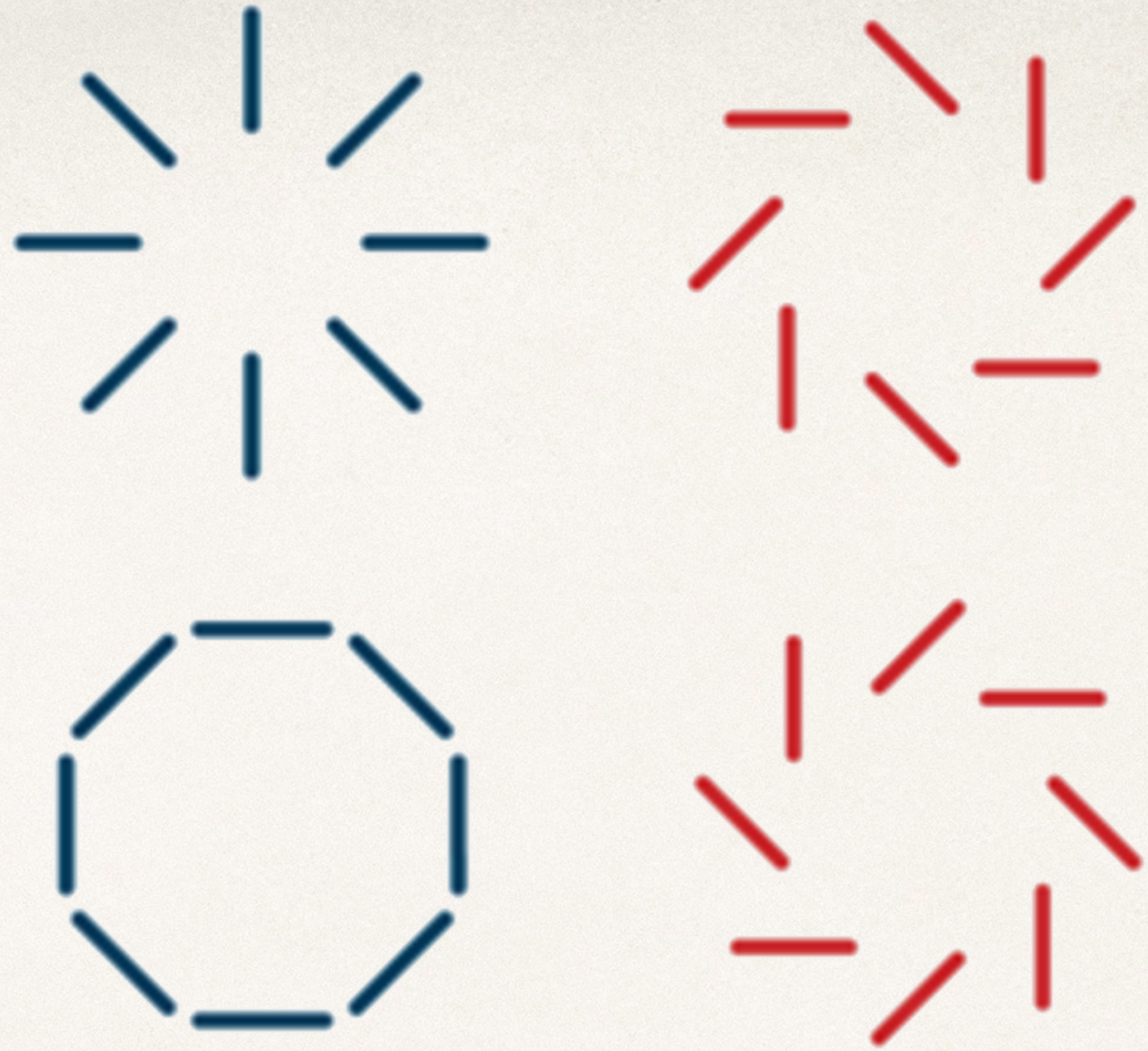

Helicity proxies from linear polarisation for solar active regions

Ameya Prabhu, Axel Brandenburg, Maarit Käpylä, Andreas Lagg

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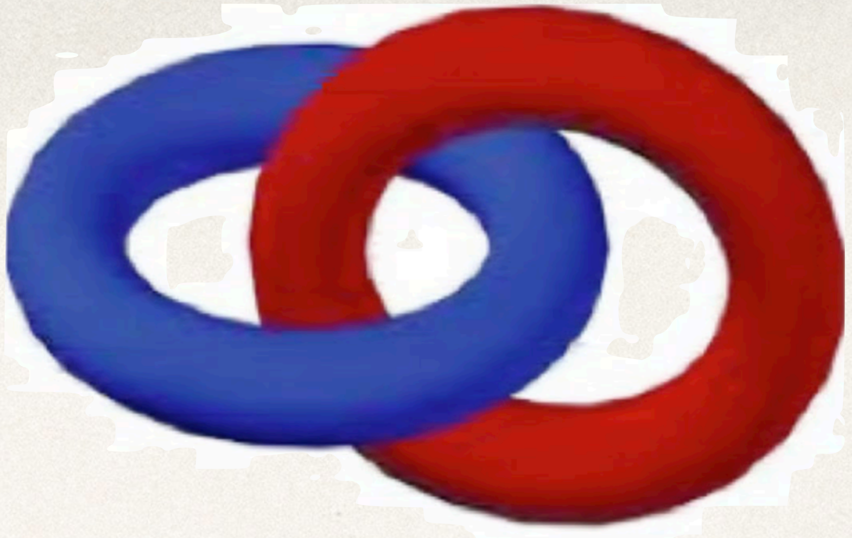
Why magnetic helicity?

$$H_m = \int_V \overrightarrow{A} \cdot \overrightarrow{B} \, \mathrm{d}V$$



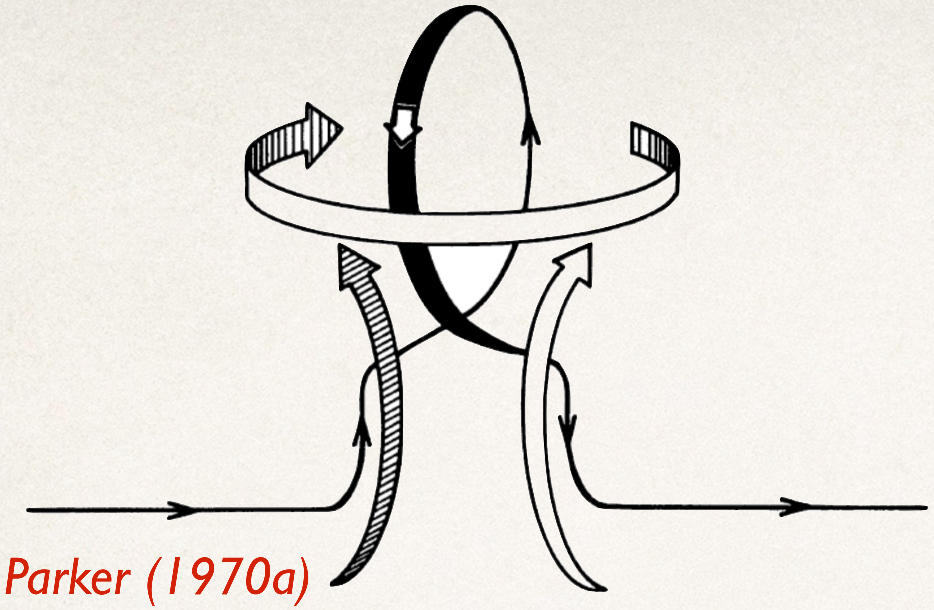
- It's a measure of complexity or internal twist of magnetic fields. Can be understood in terms of twists or linkage flux tubes (*Berger & Field 1984*)

