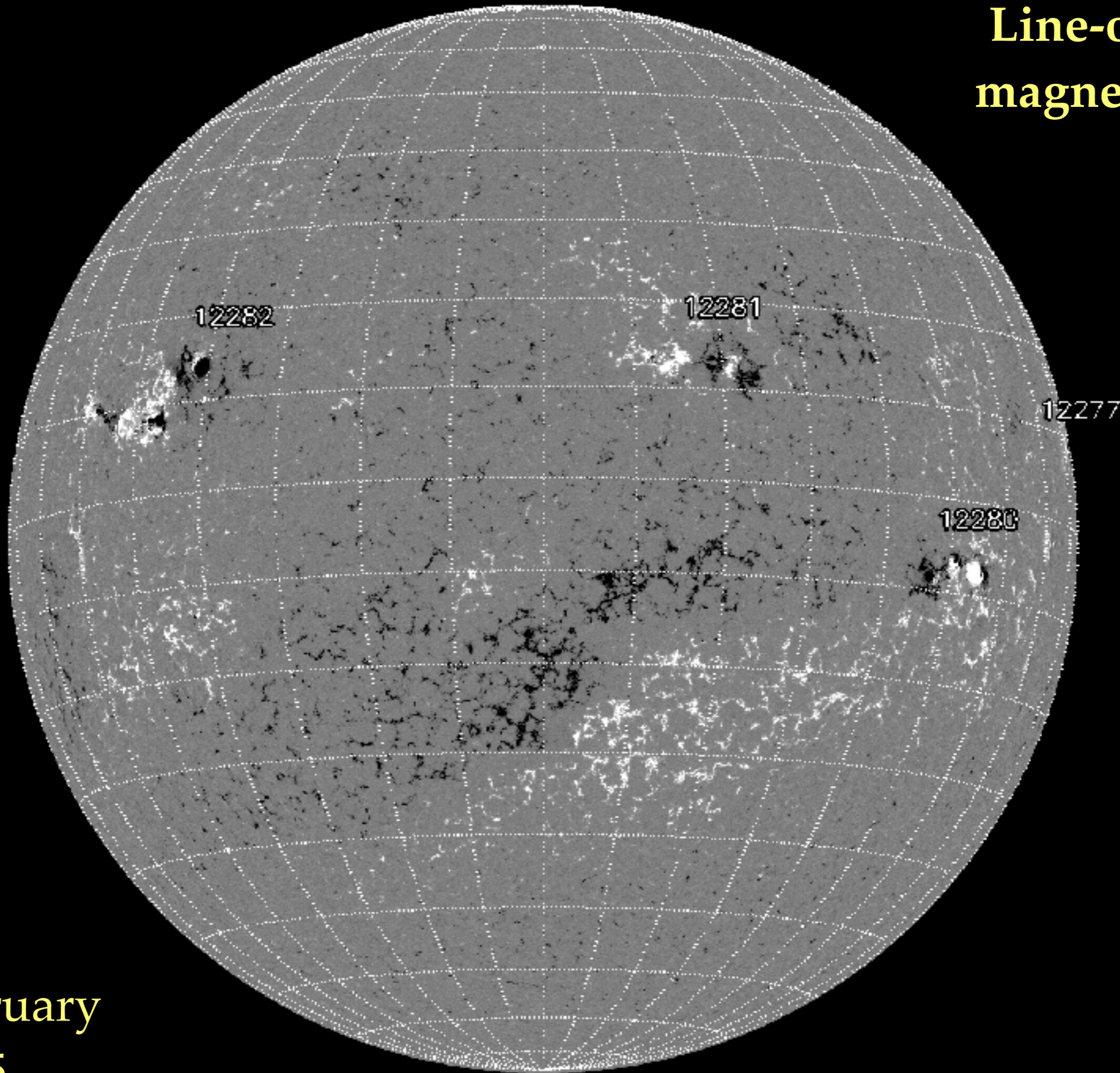
H-alpha



10th February
2015

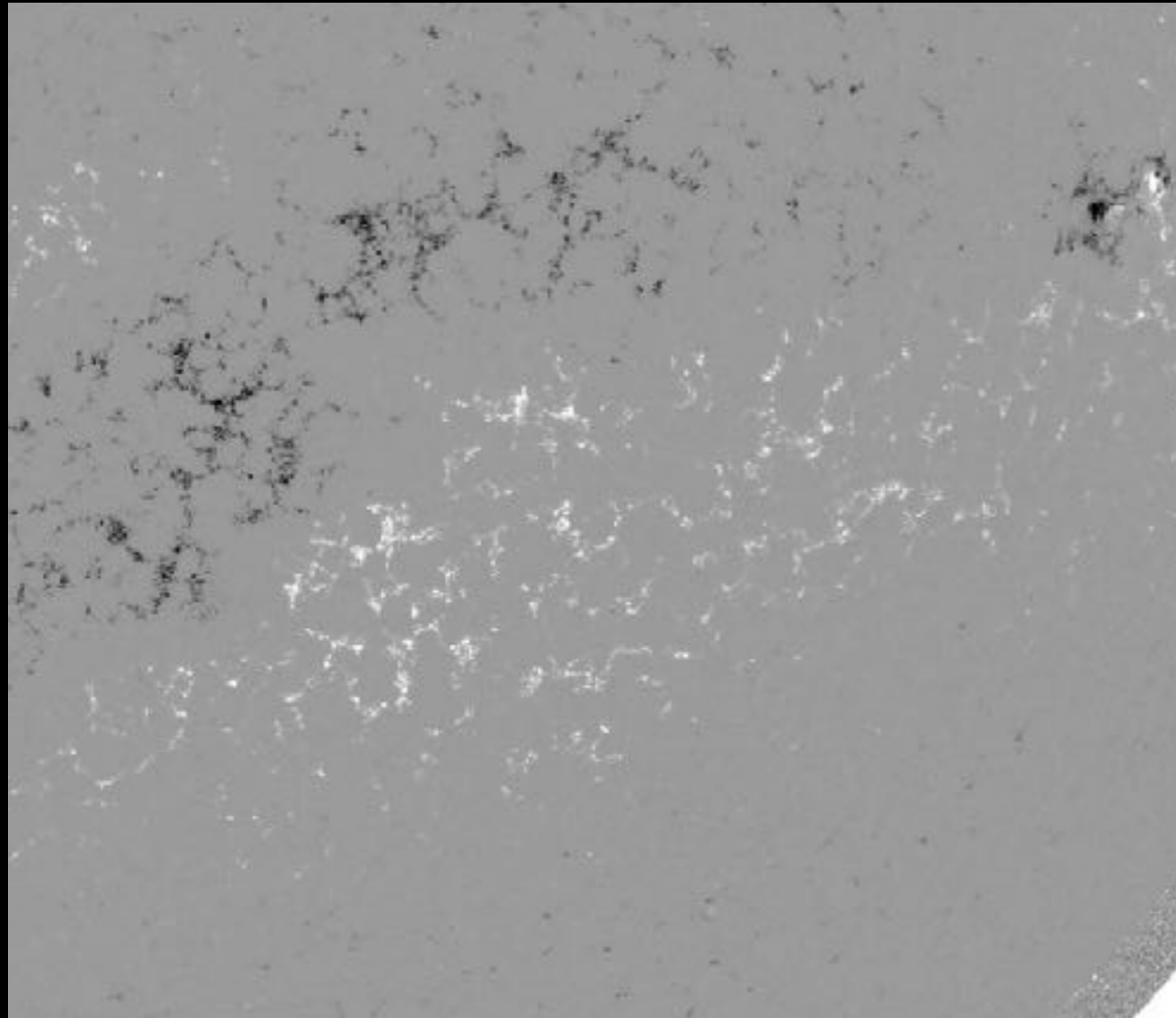
SolarMonitor.org

Line-of-sight magnetic field



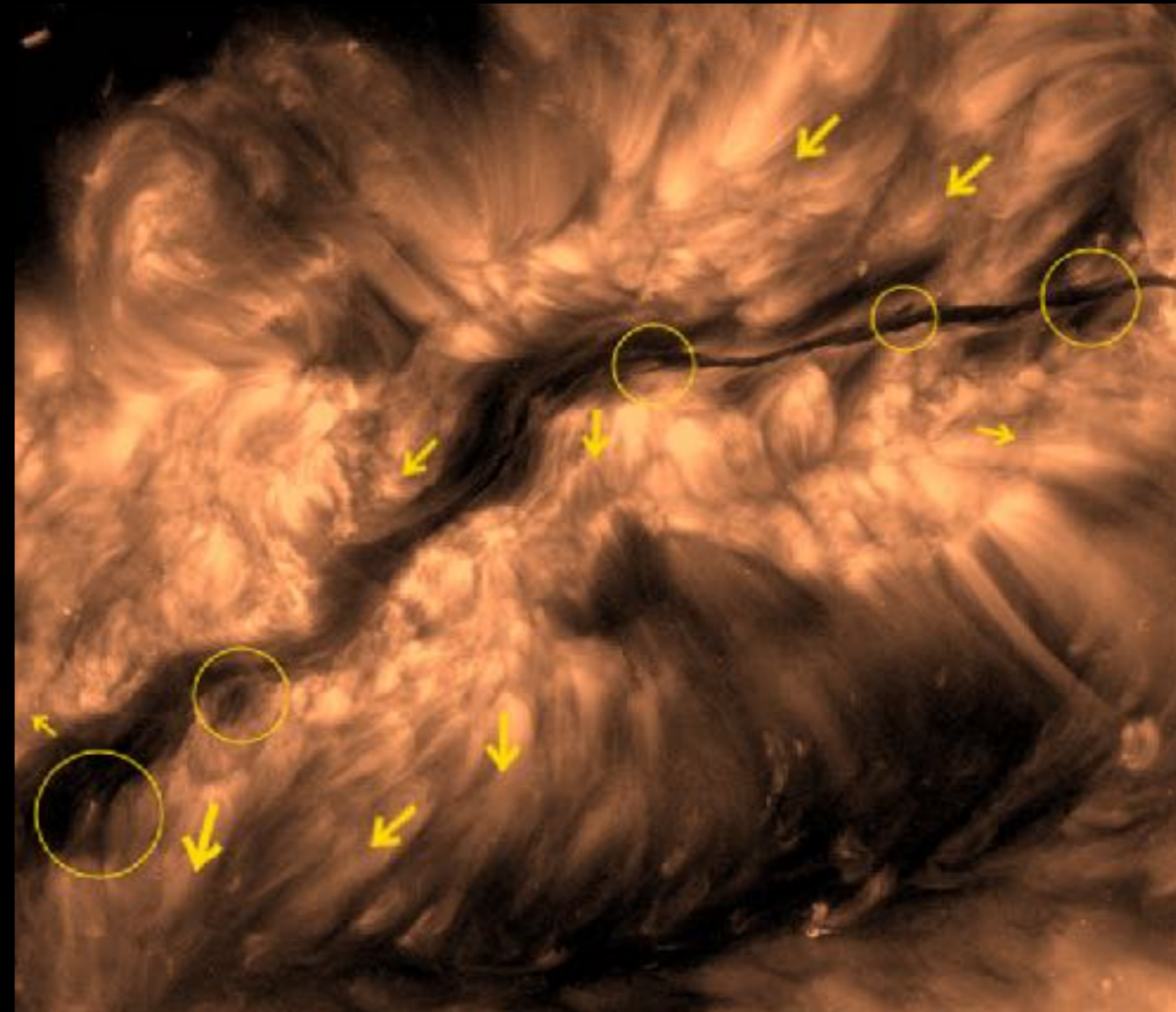
10th February
2015

**Line-of-sight
magnetic field**



**10th February
2015**

EUV

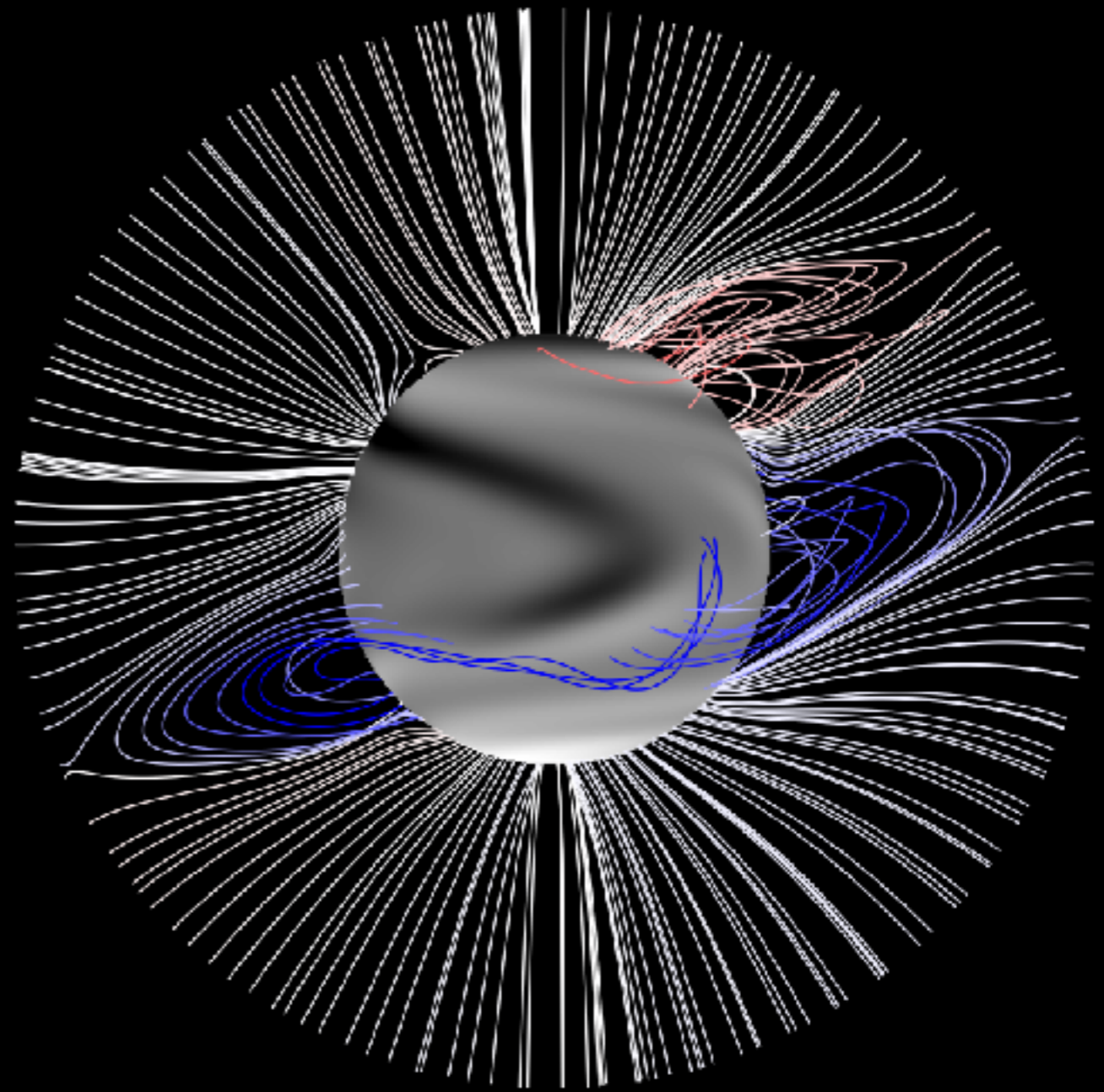
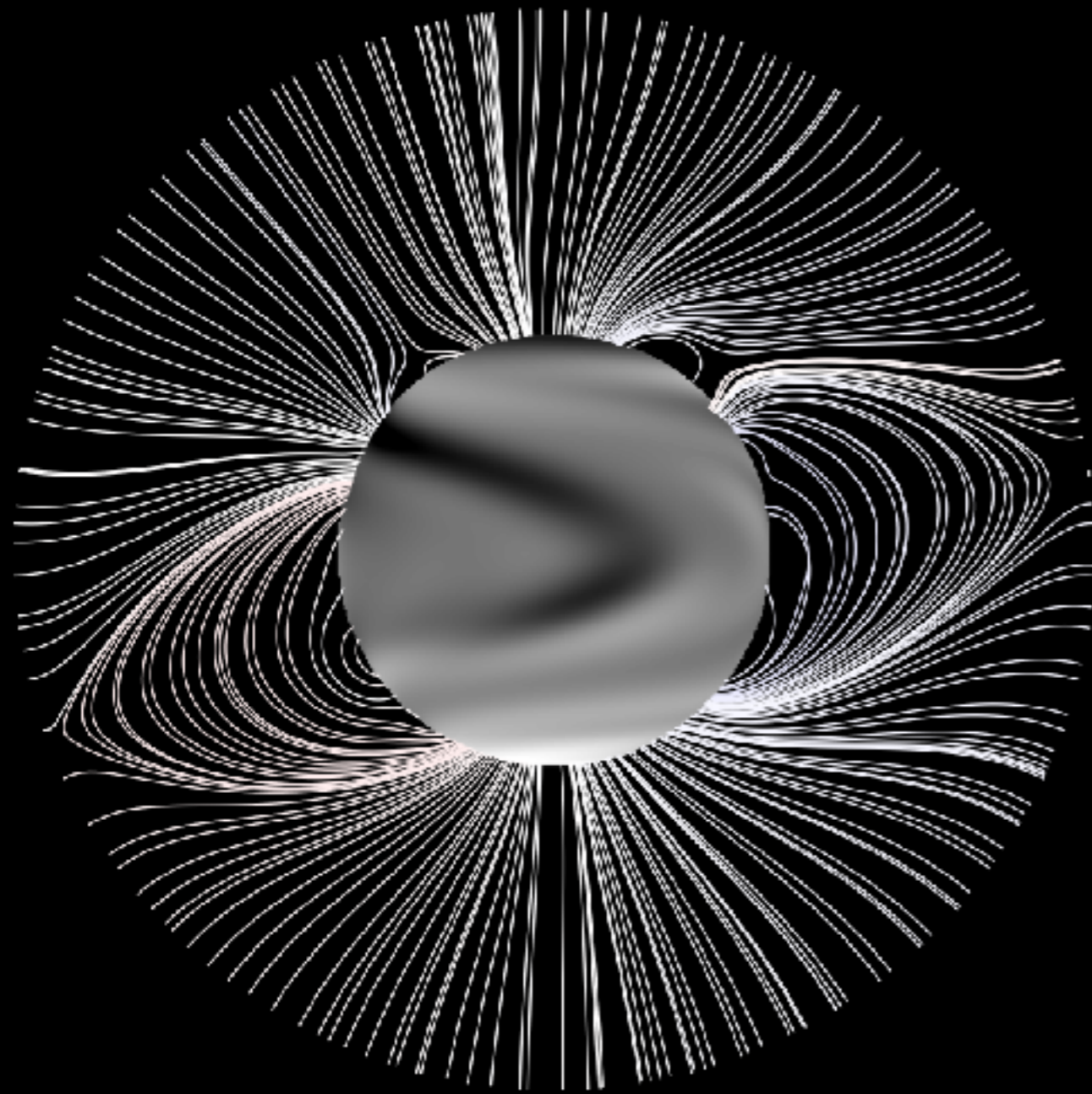


McMaken & Petrie, *ApJ* [2017]



04-Aug-12 00:00:06

(courtesy David Long)



FUNDAMENTALS OF CORONAL EVOLUTION:

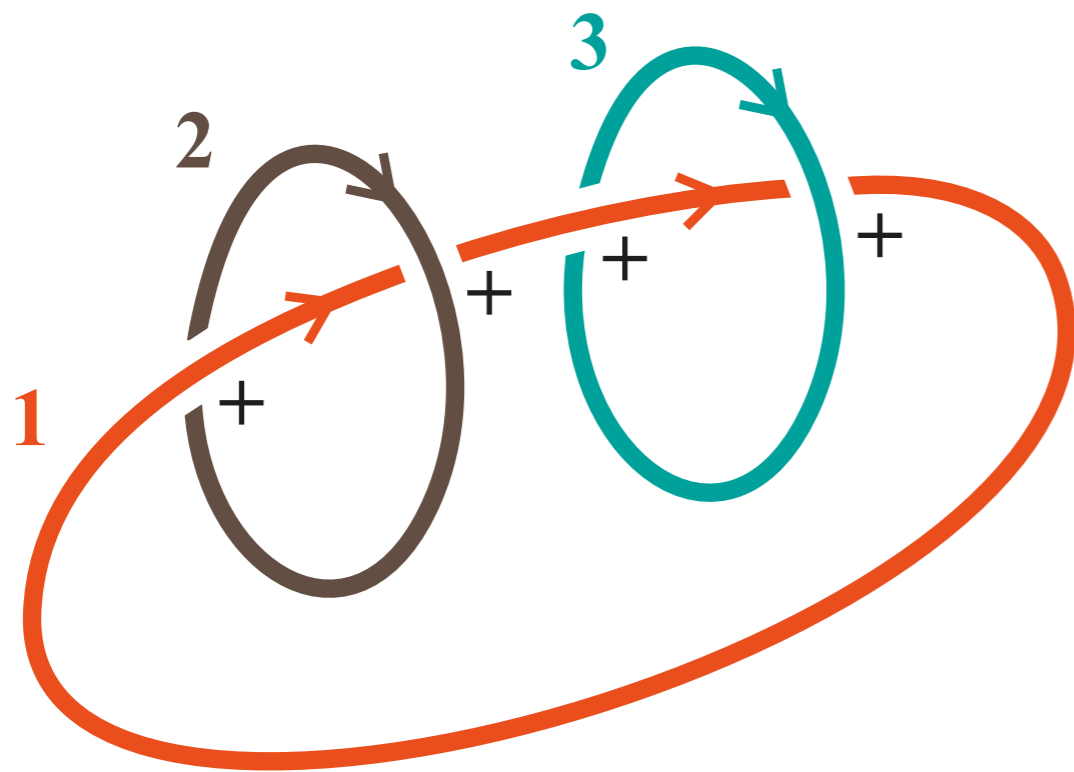
- 1. Magnetic helicity is injected by surface motions.**
- 2. It accumulates at polarity inversion lines.**
- 3. It is removed by coronal mass ejections.**

FUNDAMENTALS OF CORONAL EVOLUTION:

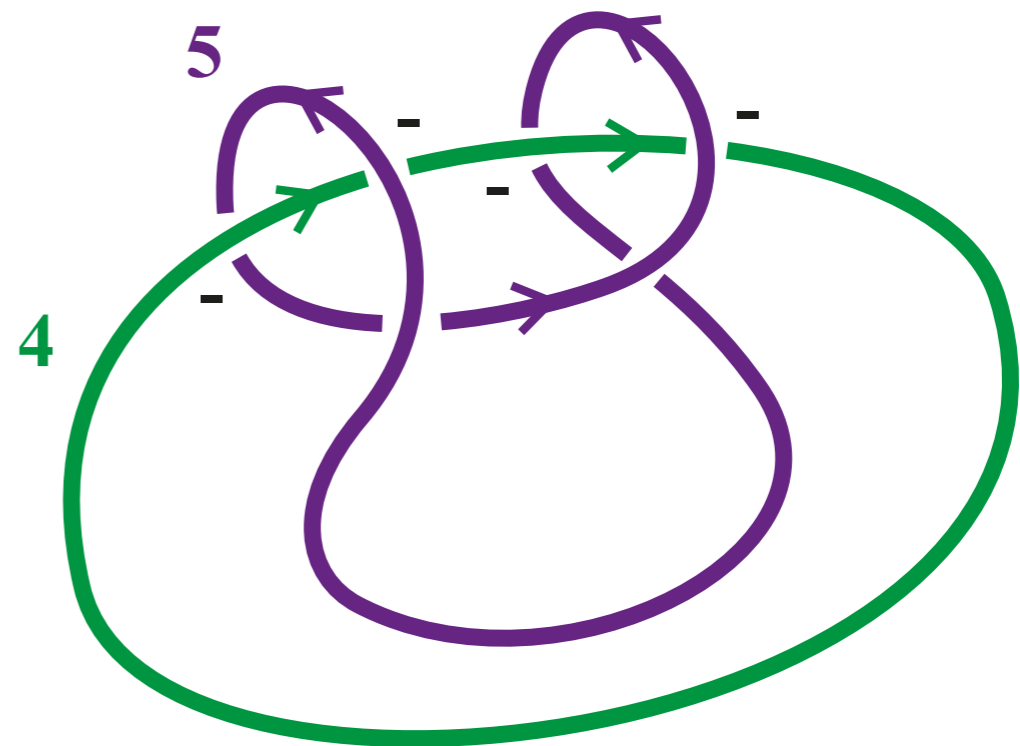
1. **Magnetic helicity** is injected by surface motions.
2. It accumulates at polarity inversion lines.
3. It is removed by coronal mass ejections.

Magnetic helicity - the net linkage of magnetic flux.

$$H = \frac{1}{2} \sum_i \sum_j L_{ij} \Phi_i \Phi_j$$



$$H = \Phi_1 \Phi_2 + \Phi_1 \Phi_3$$



$$H = -2\Phi_4 \Phi_5$$

Alfvén's theorem - magnetic flux tubes preserve their topology in a perfectly-conducting plasma.

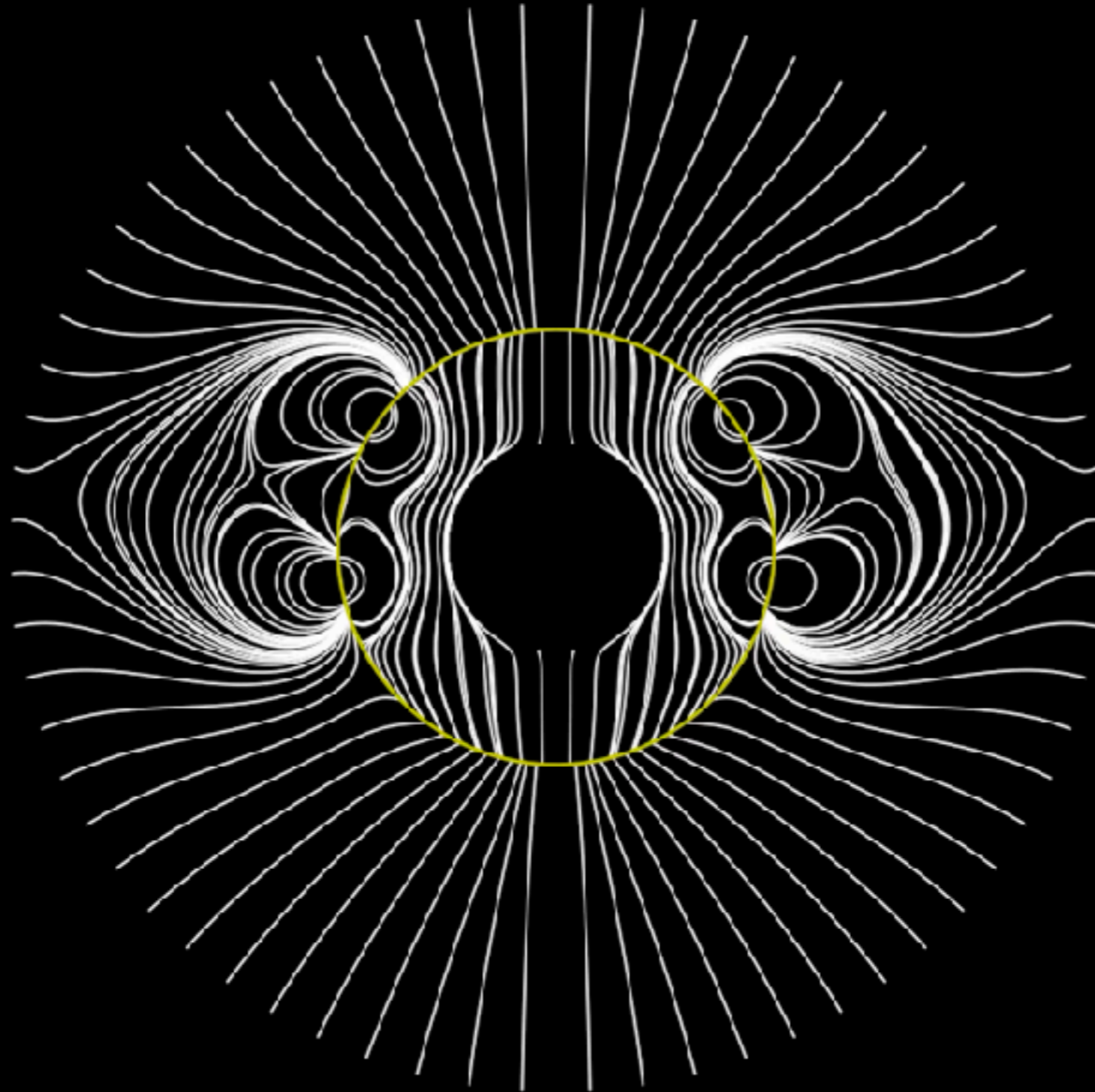


H. Alfvén, Nobel Prize for Physics, 1970

So magnetic helicity must be injected from the boundary.

Relative helicity - magnetic helicity of the coronal field closed with no external source currents.

Berger & Field, *J. Fluid Mech.* [1984]



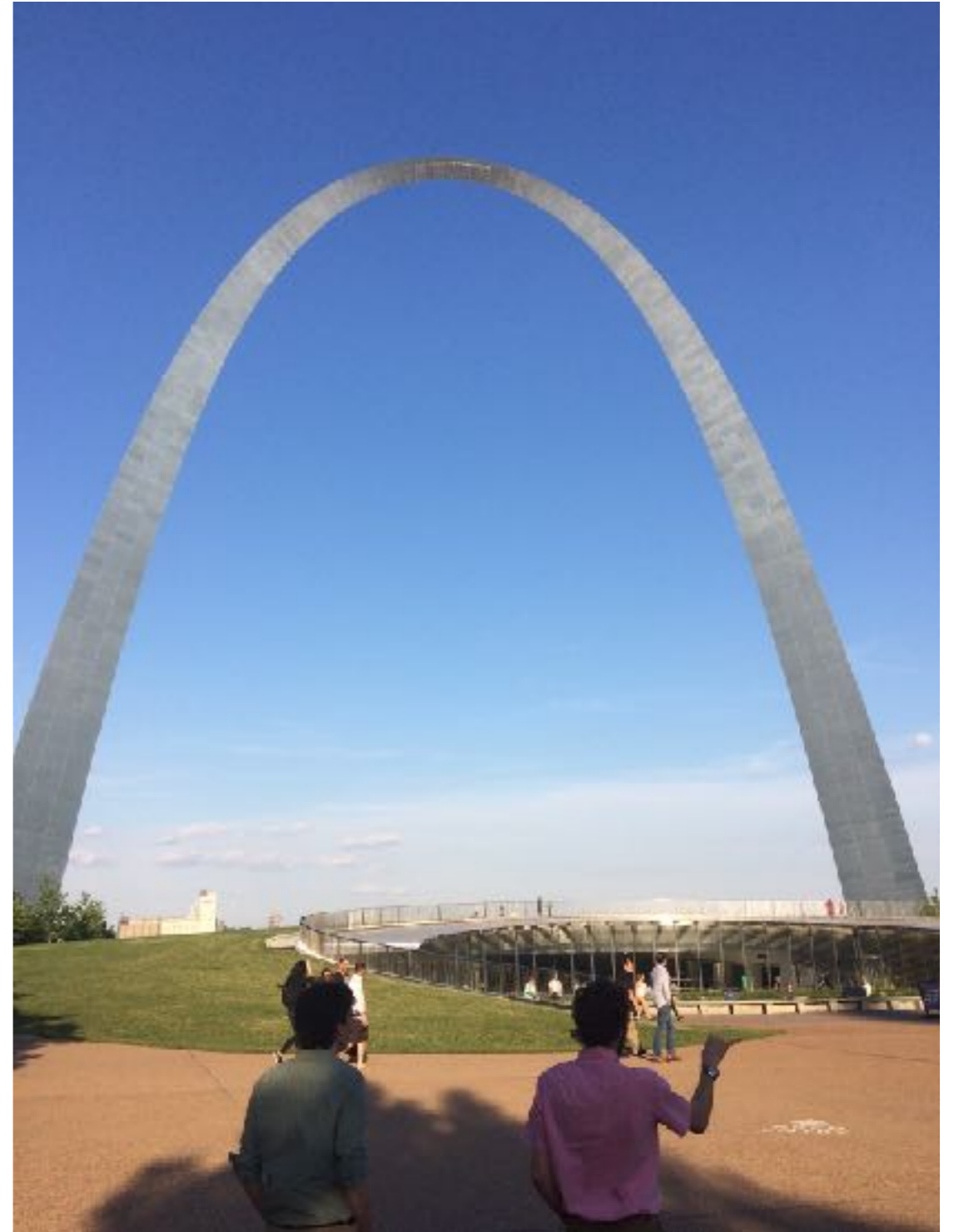
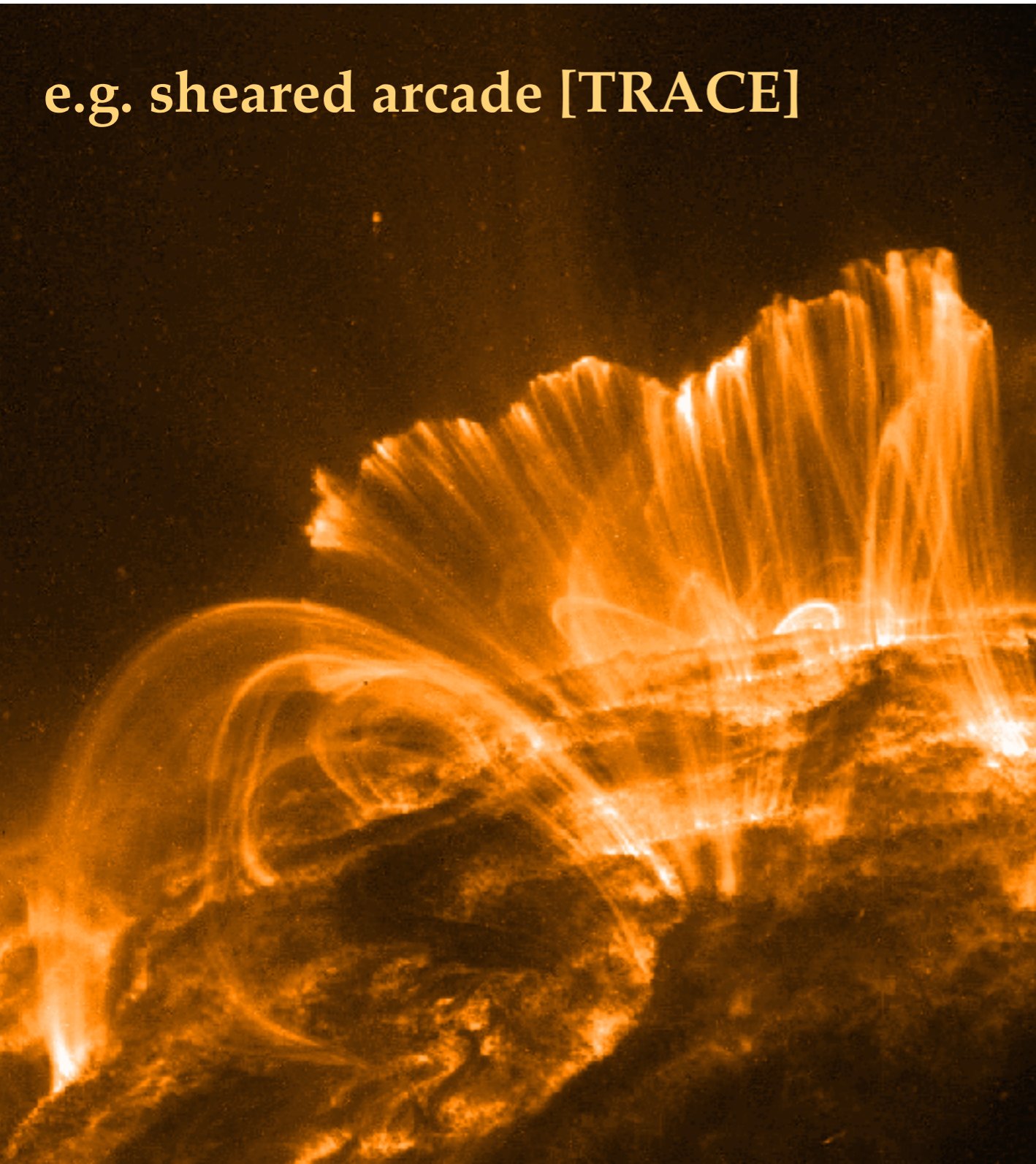
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- 1. Magnetic helicity is injected by surface motions.**
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Footpoint motions can inject relative helicity.