- H_m is a topological invariant of ideal MHD, *almost* perfectly conserved even in non-ideal MHD (*Berger 1984, Pariat et al. 2015*)

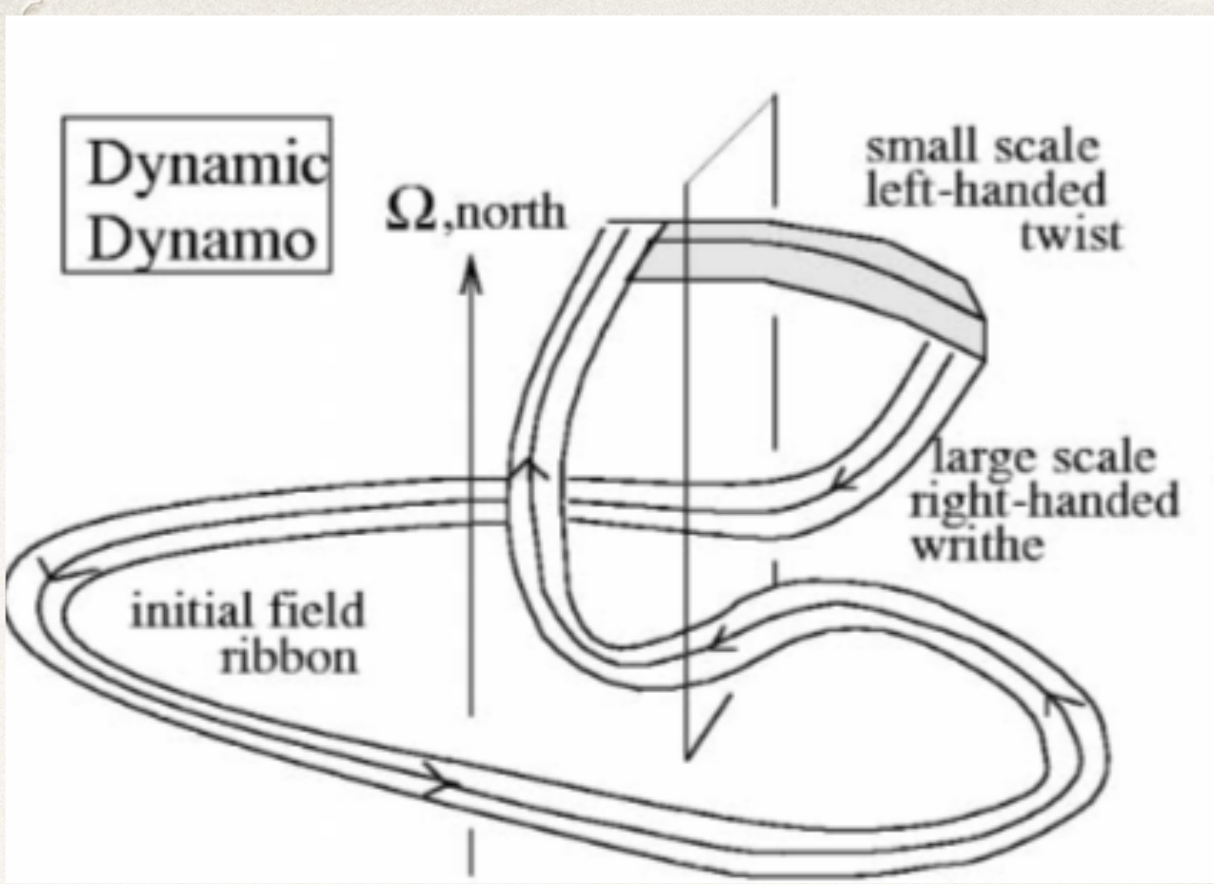
- Imposes crucial constraint on the evolution of magnetic fields via a dynamo mechanism (*Brandenburg and Subramanian 2005*)

- Solar magnetic field and it's spatio-temporal features ⟶ dynamo process acting within the Sun's convection zone

- One scenario : turbulent dynamo ⟶ α effect i.e. a measure of *helicity* of turbulence in the convection zone