Berger & Field, *J. Fluid Mech.* [1984]
Démoulin & Berger, *Solar Phys.* [2003]

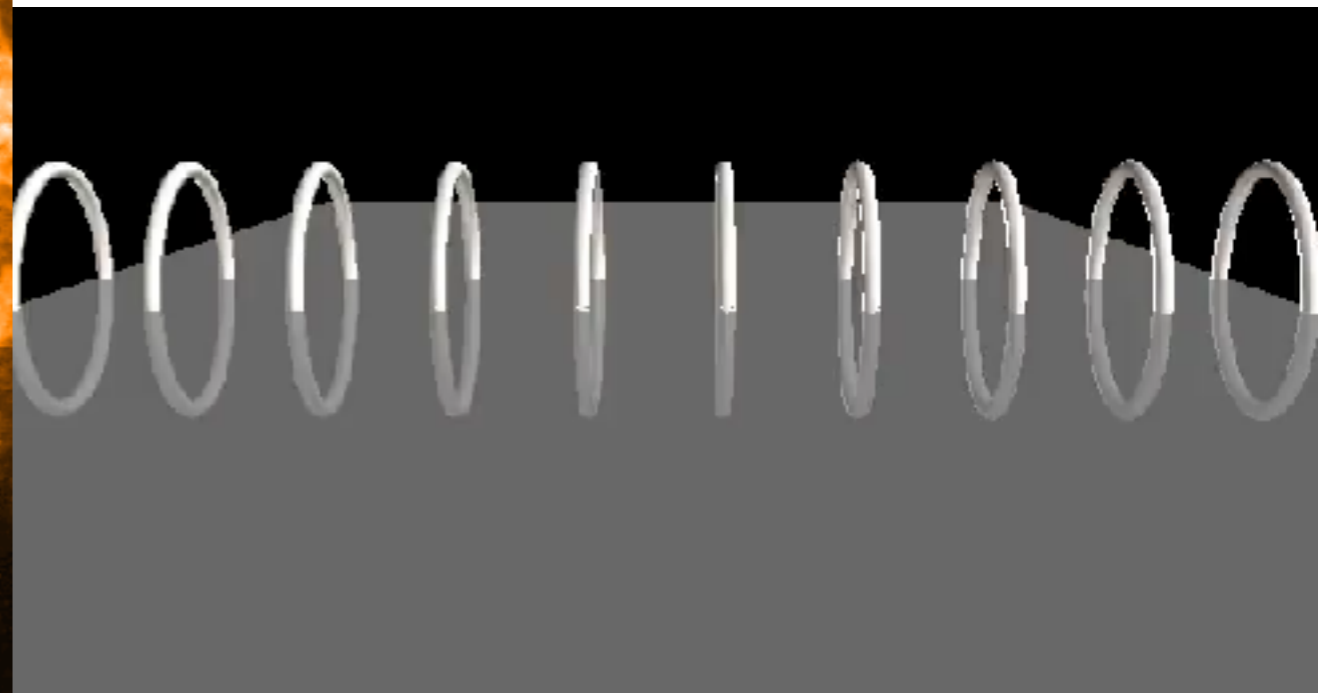
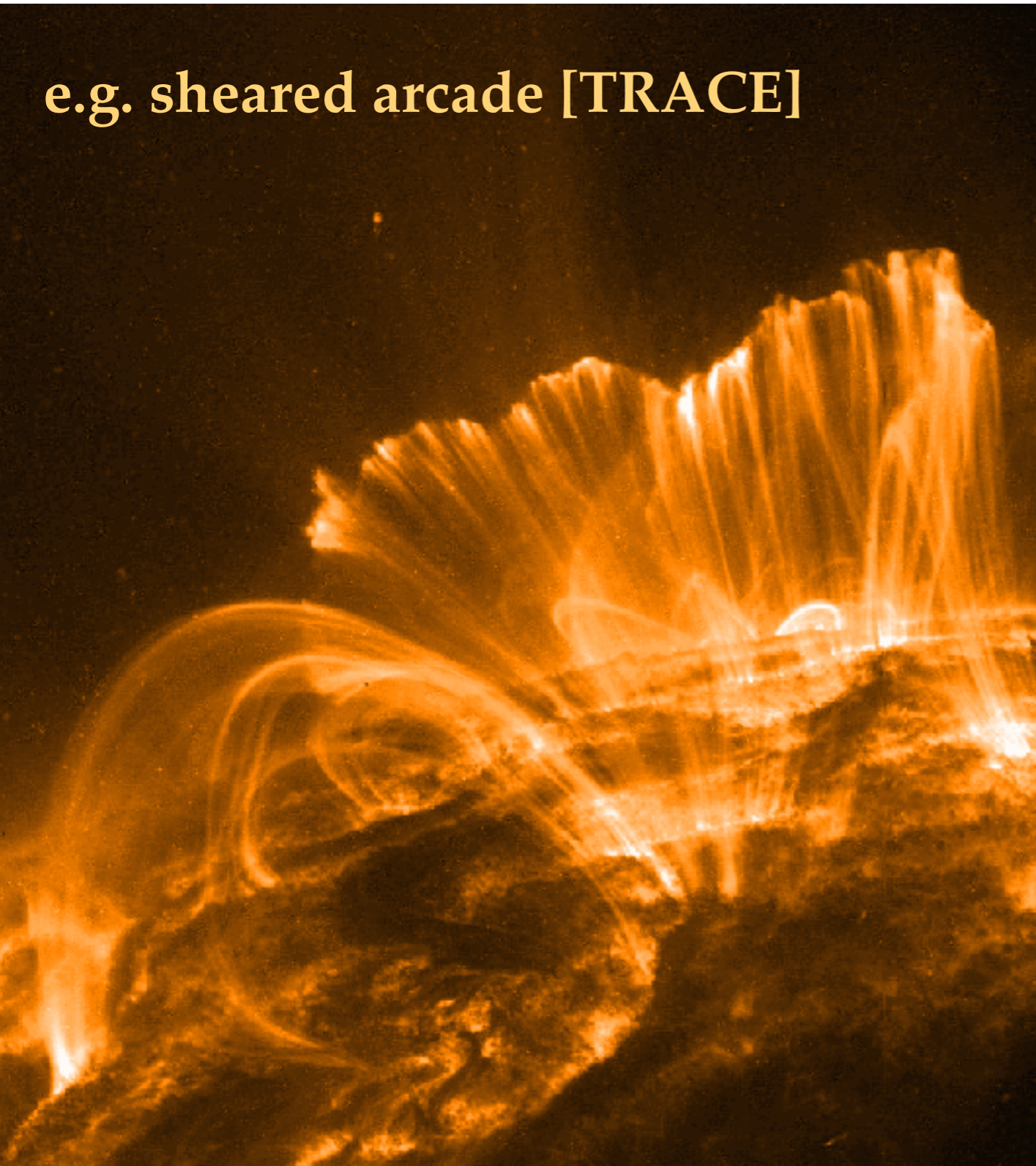
e.g. sheared arcade [TRACE]



Footpoint motions can inject relative helicity.

Berger & Field, *J. Fluid Mech.* [1984]
Démoulin & Berger, *Solar Phys.* [2003]

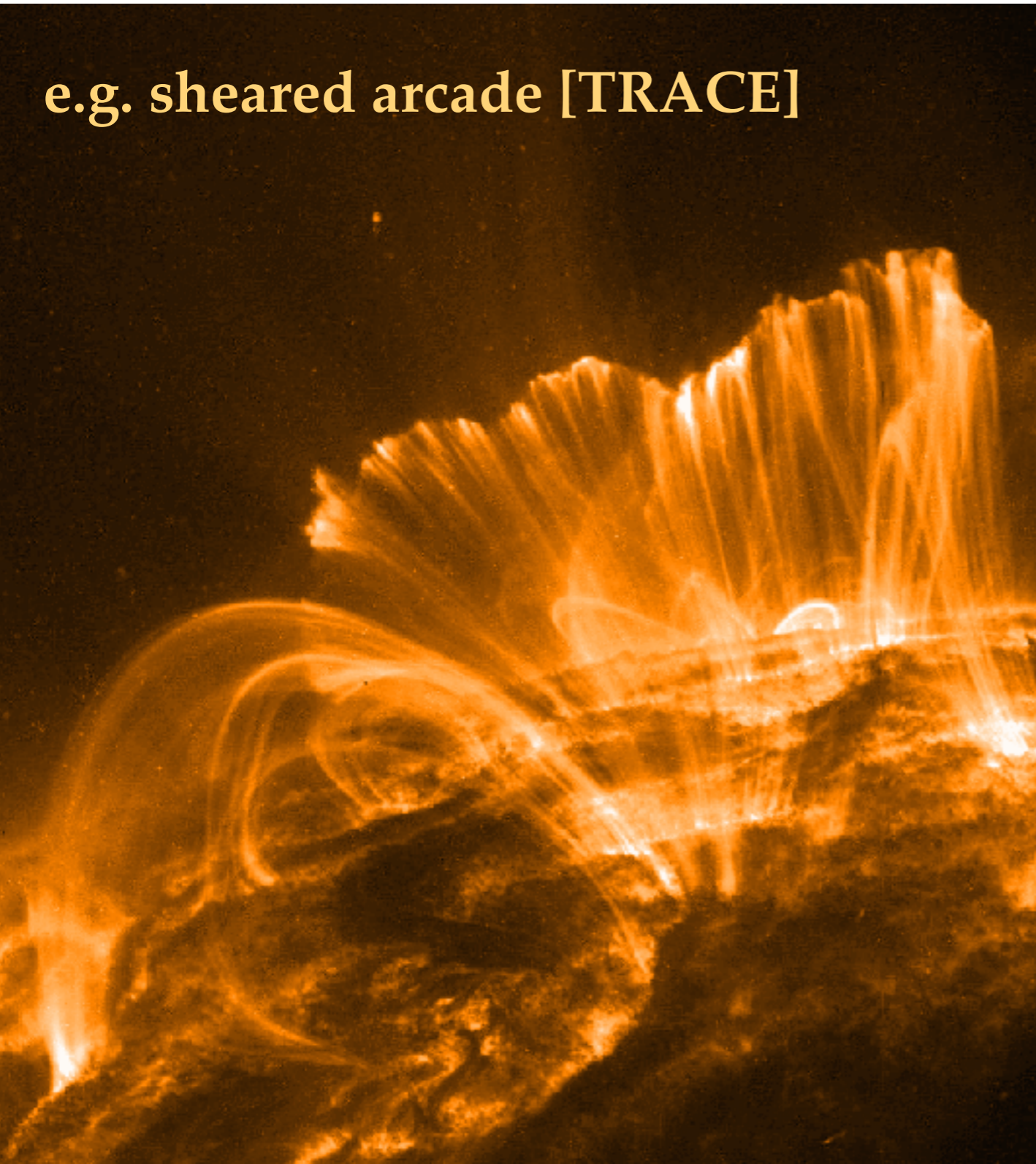
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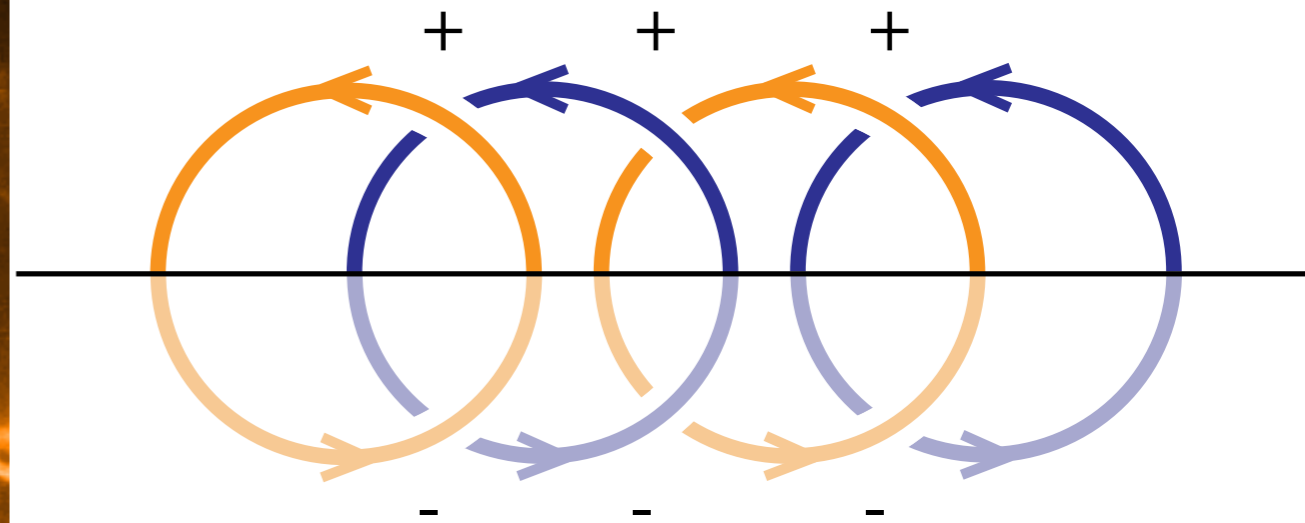
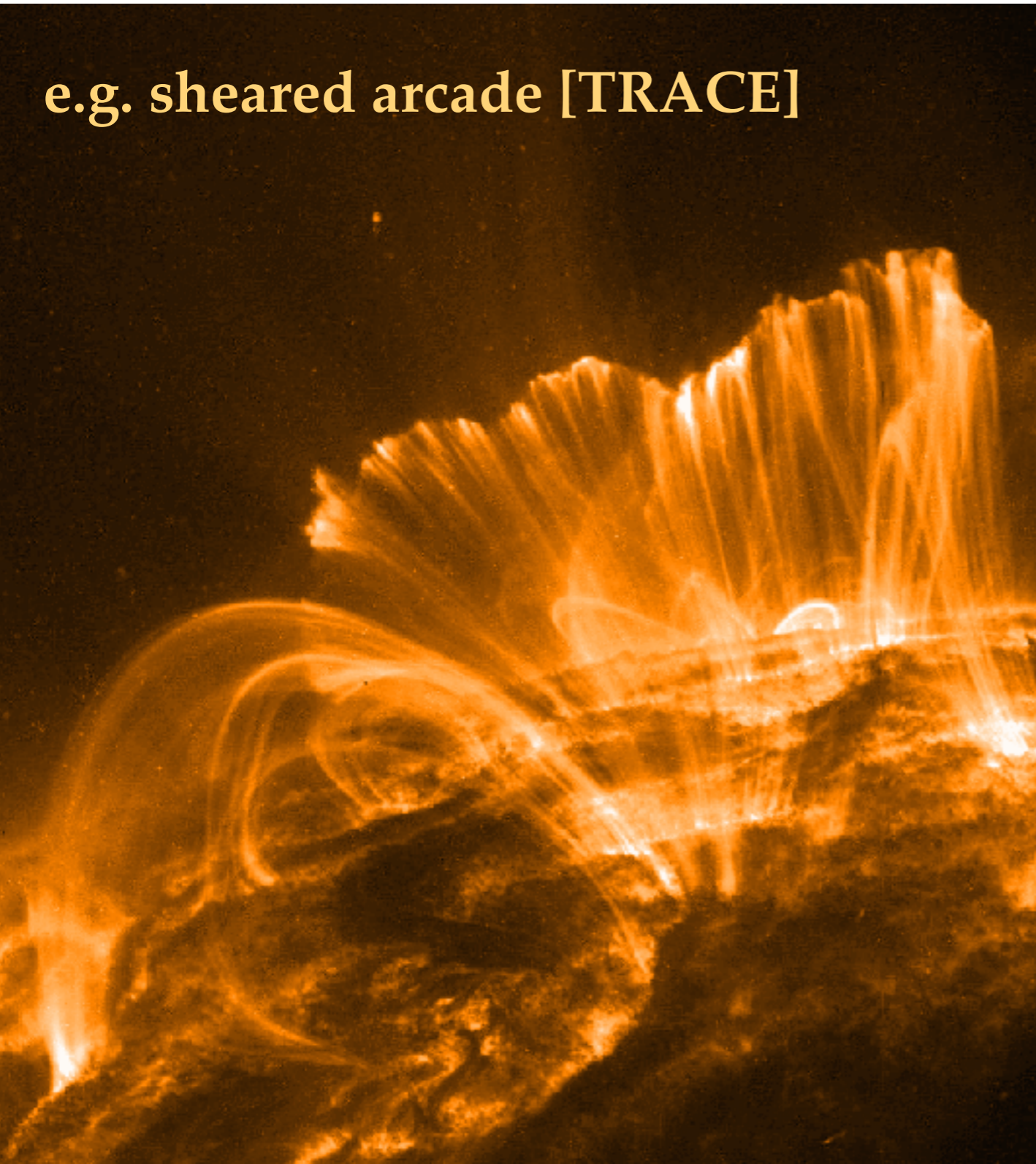
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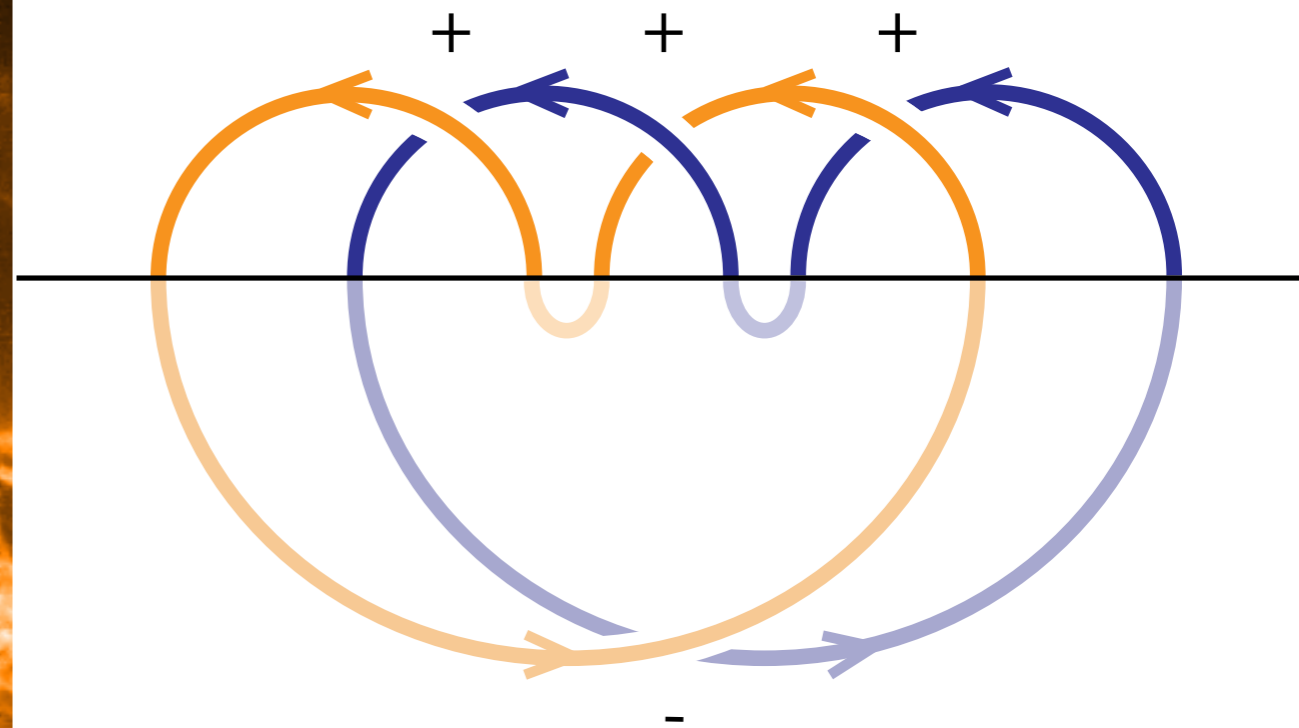
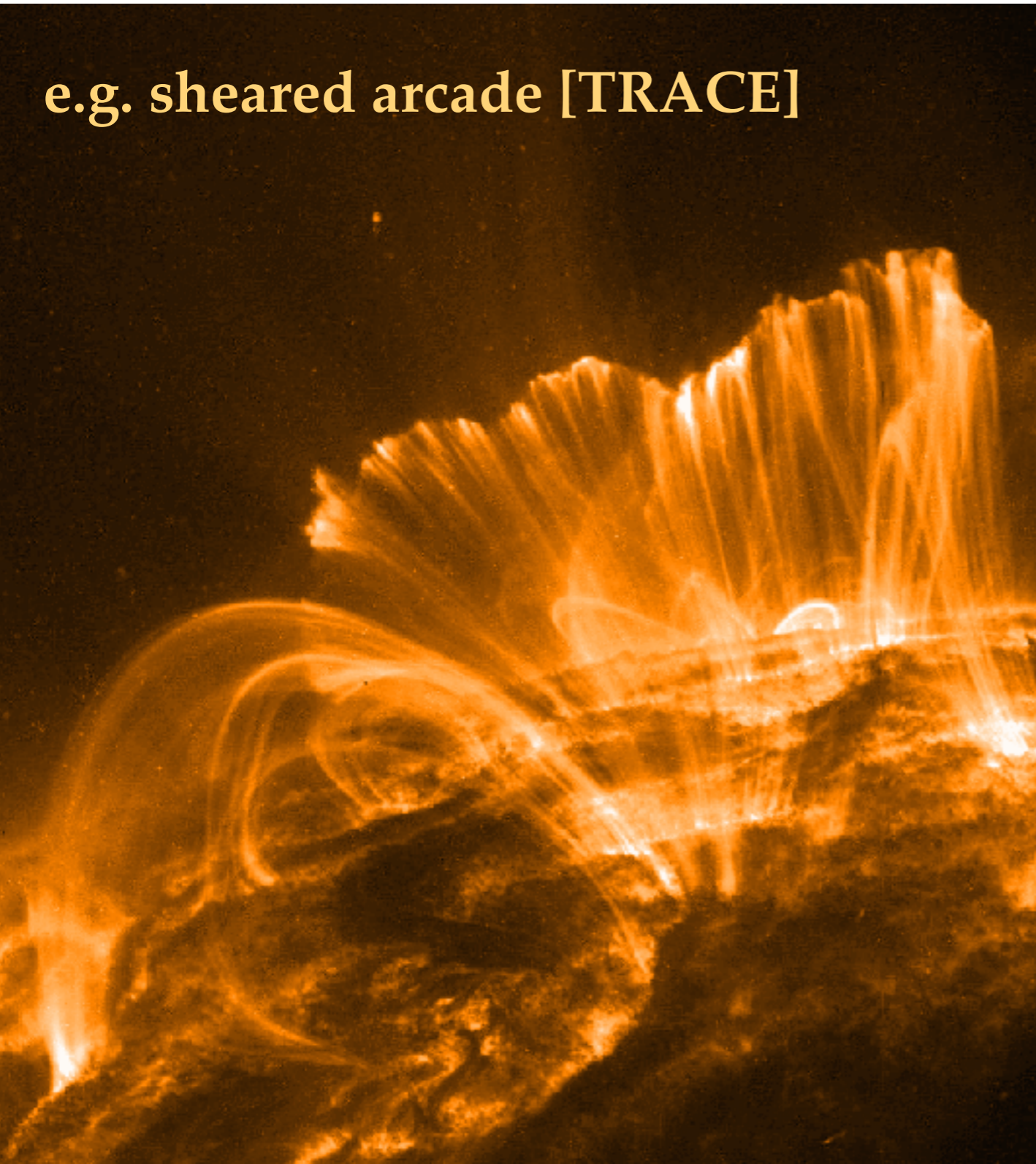