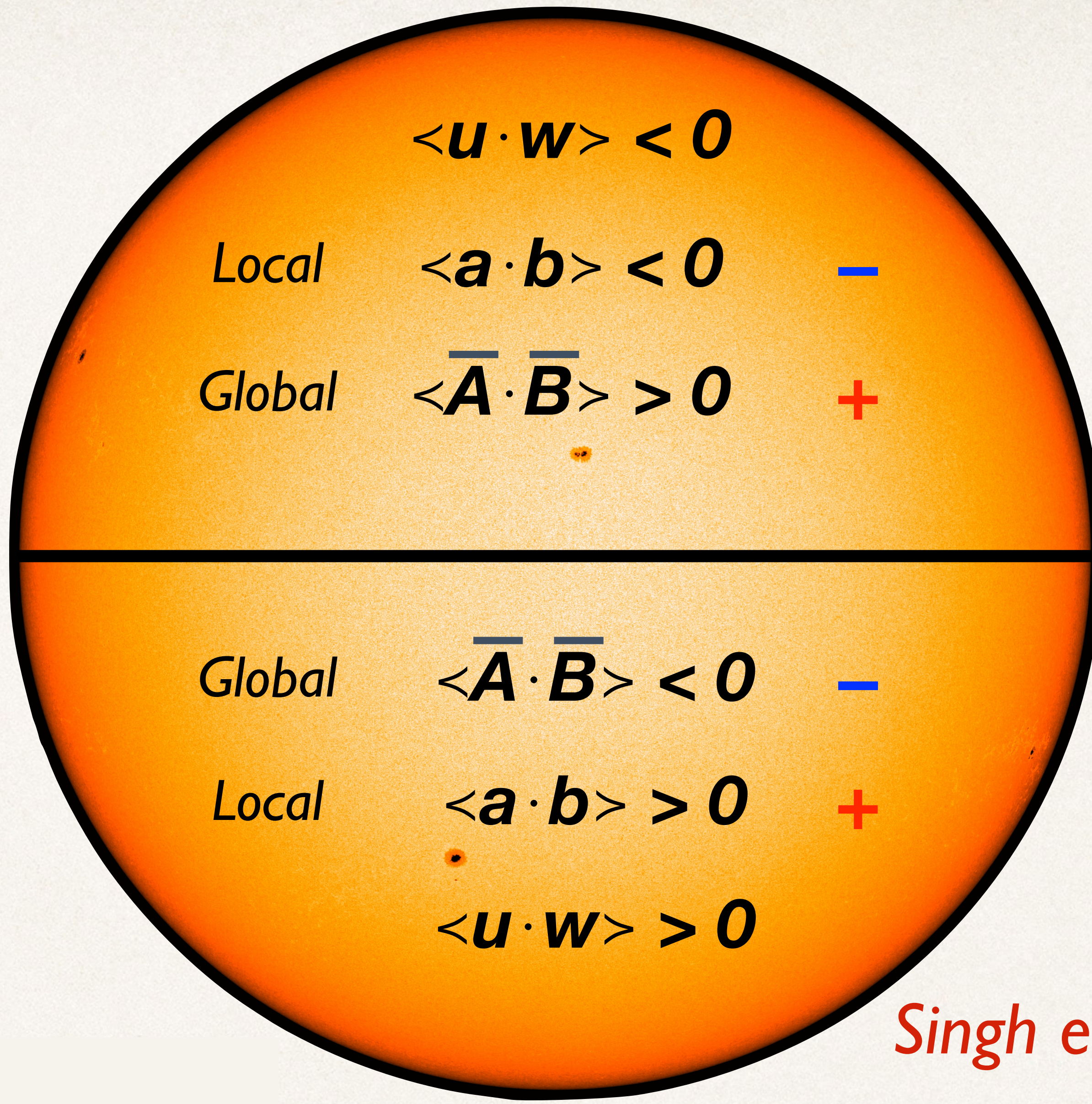
Parker (1970a)



A sketch from *Blackman and Brandenburg (2002)*

- Convective turbulence under the effect of stratification and rotation posses small-scale kinetic helicity → results in magnetic helicity of same handedness at small scales
- Helicity is conserved; helicity of equal magnitude but opposite sign is generated at larger scales (see for eg. Seehafer 1996). Thus theory predicts a helicity spectrum with opposite signs on small and large scales!
- Coriolis force breaks reflectional symmetry across the equator
- Another key consequence: magnetic helicity changes sign across the equator

IF an α effect is a key ingredient of the solar dynamo then…

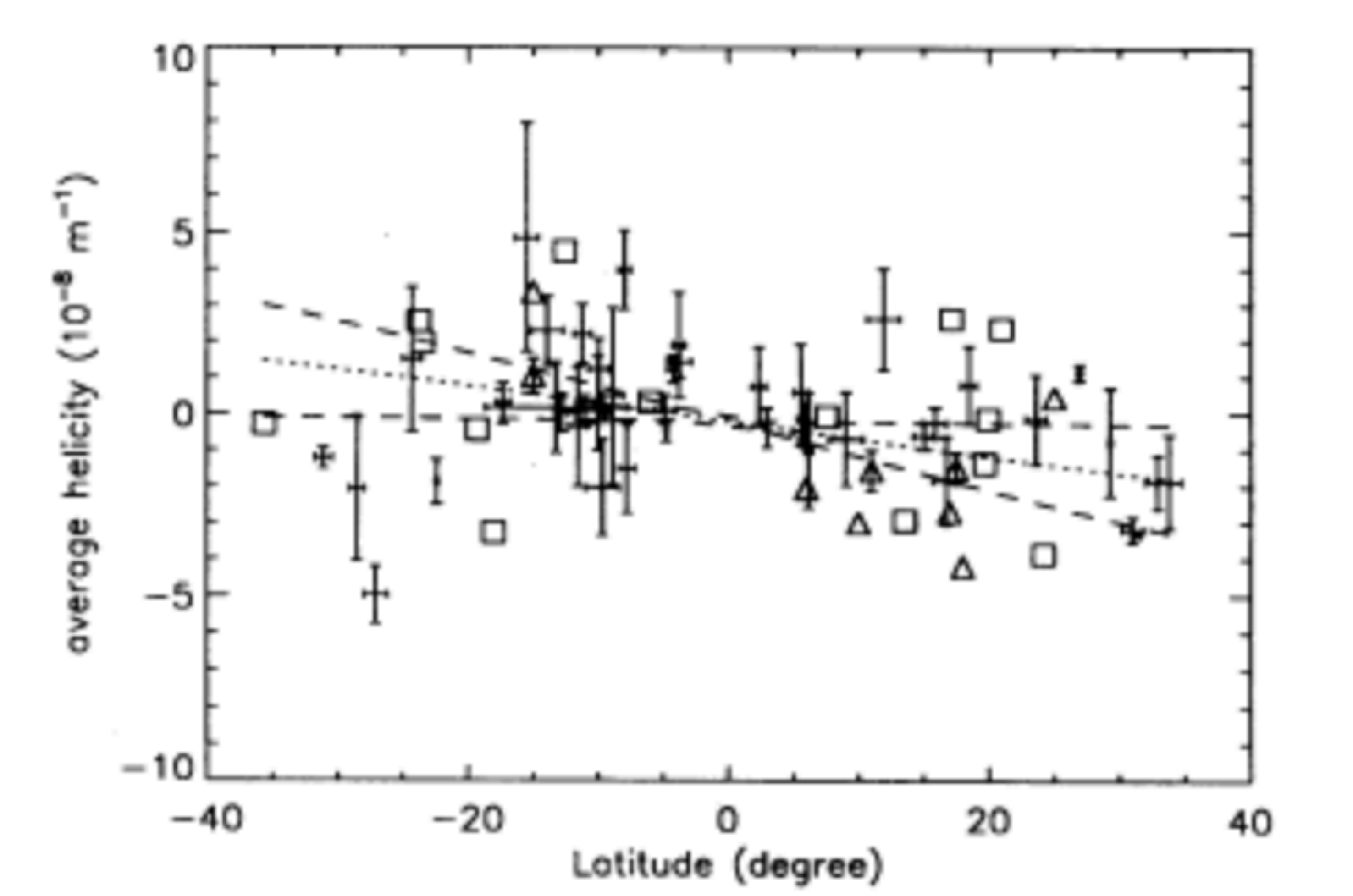


Singh et al. (2018)

- A prediction is the hemispheric sign rule for magnetic helicity
- Goal : To test if we indeed see this sign rule from actual solar observations and thus verify the significance of the α effect for the dynamo

Observations of helicity on the Sun

- Seehafer (1990), Pevtsov et al. (1995) looked at current helicity as a proxy
- $\nabla \times \overrightarrow{B} = \alpha \overrightarrow{B}$
- This does not however, elucidate the scale dependence of helicity, thus spectra are desirable