currents

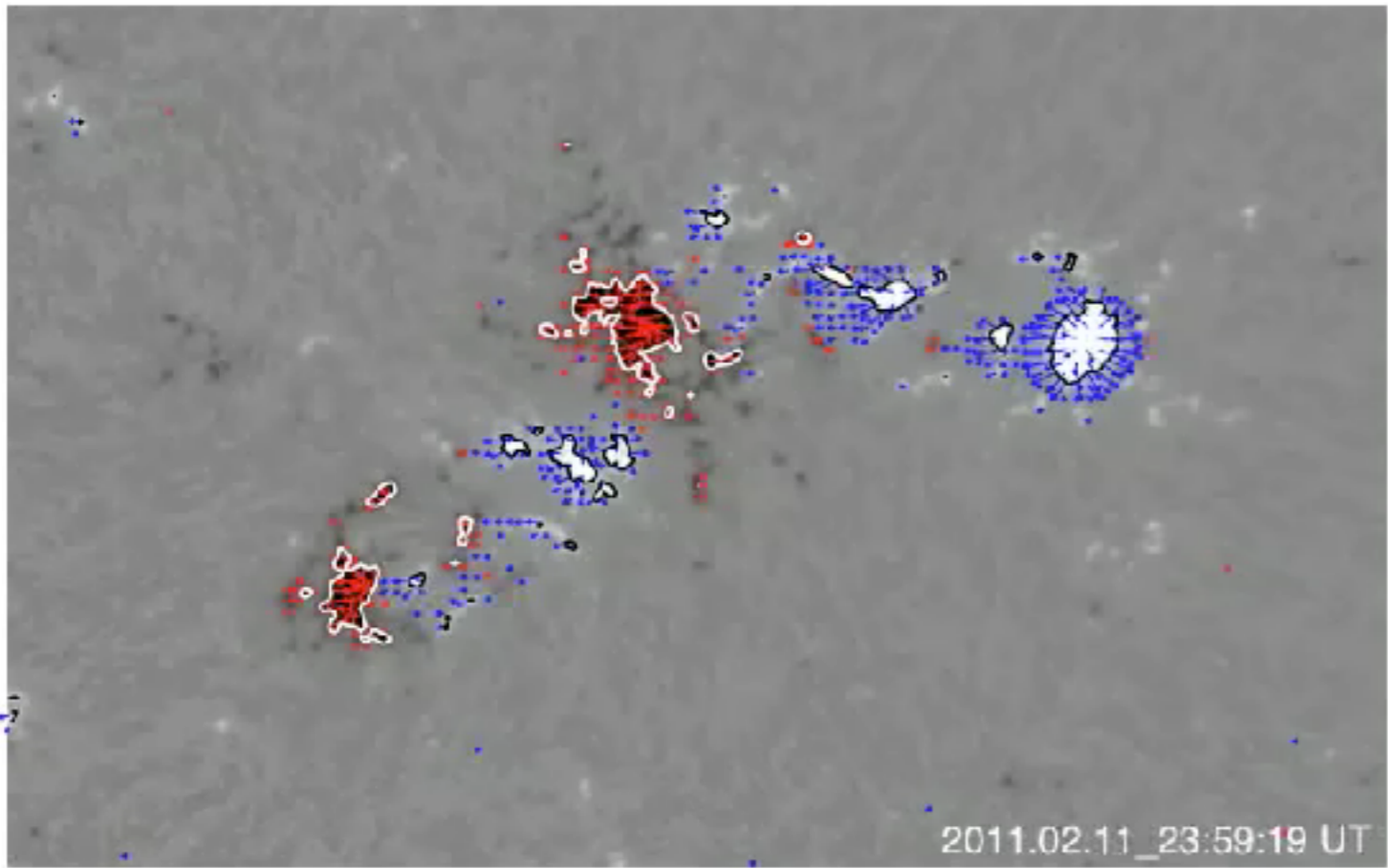
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Berger & Field, *J. Fluid Mech.* [1984]
Démoulin & Berger, *Solar Phys.* [2003]

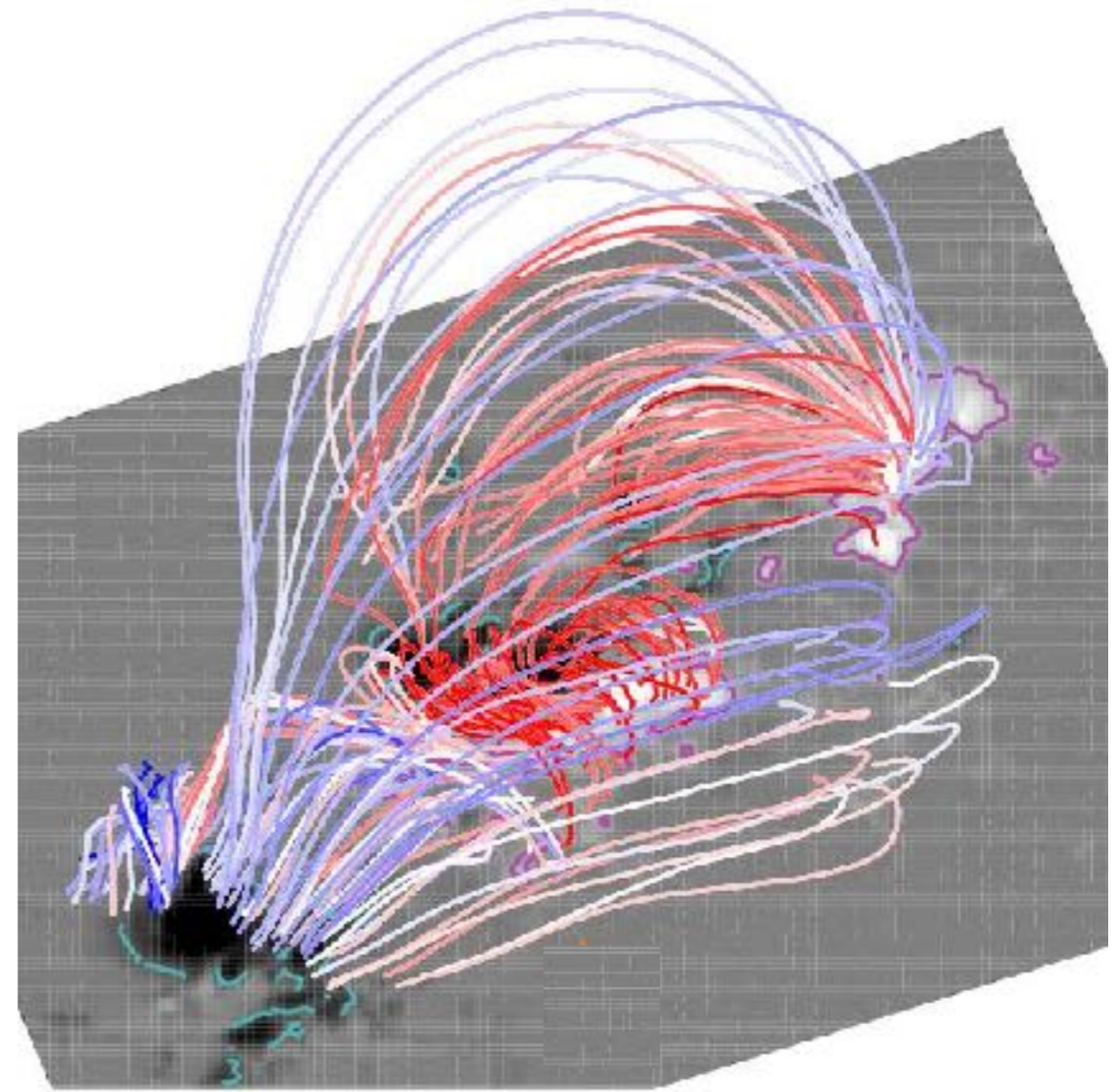
e.g. sheared arcade [TRACE]



no currents in extension



e.g. Sun et al., *ApJ* [2012]



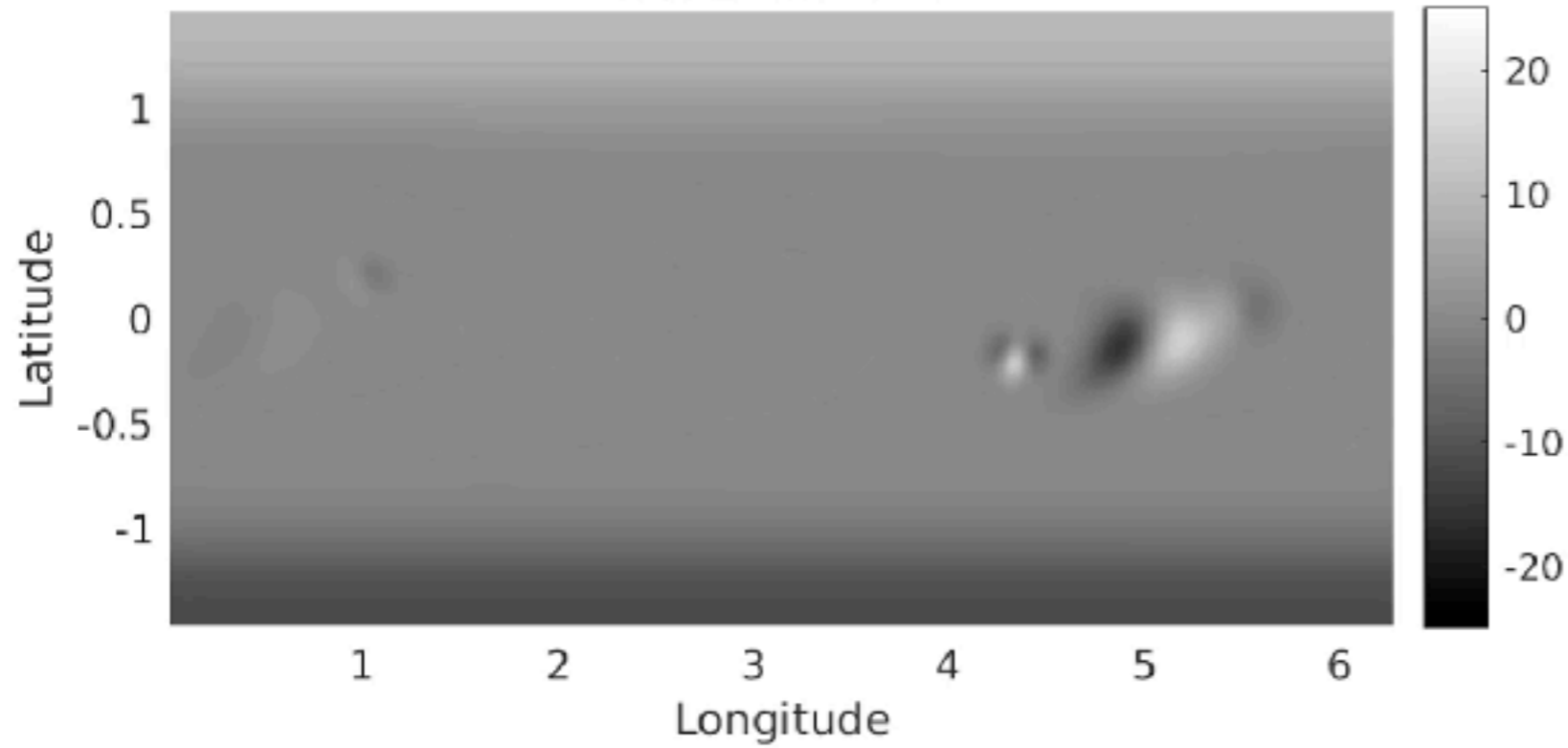
e.g. Dalmasse et al., *A&A* [2013]

Observation 1:

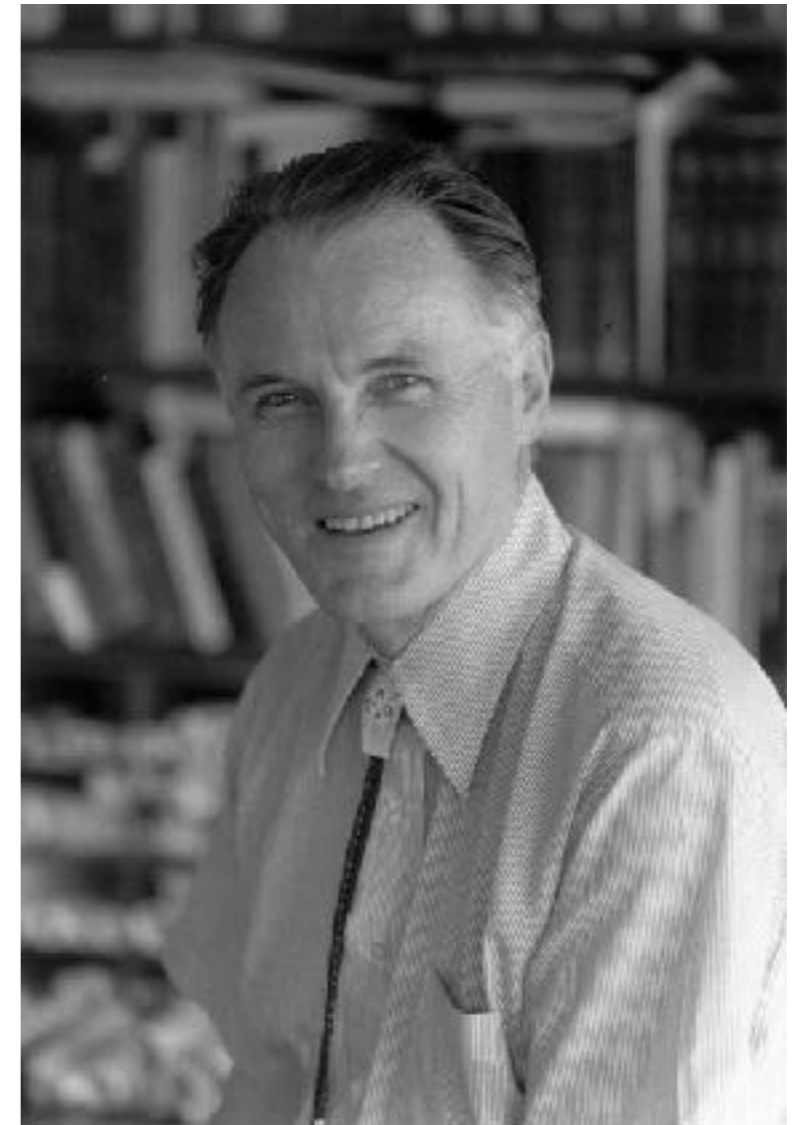
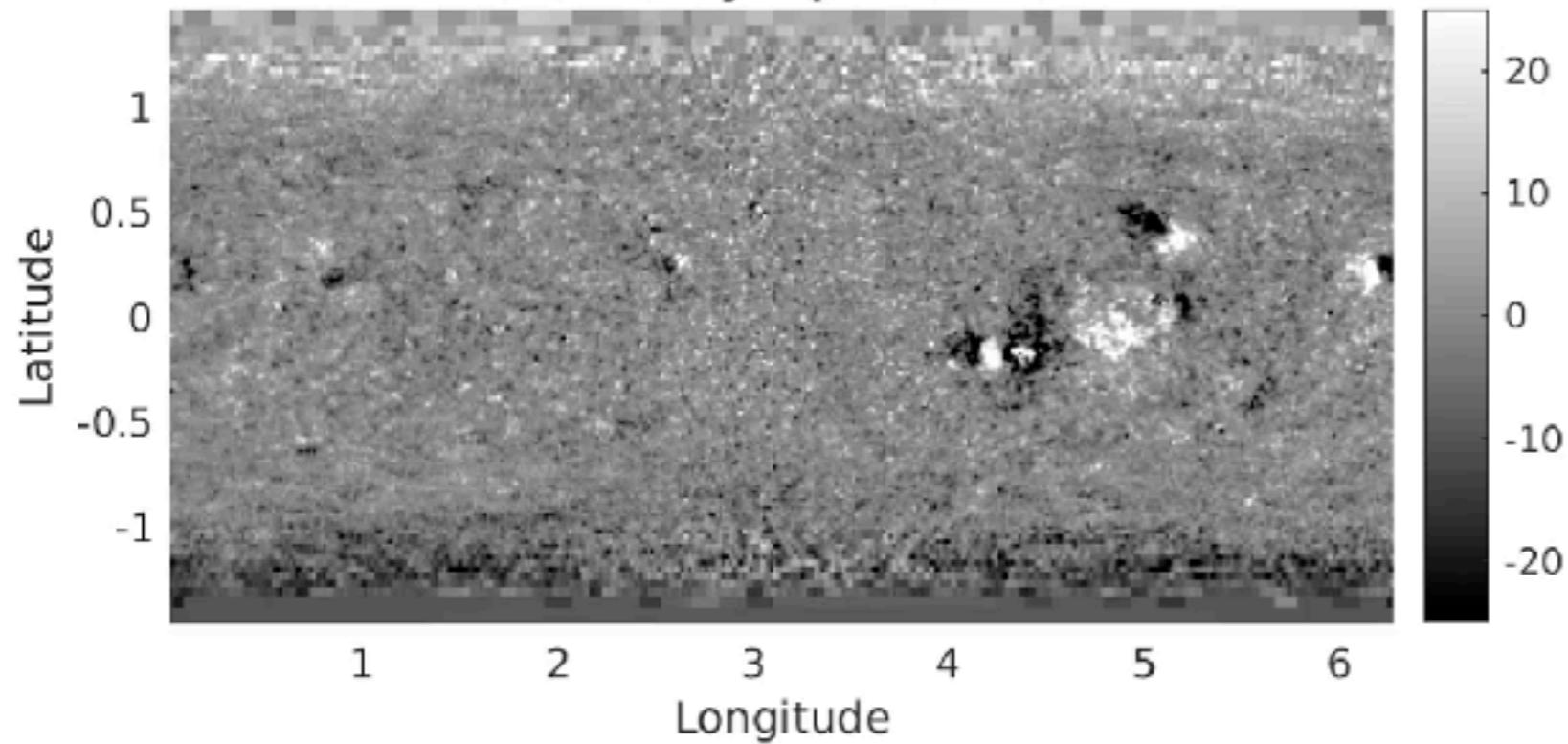
Active region emergence generates $\sim 10^{46}$ Mx² per cycle.

LaBonte et al., *ApJ* [2007]
Georgoulis et al., *ApJL* [2009]

End of CR 1911

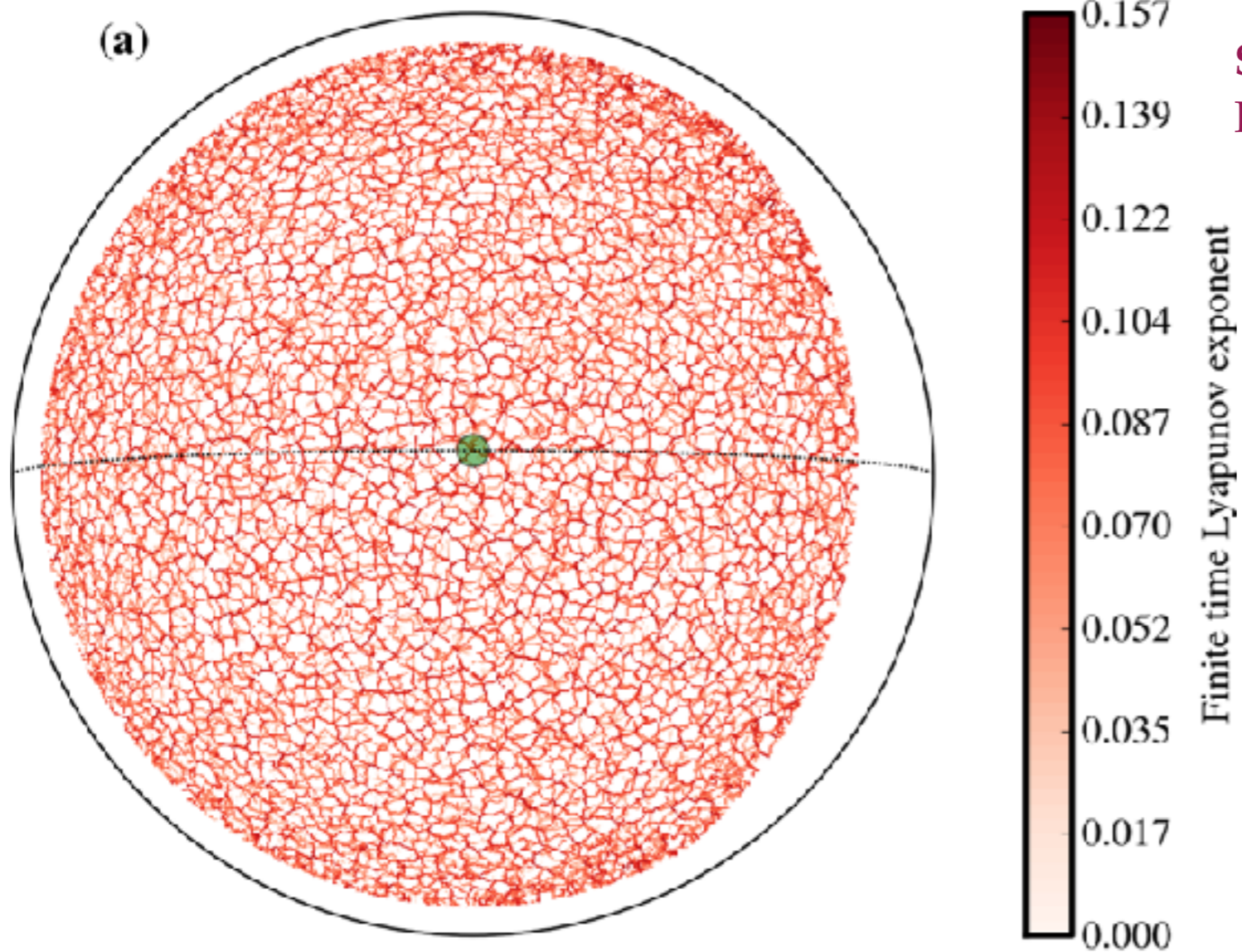


Observed synoptic CR 1911



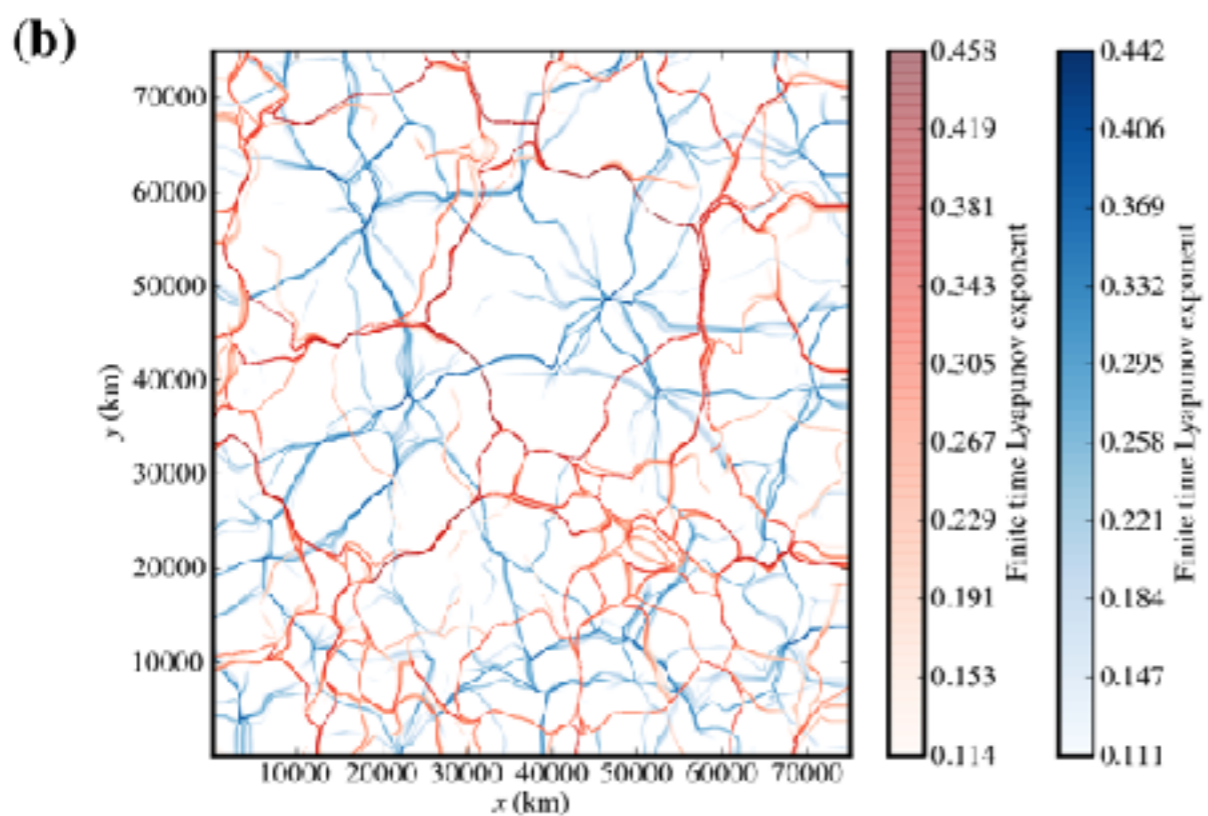
Leighton, *ApJ* [1964]

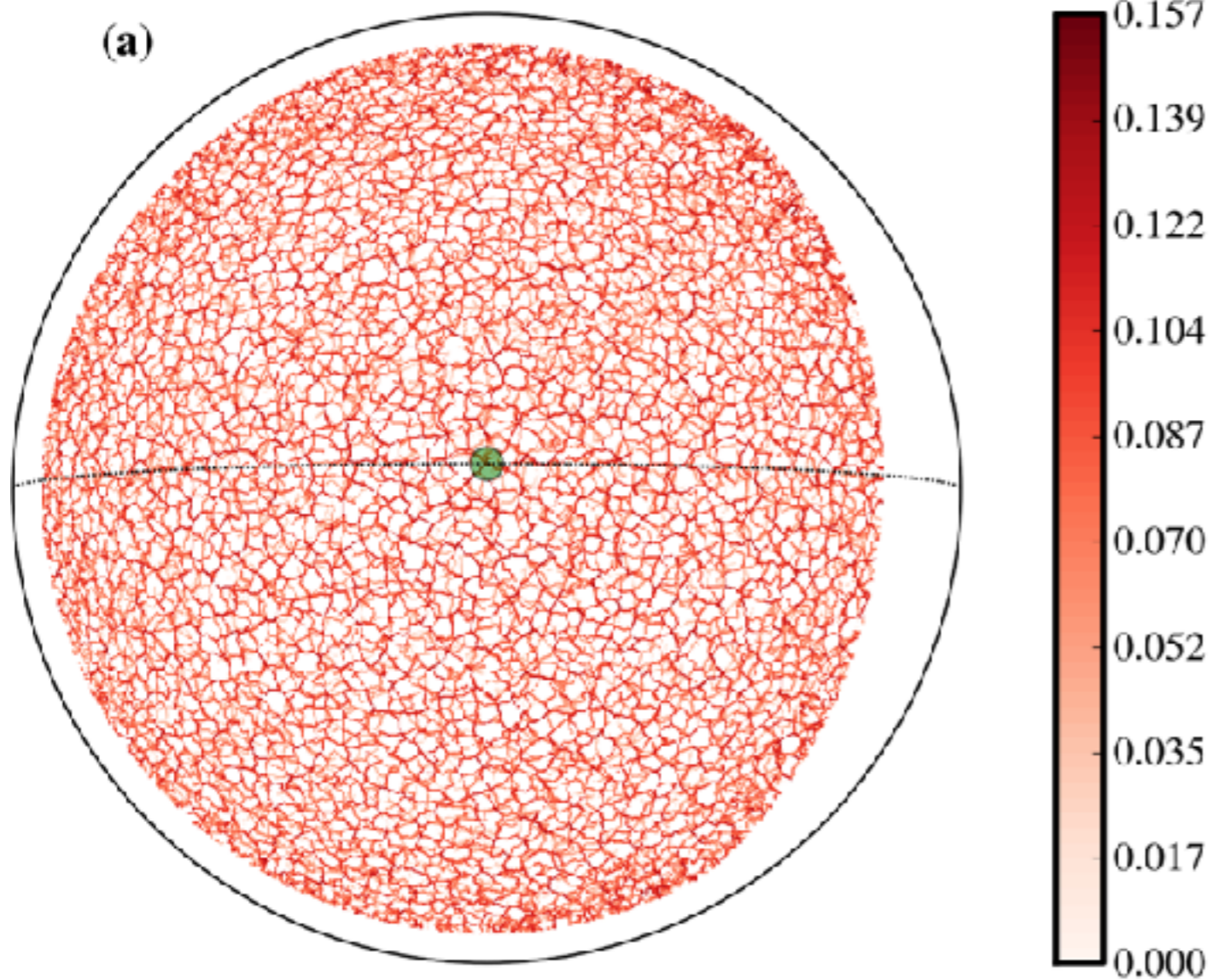
DeVore et al, *Solar Phys.* [1984]



SDO data:

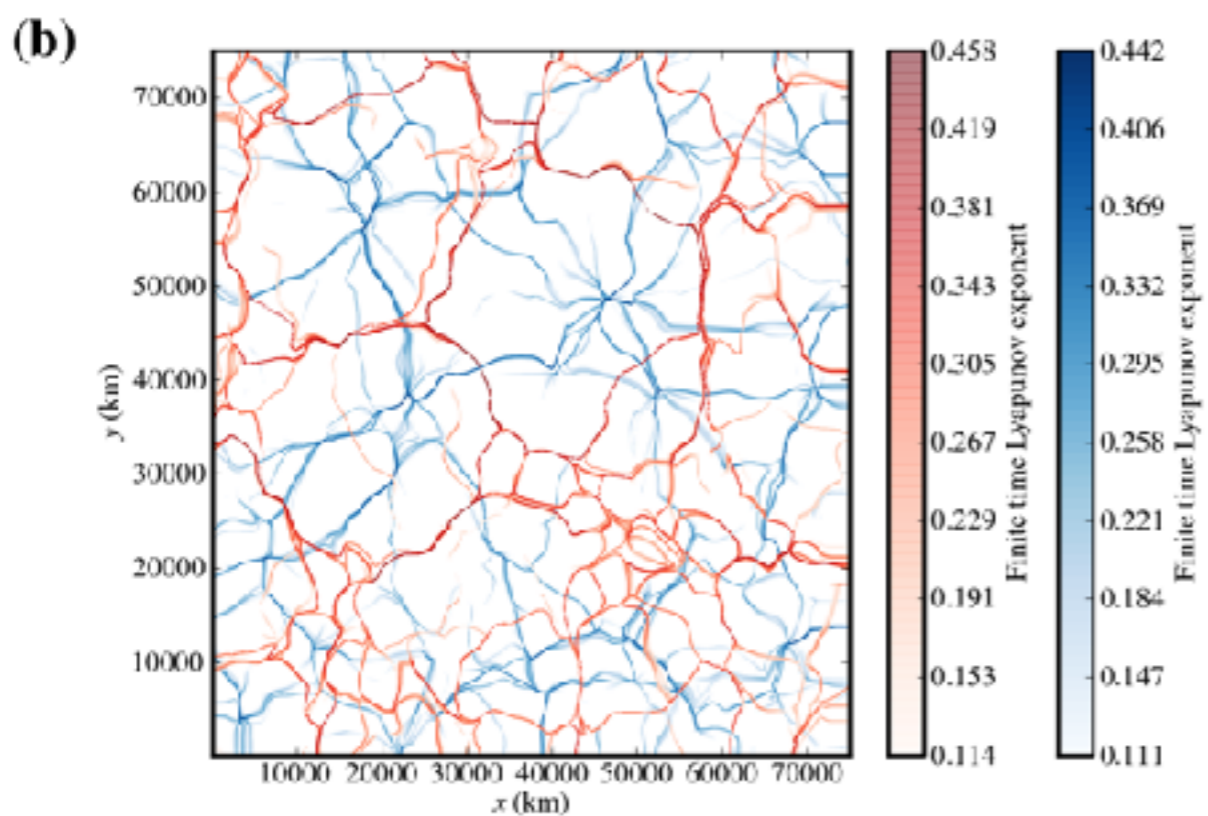
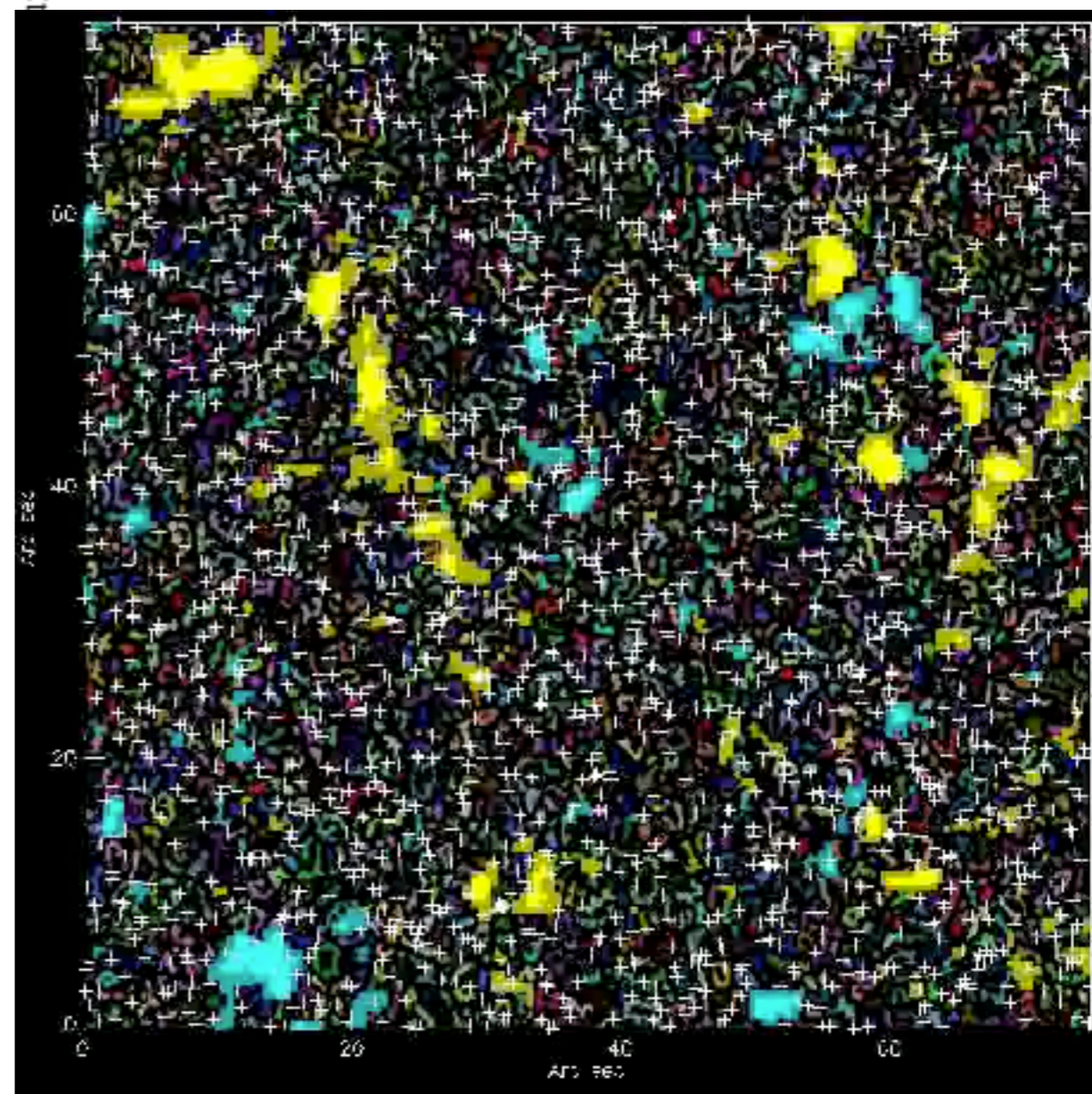
Rincon & Rieutord, *Living Rev. Solar Phys.* [2018]