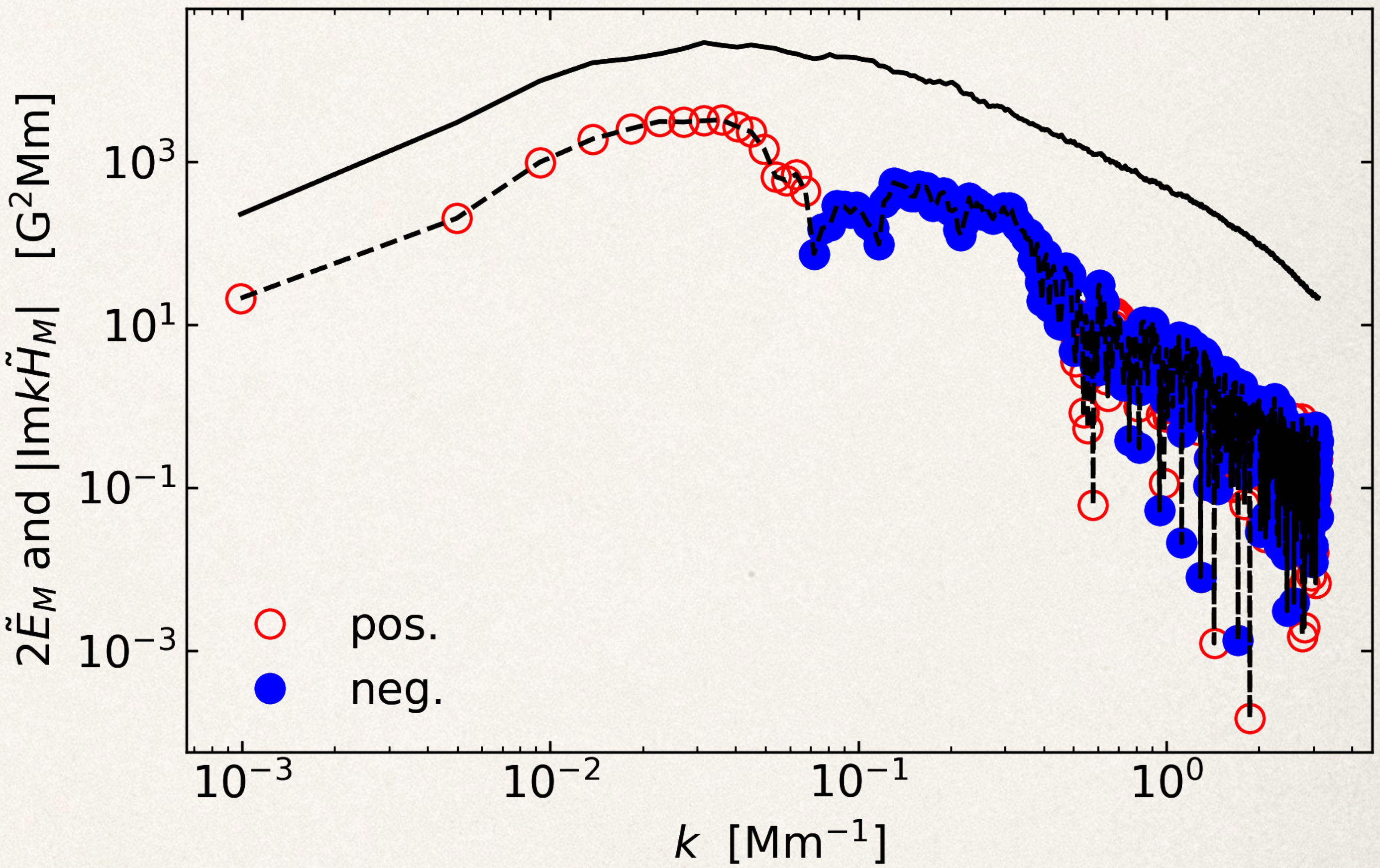
Pevtsov et al. (1995)

Observations of helicity on the Sun

$$M_{ij}(\vec{x}) = \int < B_i(\vec{X}) B_j(\vec{X} + \vec{x}) > \ \mathrm{dX}$$

$$M_{ij}(\vec{k}) = \frac{2E_M(k)}{4\pi k}(\delta_{ij} - \hat{k}_i\hat{k}_j) + \frac{iH_m(k)}{4\pi k}\epsilon_{ijk}k_k$$

- Zhang et al. 2014, 2016 computed "local" spectra from active regions
- Brandenburg et al. 2017, Singh et al. 2018 computed "global" spectra from synoptic maps



HMI, CR 2156-2158

Observations of helicity on the Sun

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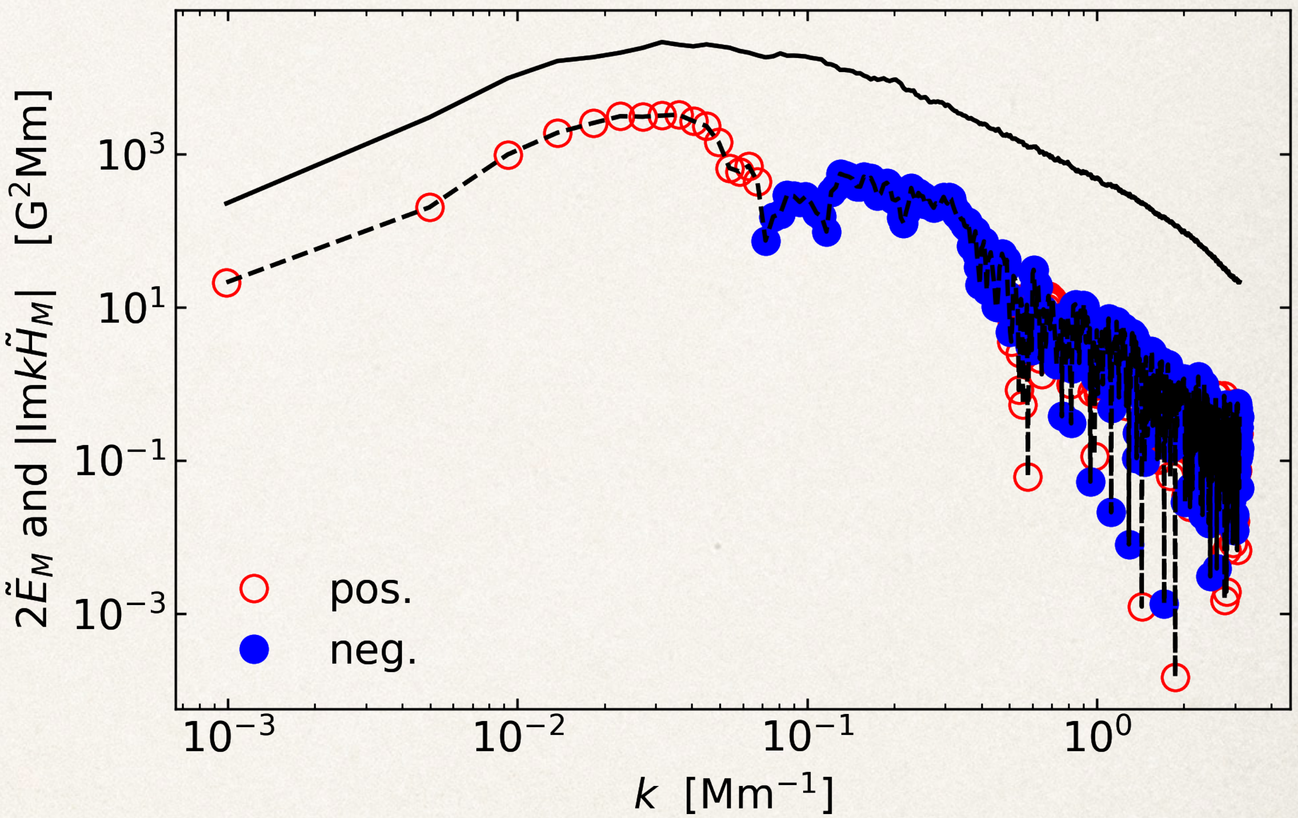
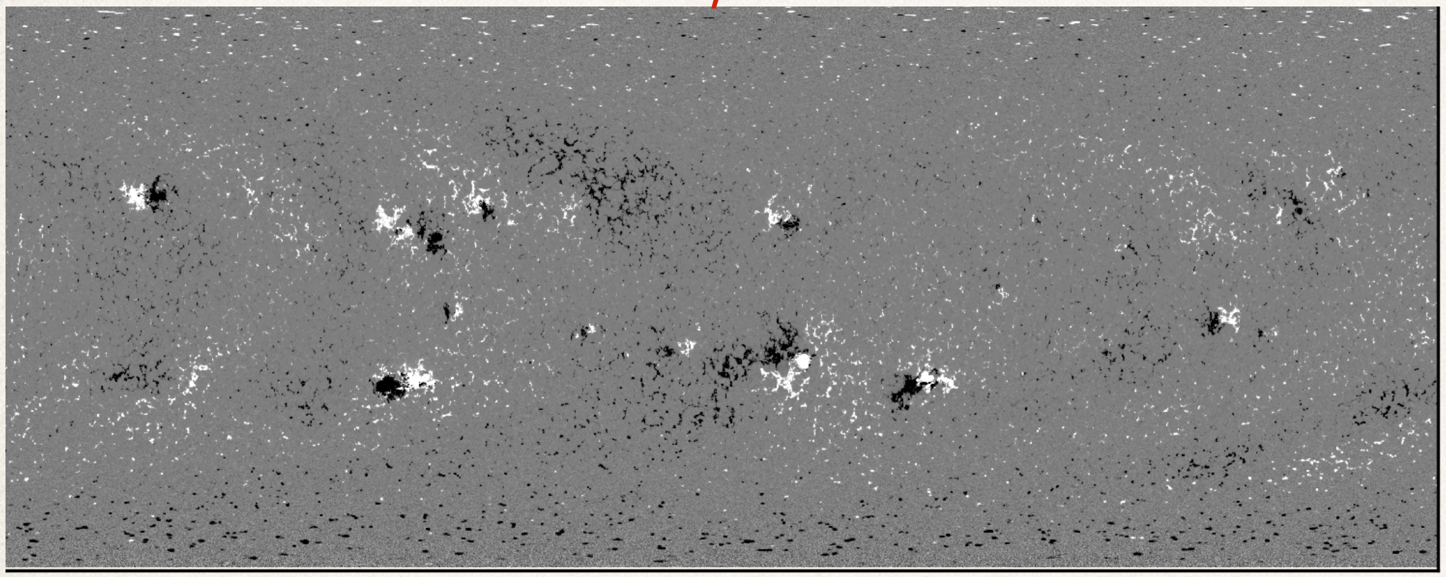
- All these studies are based on (directly or indirectly) on the magnetic field
- Photospheric magnetic fields are inferred using inversions of solar spectra via Zeeman effect ⟶ π ambiguity
- One can only measure the transverse field without arrow heads



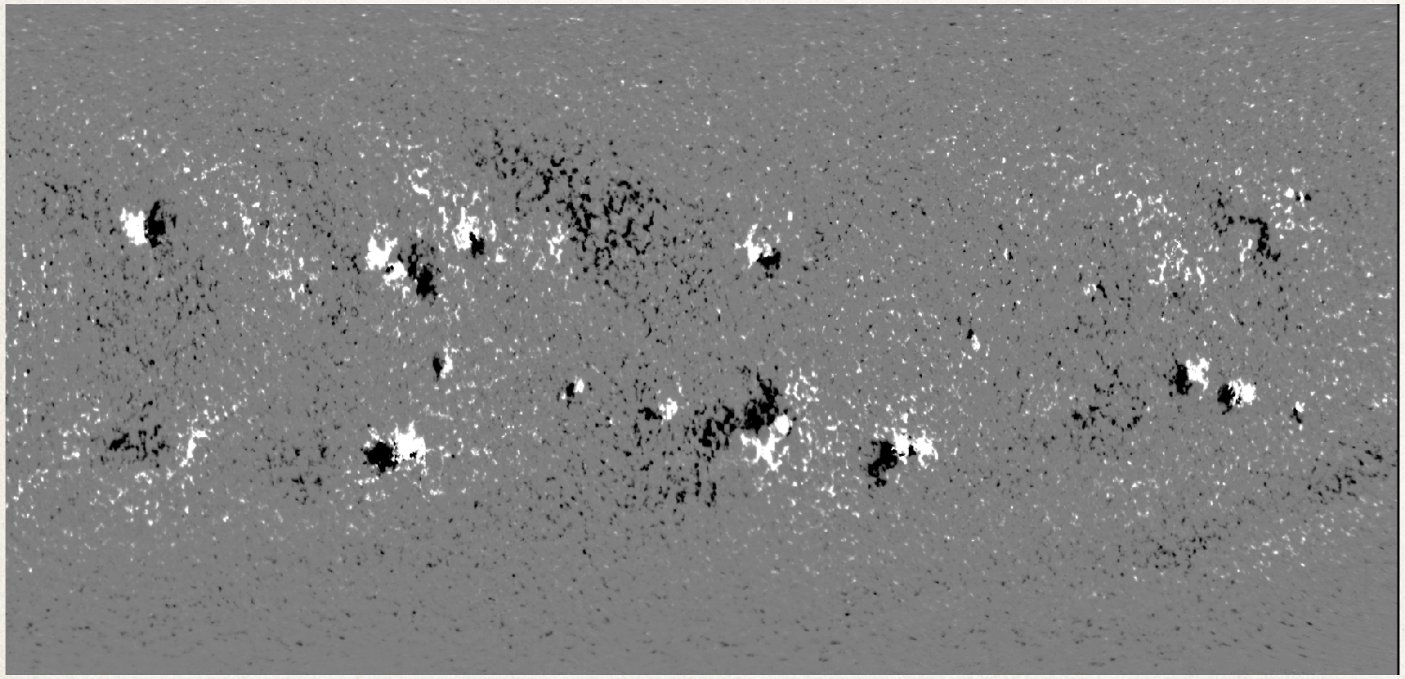
HMI, CR 2156-2158

- To disambiguate the transverse component of the magnetic field and transform from a line-of-sight coordinate system to a solar coordinate system several methods exist (see *Metcalf et al. 2006*)