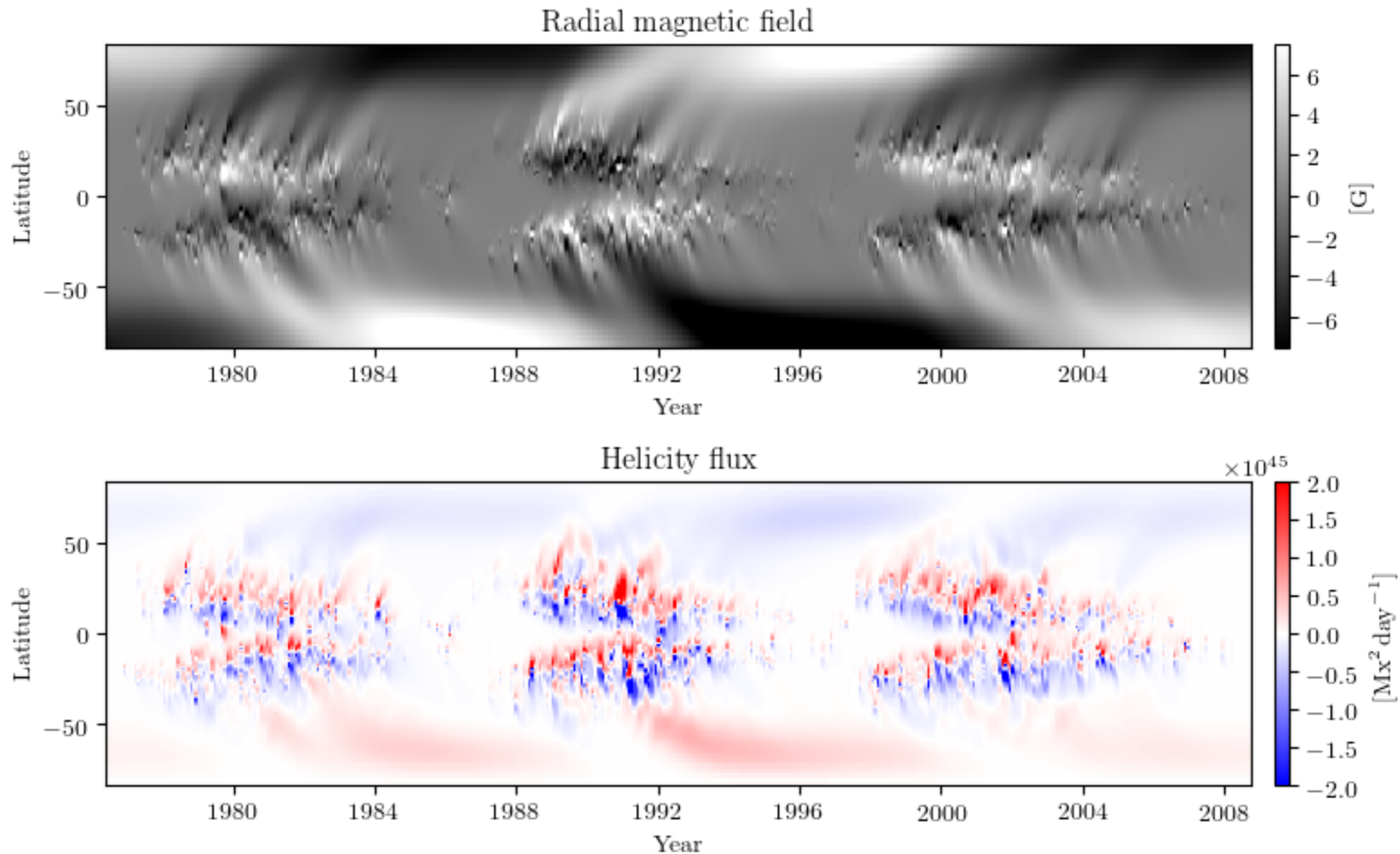
SDO data:

Rincon & Rieutord, *Living Rev. Solar Phys.* [2018]



Hinode and SDO data (24 hrs):

Roudier, Malherbe, Rieutord & Frank, *A&A* [2016]



Berger & Ruzmaikin, *JGR* [2000]
 Hawkes & Berger, *Solar Phys.* [2018]
 Hawkes & Yeates, *in preparation.*

Observation 2:

Solar rotation generates $\sim 2 \times 10^{46} \text{ Mx}^2$ per hemisphere per cycle.

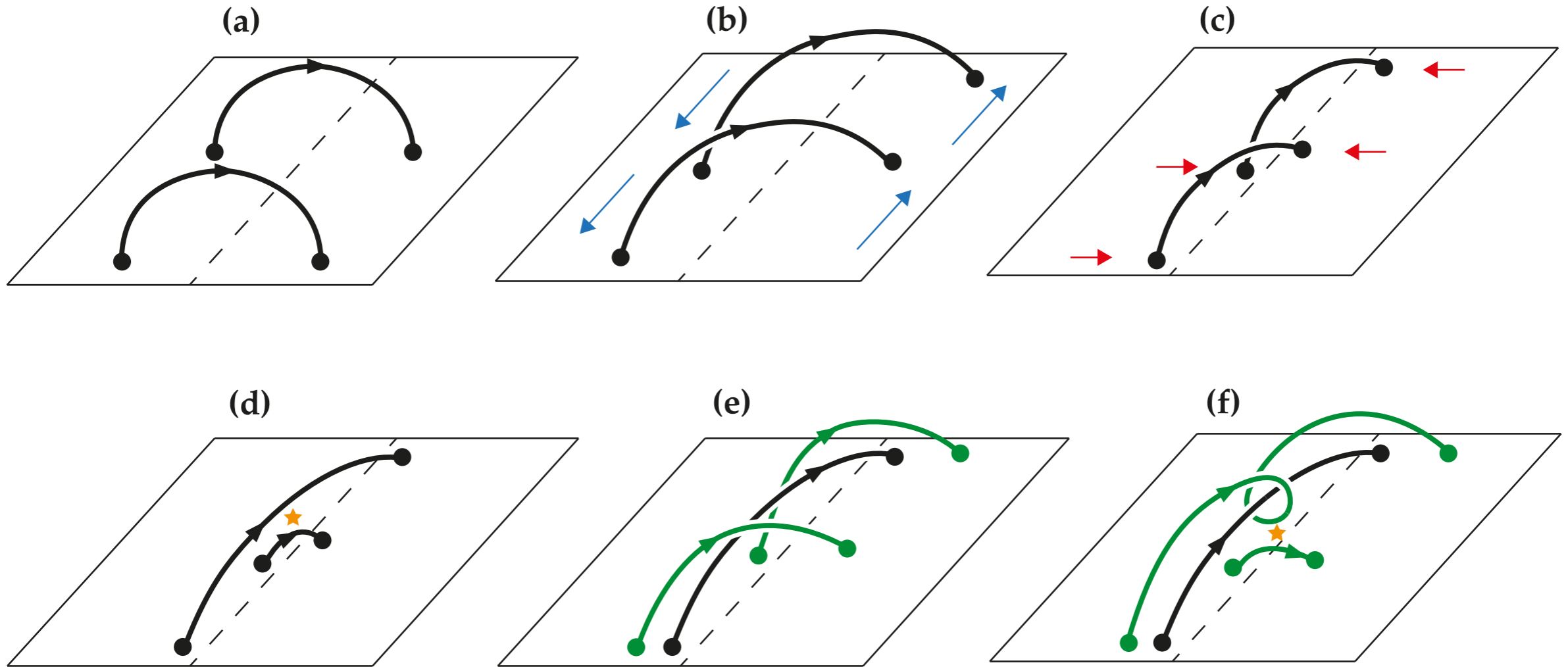
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****small-scale convection is critical!****

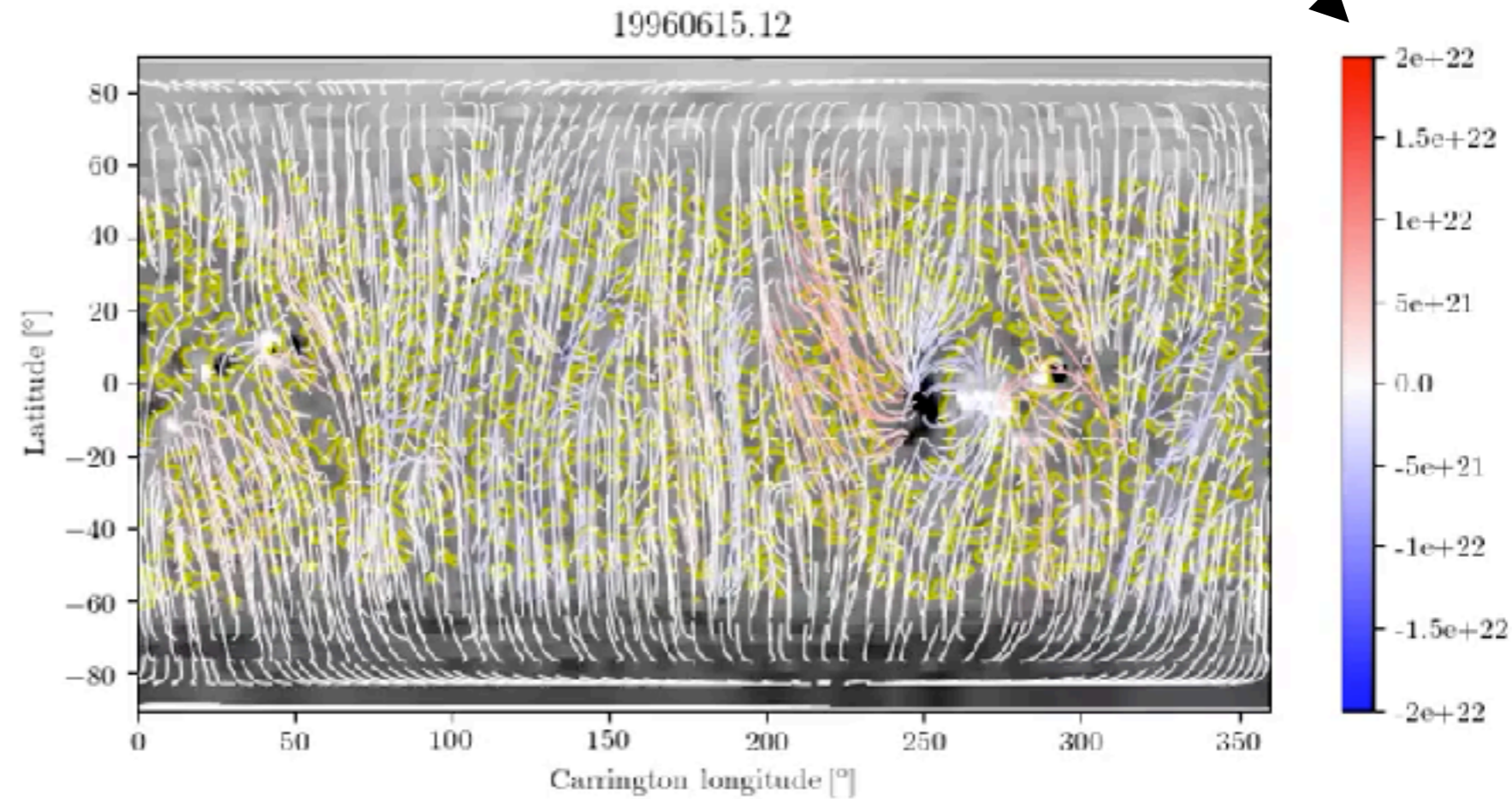
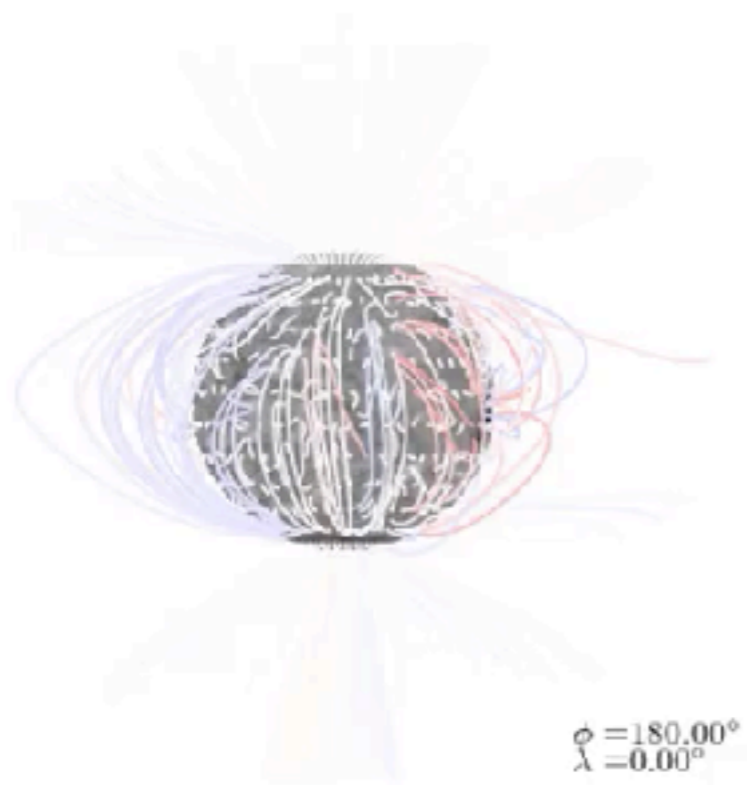
helicity
injection

diffusion



reconnection

field-line helicity

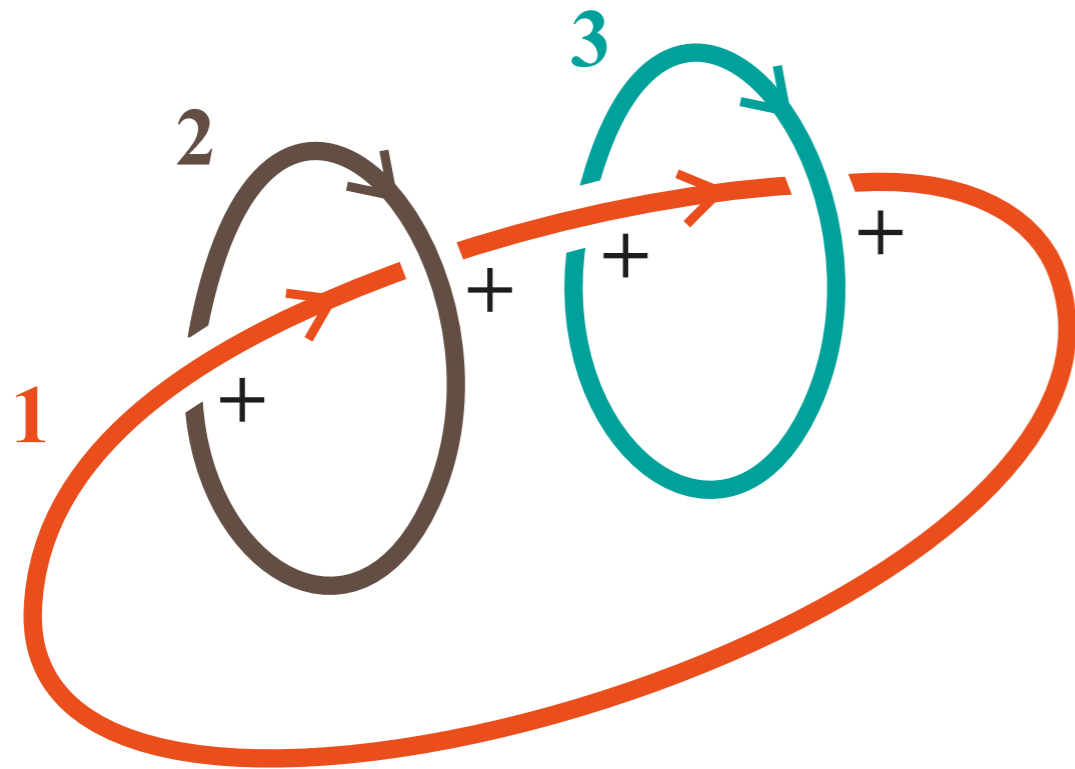


Magneto-frictional model: van Ballegooijen, Priest & Mackay, *ApJ* [2000]

Full solar cycle simulation: Yeates, *Solar Phys.* [2014]

Field line helicity - the net linkage of magnetic flux with one field line.

$$H = \frac{1}{2} \sum_i \mathcal{A}_i \Phi_i \quad \text{where} \quad \mathcal{A}_i = \sum_j L_{ij} \Phi_j$$