HMI B_r



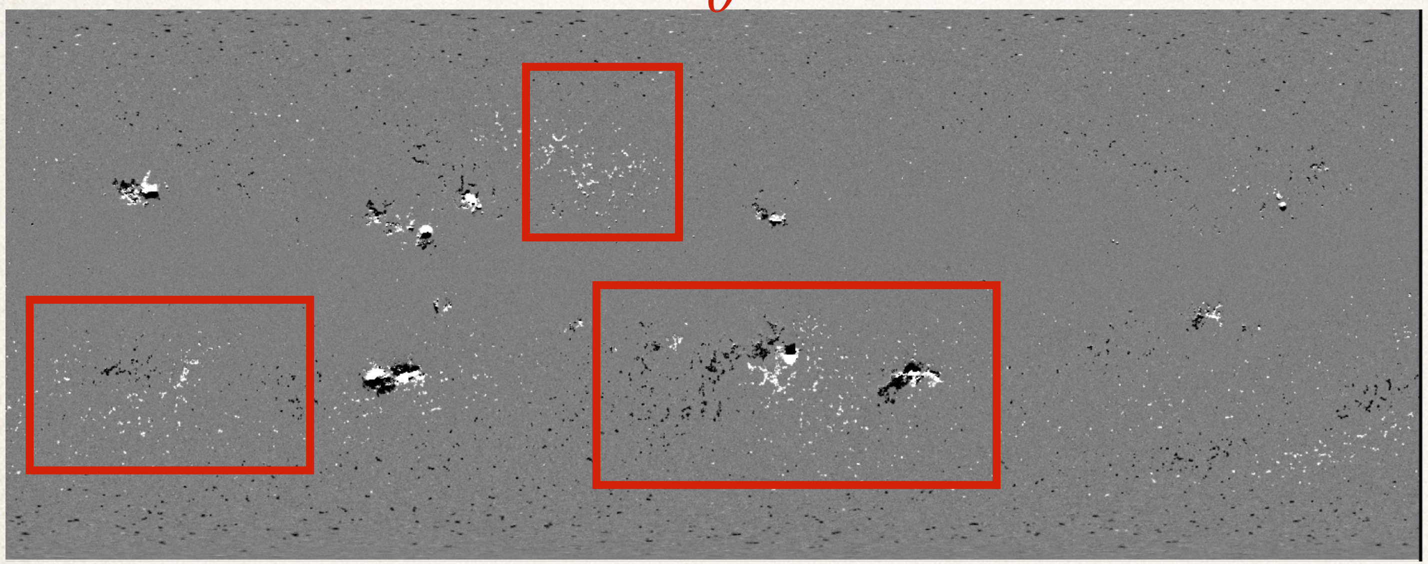
Carrington map 2168, Sep-Oct 2015.



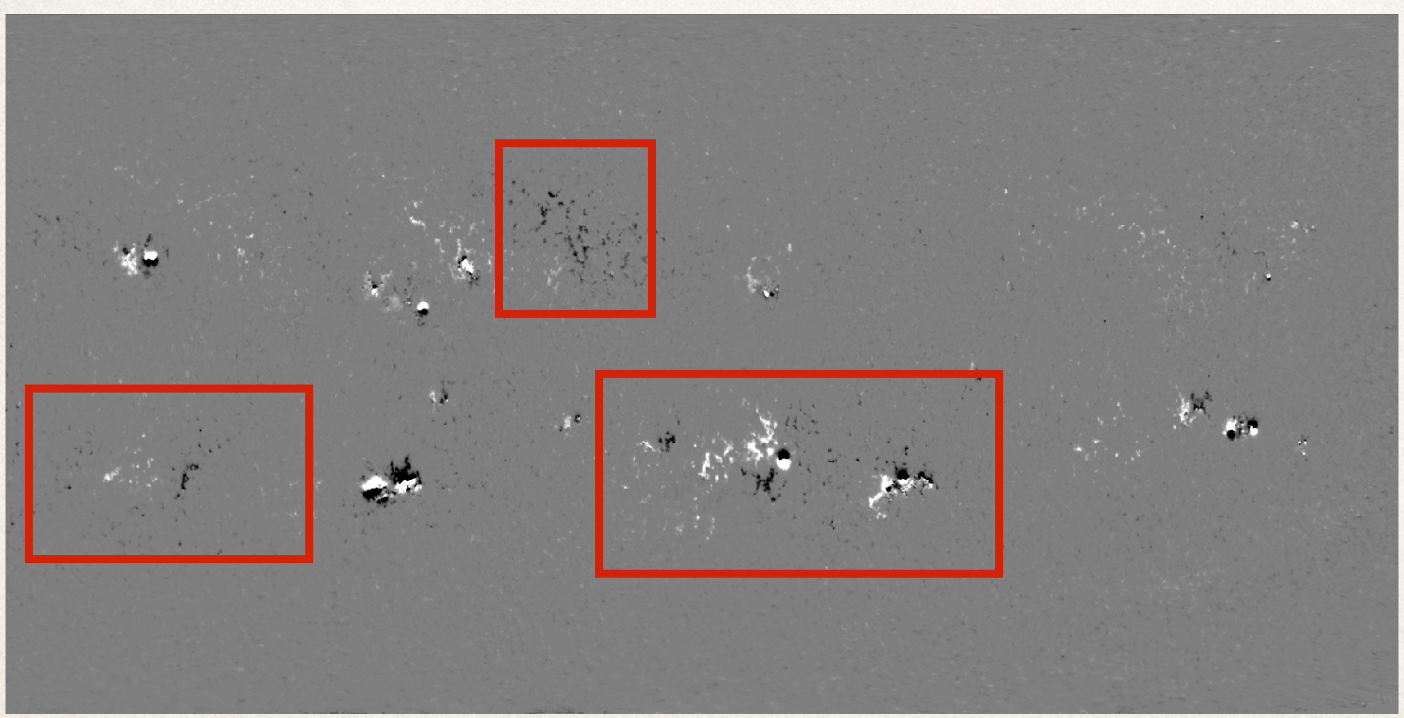
SOLIS

- These disambiguation methods face difficulties in regions of complex magnetic field geometries or where there is a strong influence of noise on the measurement

HMI B_θ



Carrington map 2168, Sep-Oct 2015.



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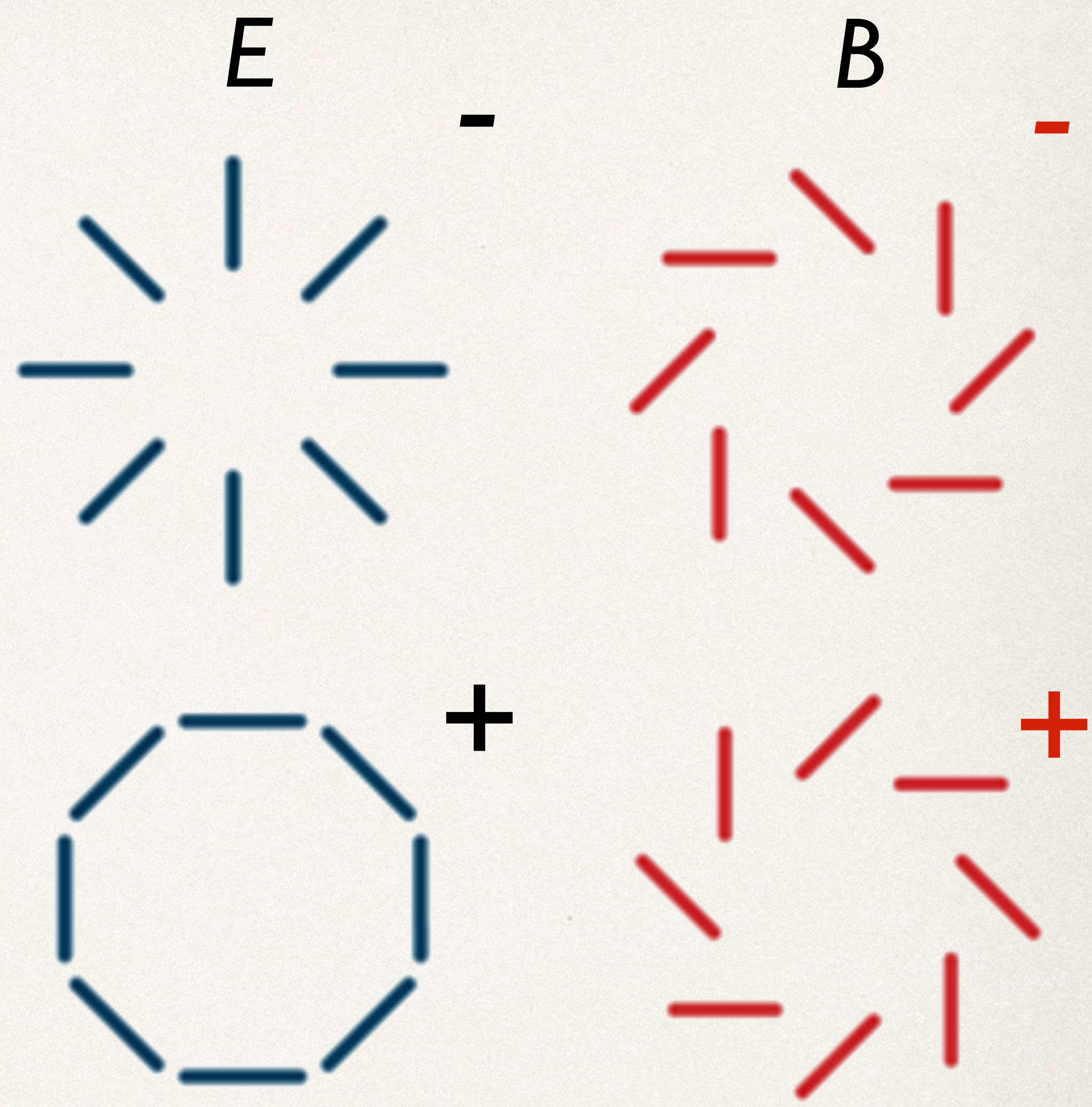
- This can lead to disagreement in the helicity spectra retrieved from different instruments.
- It highlights the need for better synoptic maps

Another proxy of magnetic helicity independent of the π ambiguity could be useful!

E and B polarisation

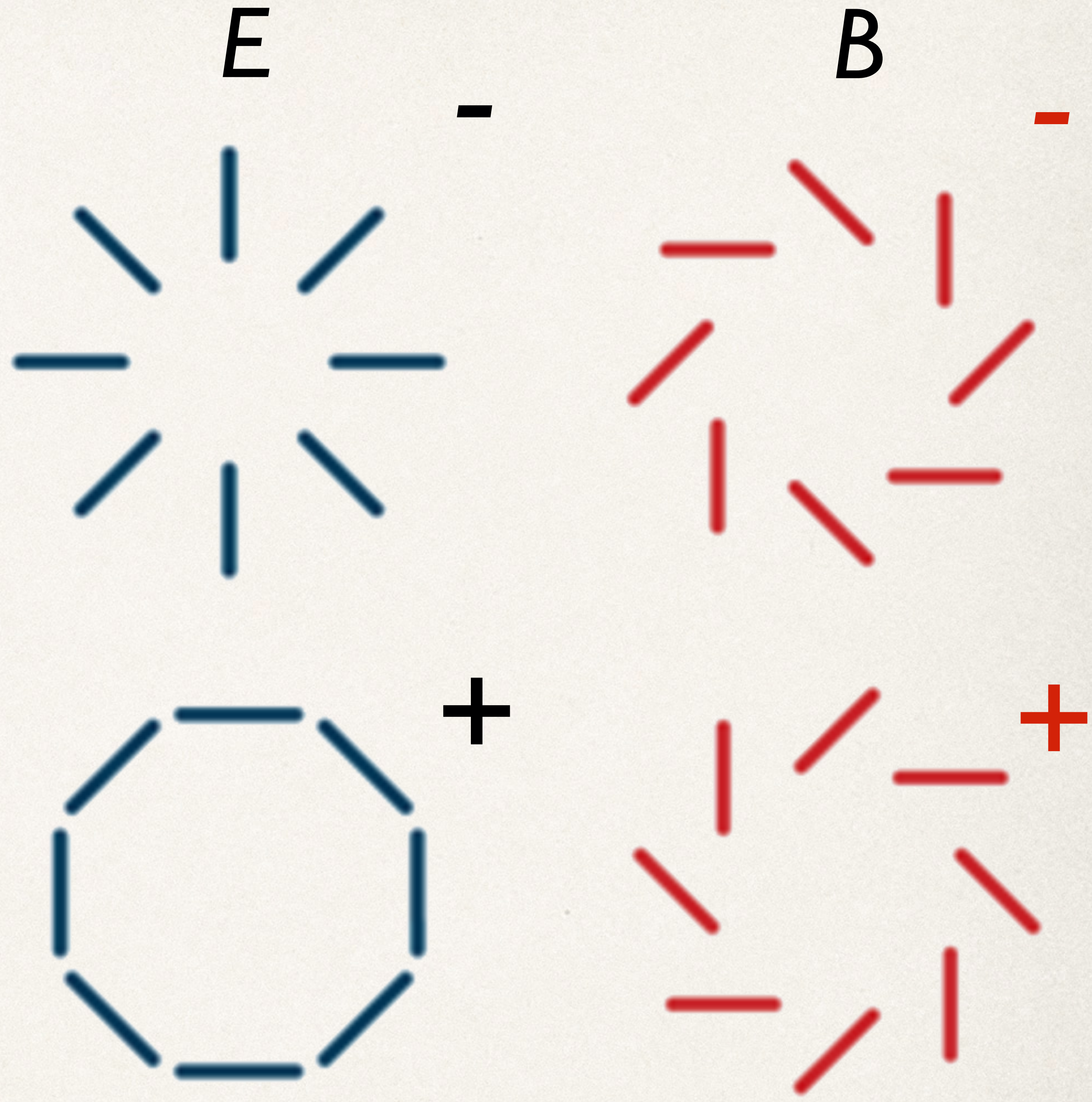
- Linear polarisation (Stokes *Q* and *U*) is decomposed into E and B.
- *E* and *B* are parity even and parity odd respectively see for eg. *Zaldariaga & Seljak 1997*
- $(\tilde{E} + i\tilde{B}) = (\hat{k}_x - i\hat{k}_y)^2(\tilde{Q} + i\tilde{U})$
- *EB* correlations are indicative of helicity of underlying magnetic field (for eg: Pogosian et al. 2002, *Kahniashvili et al. 2014*)
- First tested in the solar context by *Brandenburg et al. 2019*