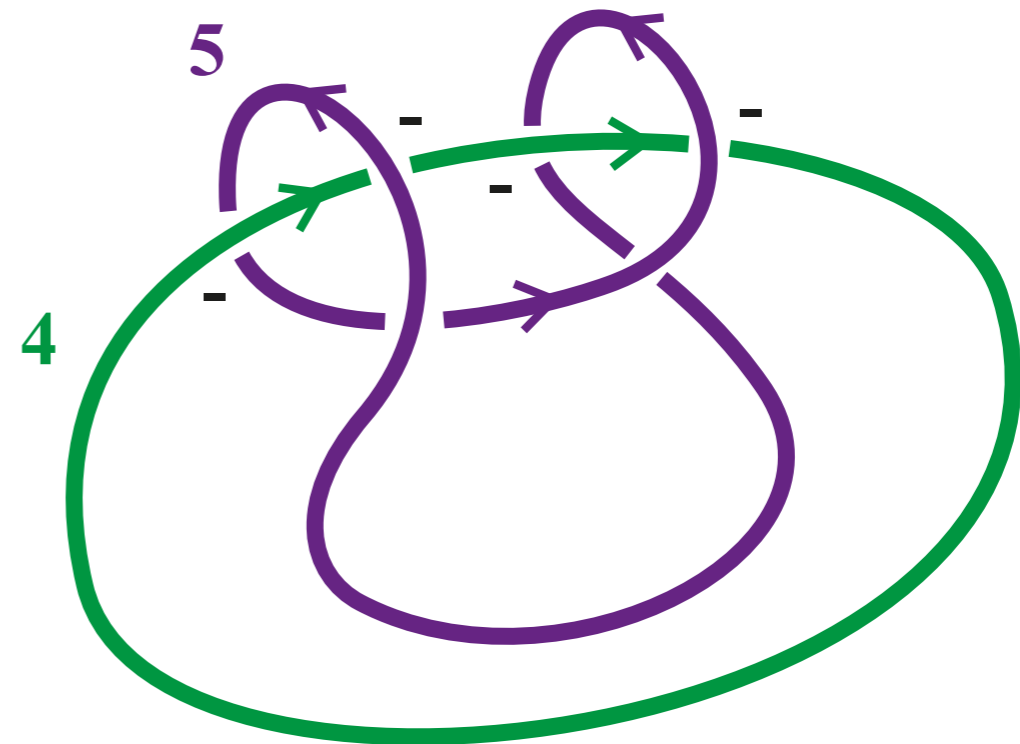


$$H = \Phi_1 \Phi_2 + \Phi_1 \Phi_3$$

$$\mathcal{A}_1 = \Phi_2 + \Phi_3$$

$$\mathcal{A}_2 = \Phi_1$$

$$\mathcal{A}_3 = \Phi_1$$



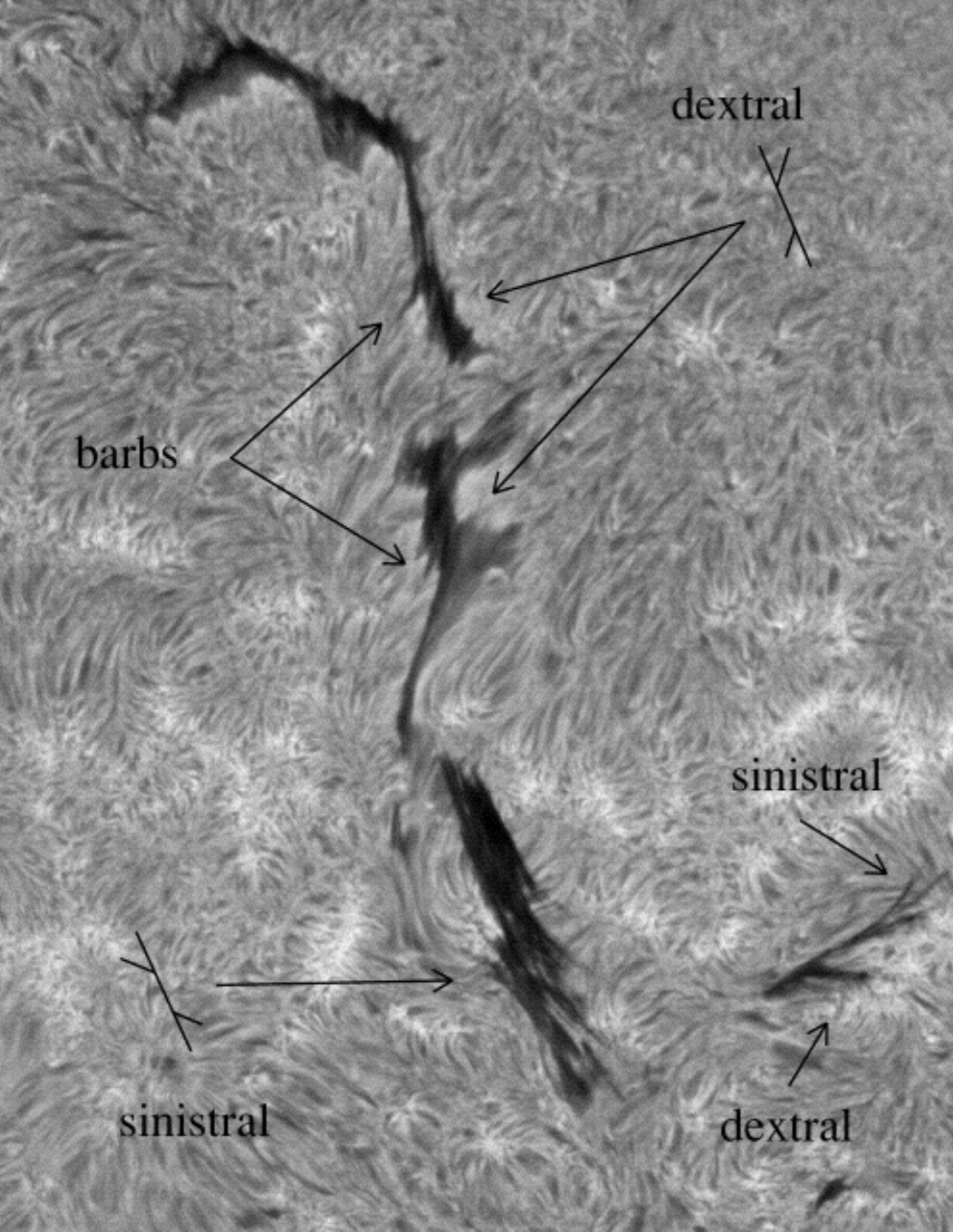
$$H = -2\Phi_4 \Phi_5$$

$$\mathcal{A}_4 = -2\Phi_5$$

$$\mathcal{A}_5 = -2\Phi_4$$

Berger, A&A [1988]

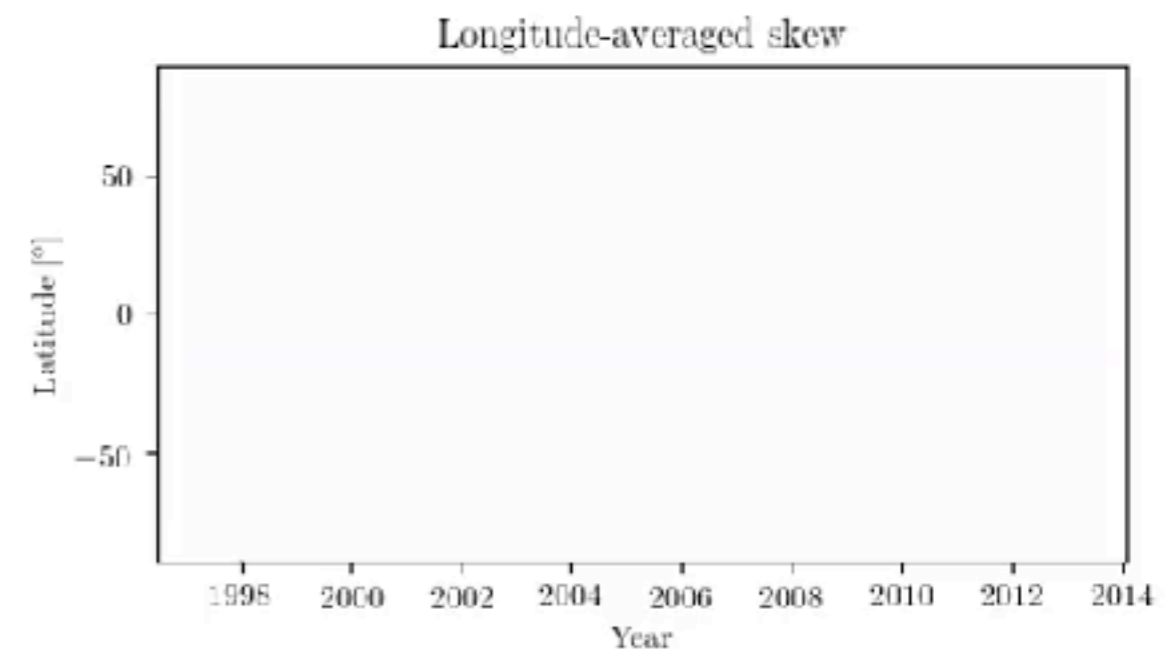
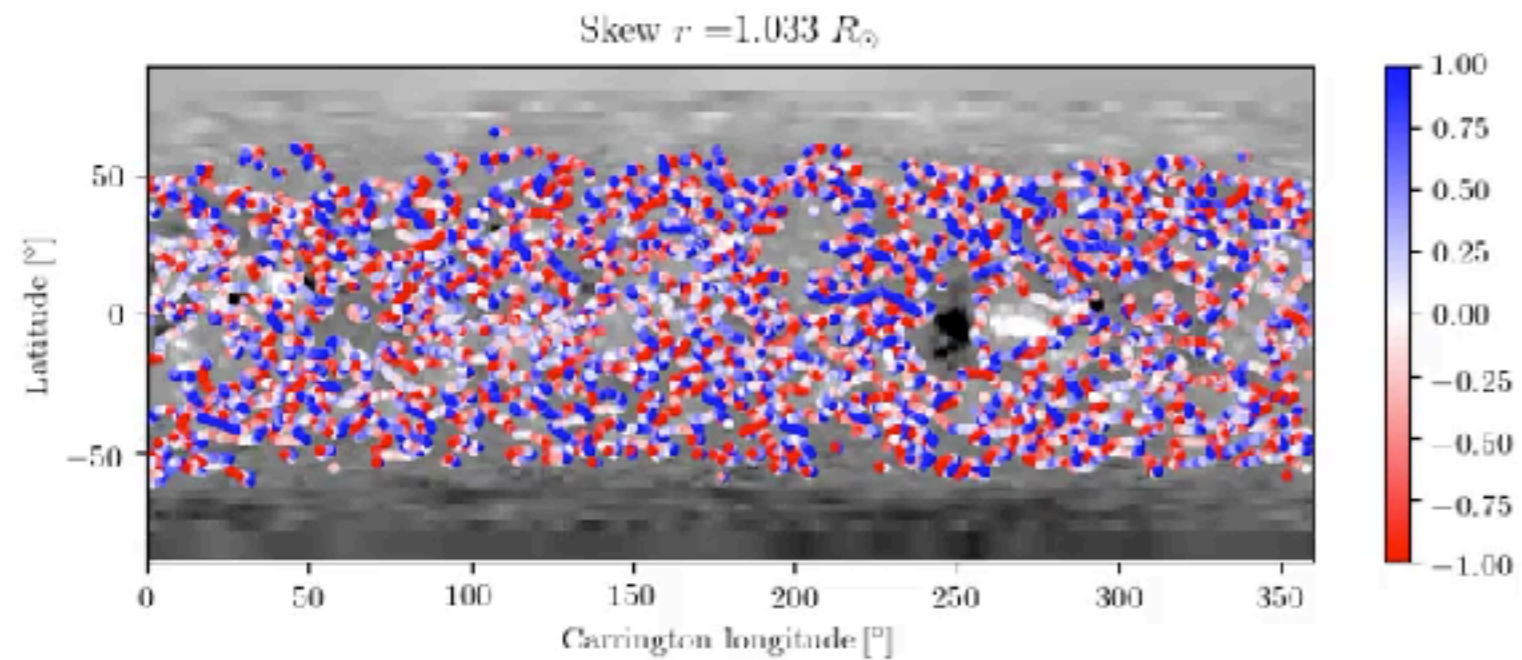
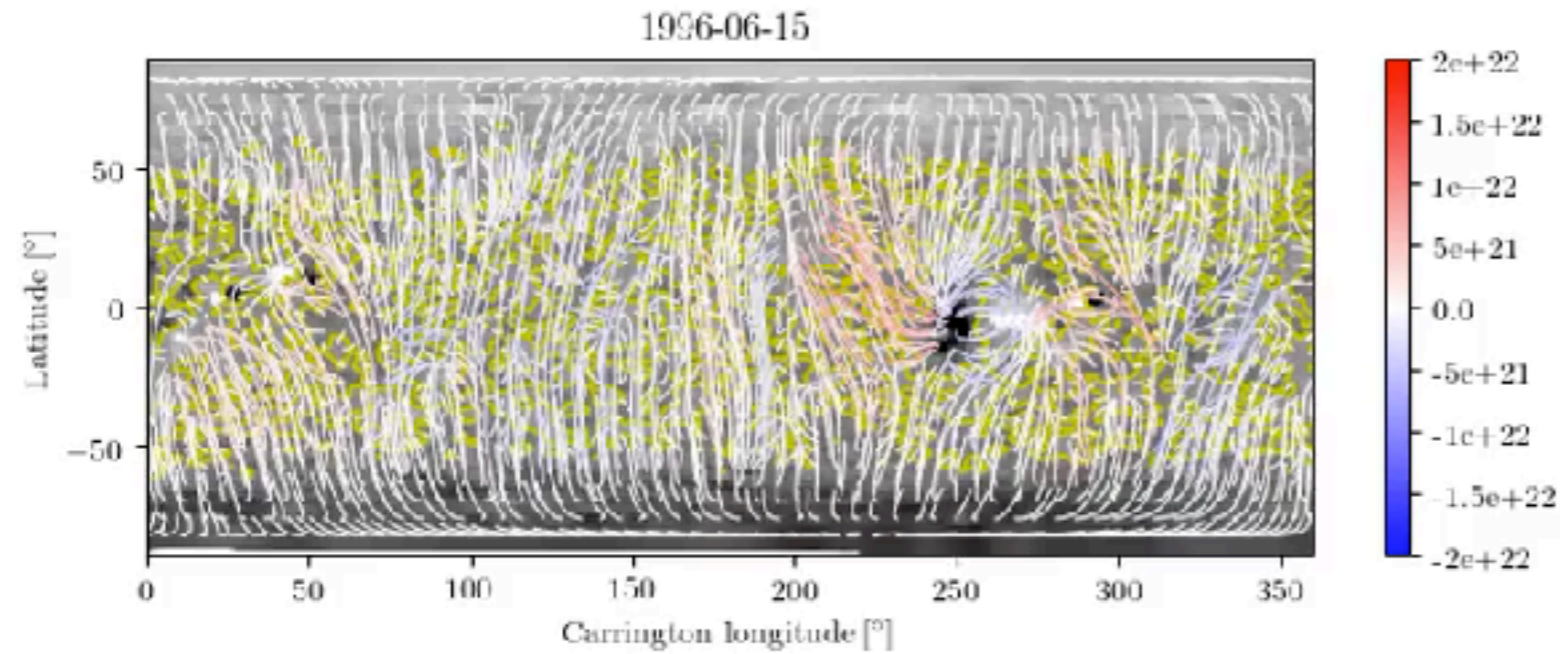
Yeates & Hornig, A&A [2016]



H α

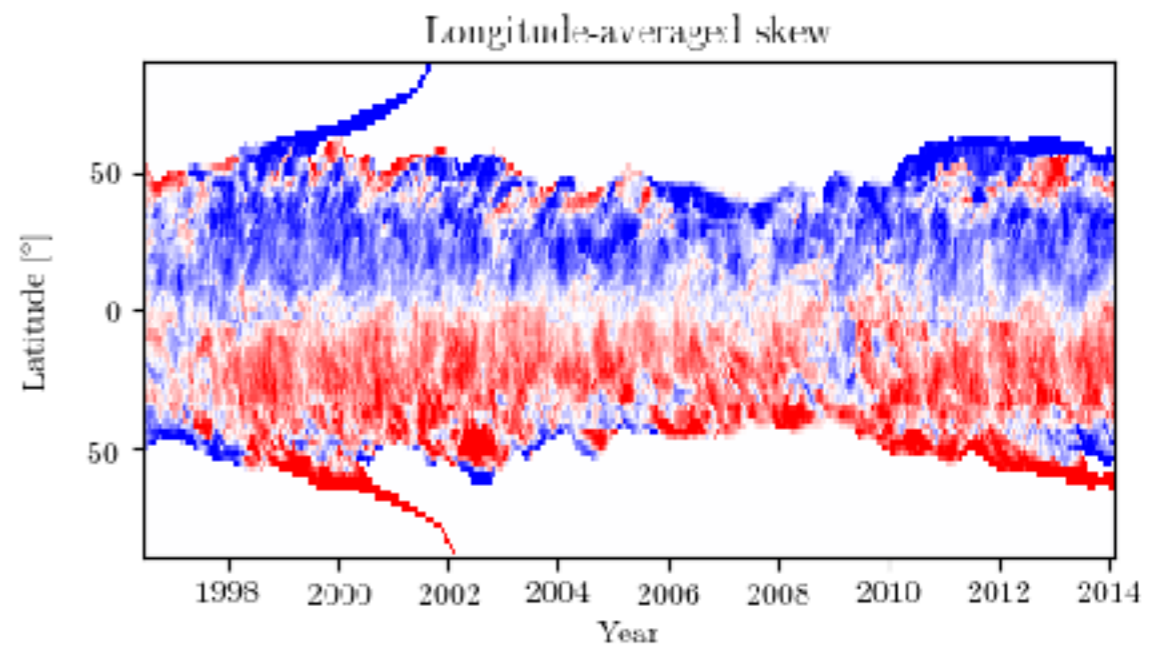
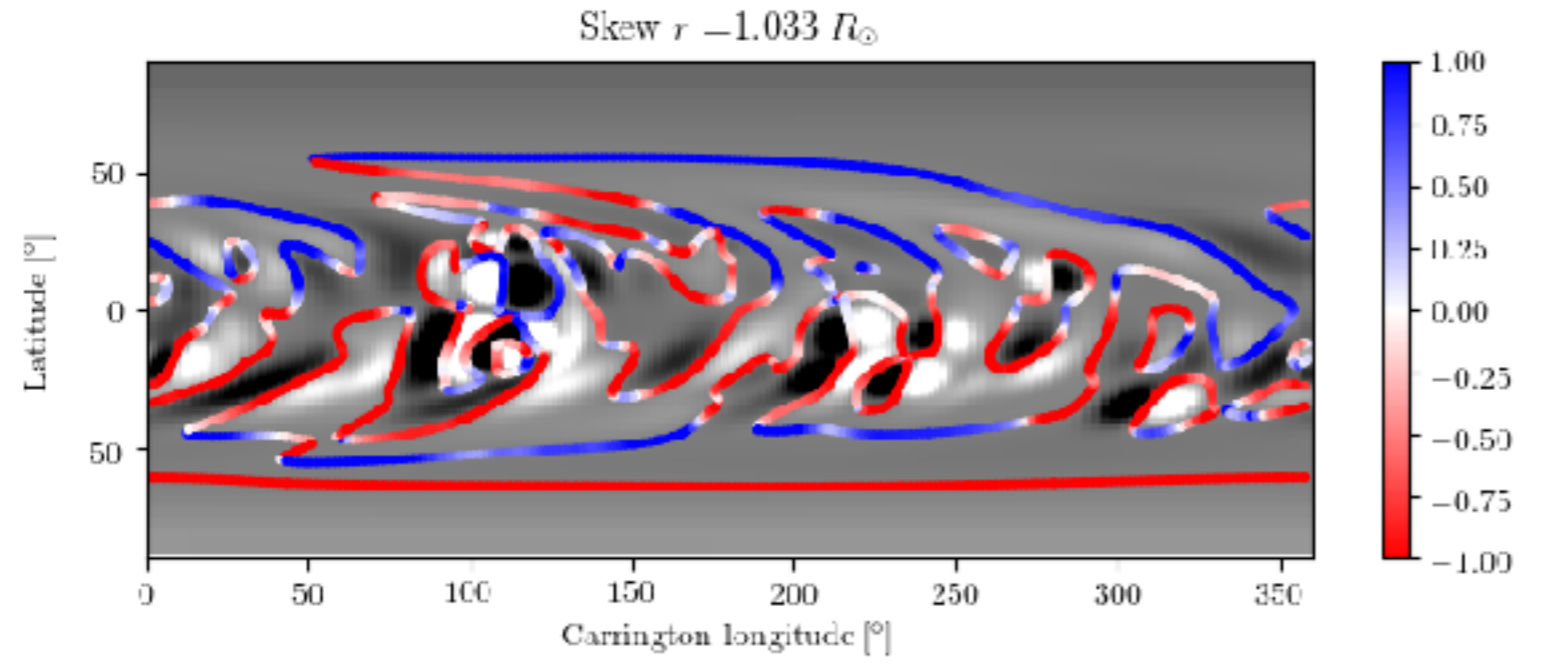
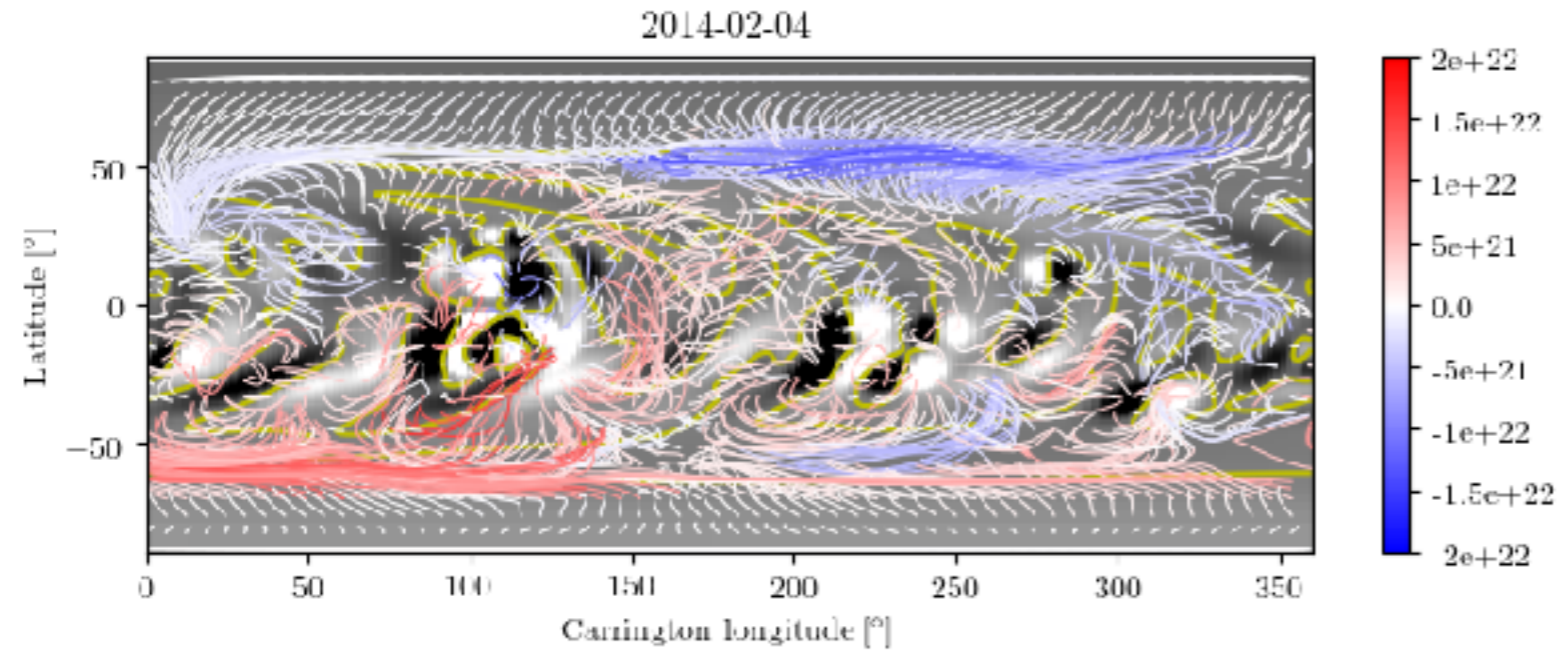
Martin, Bilimoria & Tracadas. [1994]

Pevtsov, Balasubramaniam & Rogers, *ApJ* [2003]

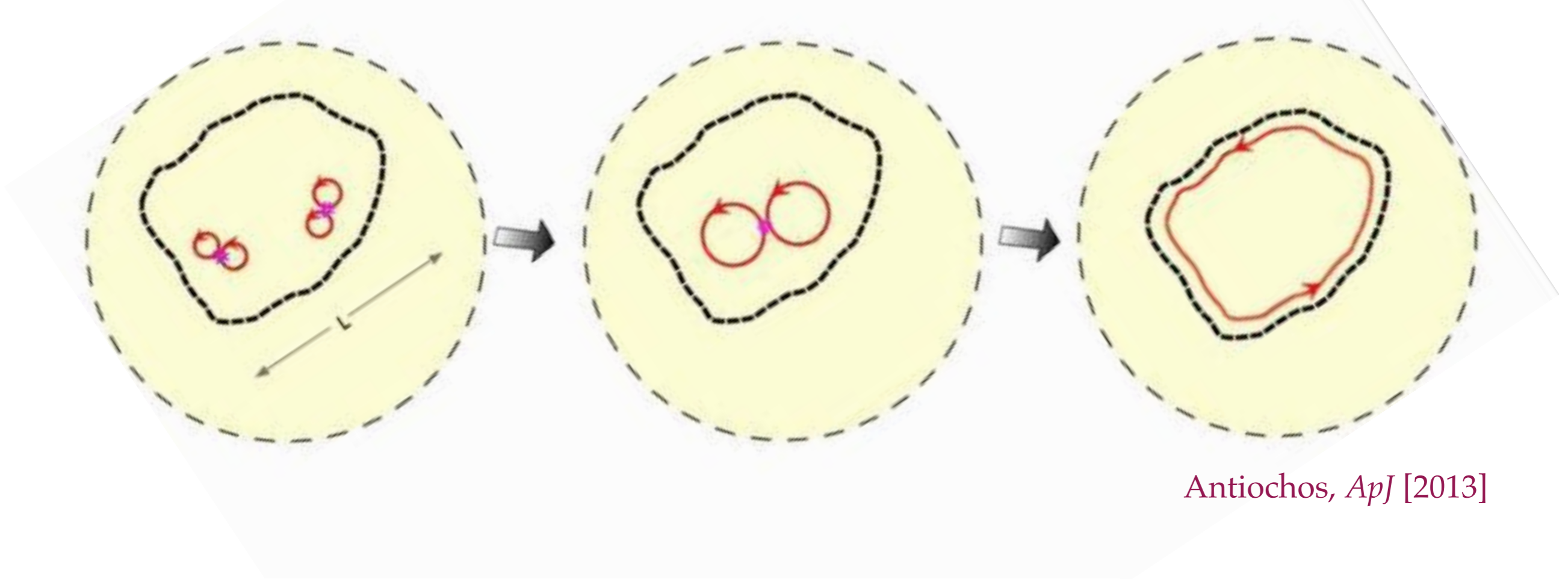


Yeates, Mackay & van Ballegooijen, *Solar Phys.* [2008, 2009]

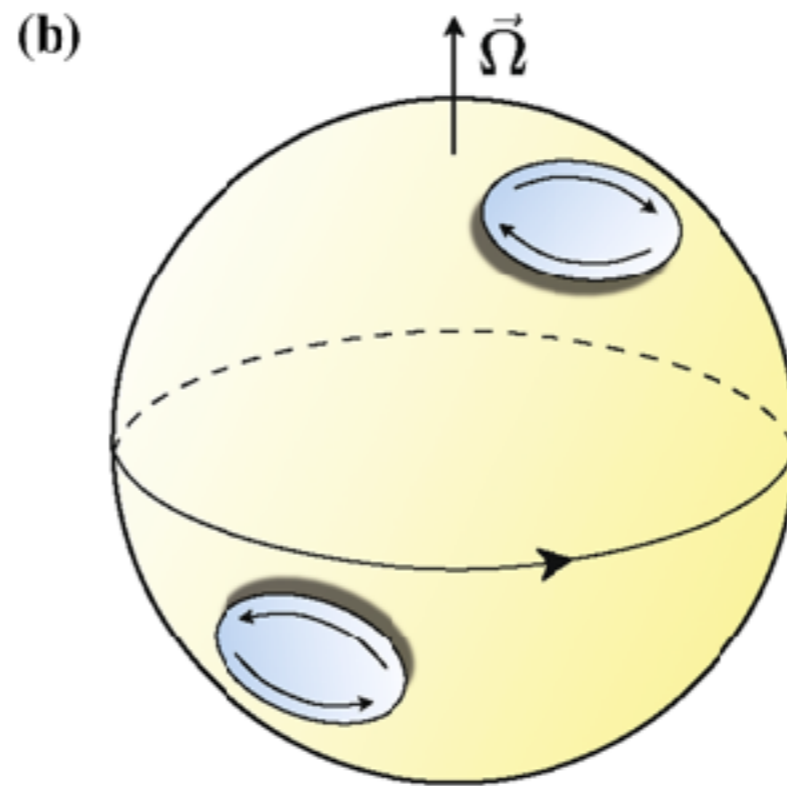
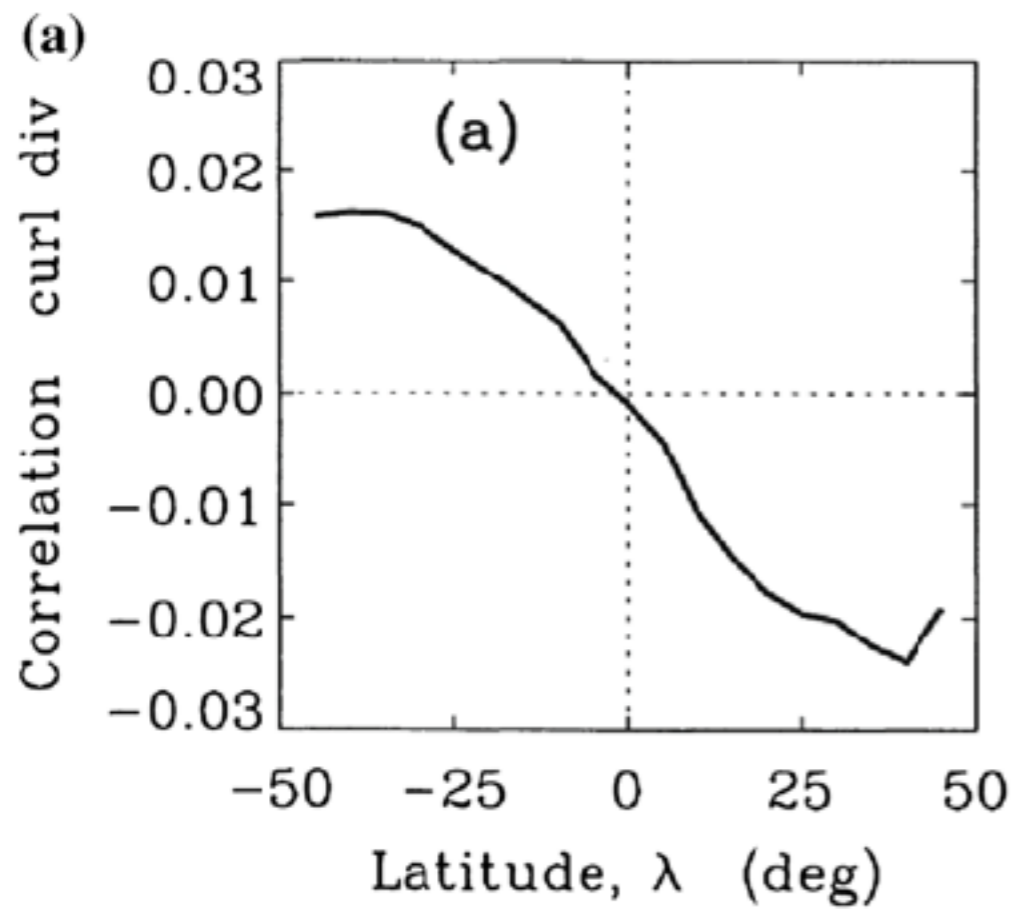
Yeates & Mackay, *ApJL* [2012]



Yeates, Mackay & van Ballegooijen, *Solar Phys.* [2008, 2009]
Yeates & Mackay, *ApJL* [2012]

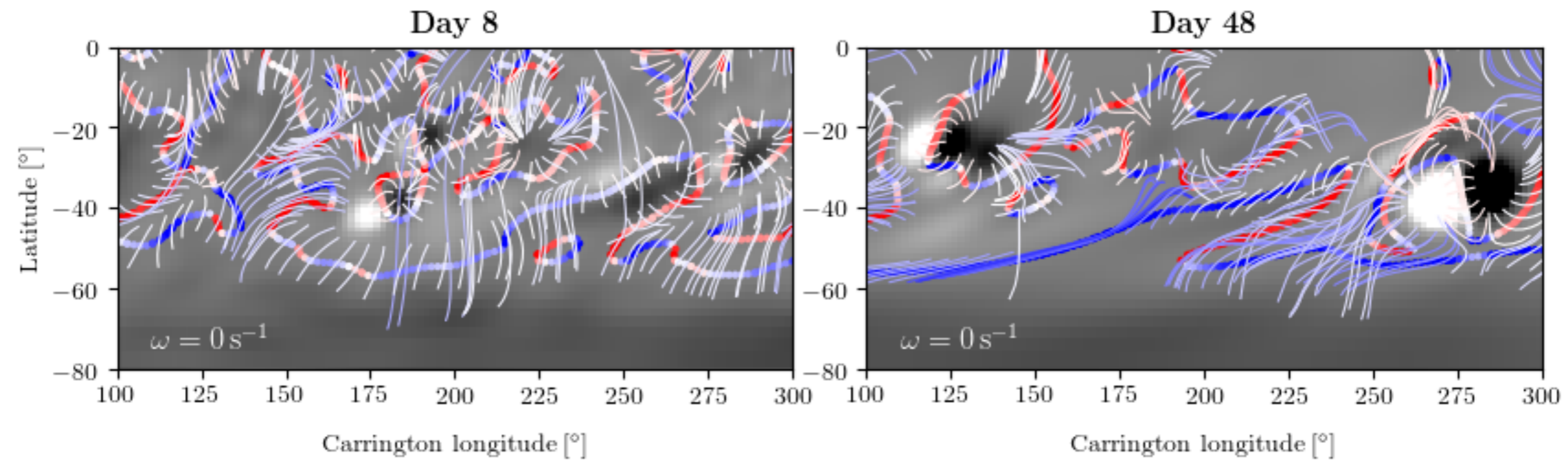


Antiochos, *ApJ* [2013]



Observed
supergranular
vorticity
 $\sim 10^{-6} \text{ s}^{-1}$

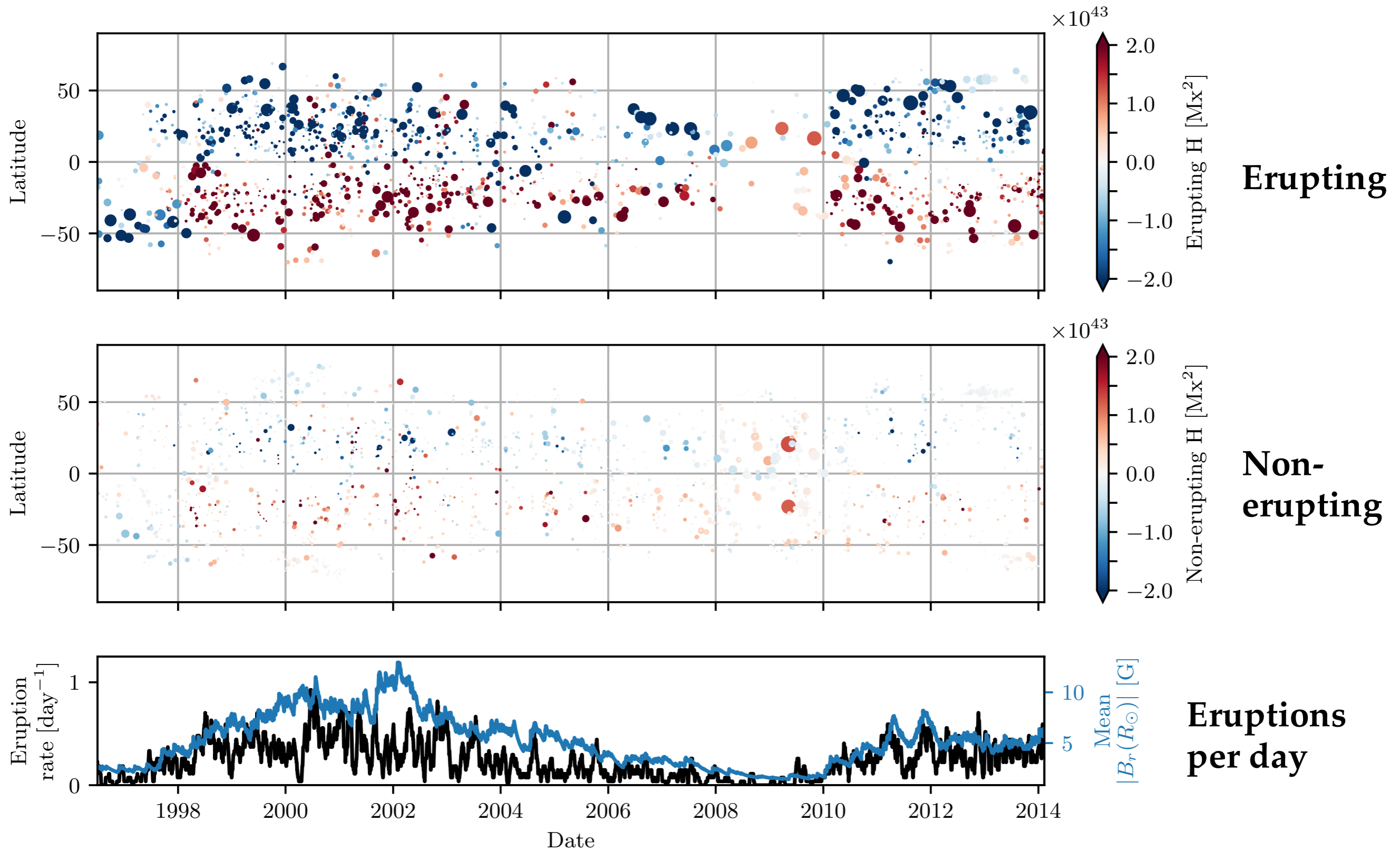
Gizon & Duvall [2003]
Komm et al., *ApJ* [2007]



Mackay, DeVore, Antiochos & Yeates, *ApJ* [2018]

FUNDAMENTALS OF CORONAL EVOLUTION:

1. Magnetic helicity is injected by surface motions.
2. It accumulates at polarity inversion lines.
- 3. It is removed by coronal mass ejections.**



Total helicity removed in eruptions $\sim 2.4 \times 10^{46} \text{ Mx}^2$

Conclusion

- 1. Magnetic helicity is injected by surface motions.**
- 2. It accumulates at polarity inversion lines.**
- 3. It is removed by coronal mass ejections.**

- **Progress this century so far:**
 - Observations and models —> general acceptance of this paradigm.
 - Quantitative measurements of helicity injected and ejected.
 - Improvement of helicity measures and computational methods.
- **In the rest of this century?**
 - Credible predictions of CME magnetic structure (and geo-effectiveness), and even advance warning of eruptions.
 - Better constraints on small-scale helicity injection.
 - Building detailed active-region models into global simulations.

<http://www.maths.dur.ac.uk/~bmjg46/>