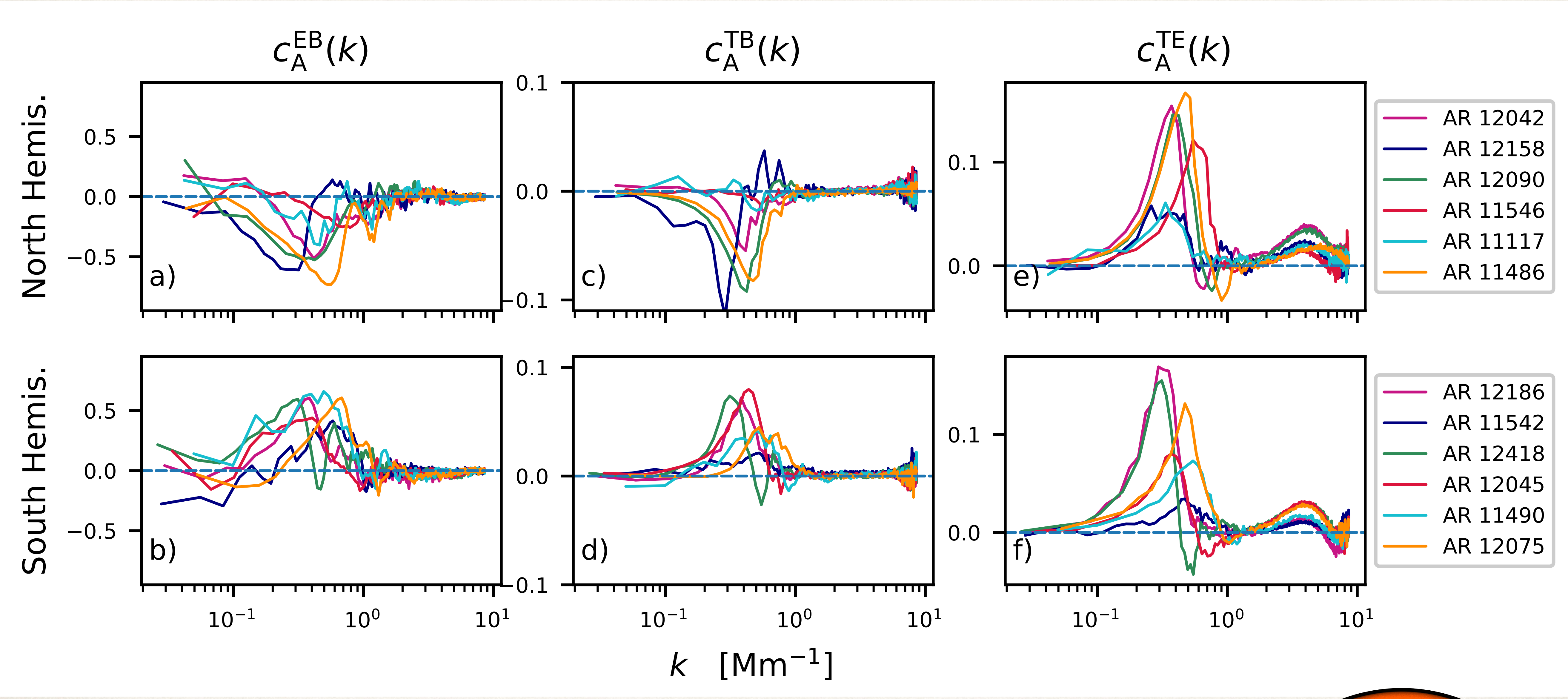
$$a^E_{lm} = -(a^2_{lm} + a^{-2}_{lm})/2 \ , a^B_{lm} = i(a^2_{lm} - a^{-2}_{lm})/2$$

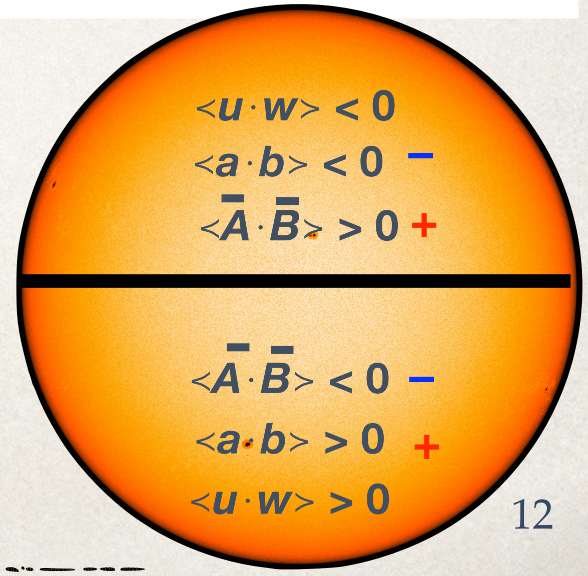
E and *B* polarisation

- One would expect that helicity and thus parity-odd correlations to ideally show different signs in different hemispheres!
- We looked at active regions in different hemispheres with SDO/HMI
- Computed EB from Q and U and checked for systematic preference for a sign based on hemisphere

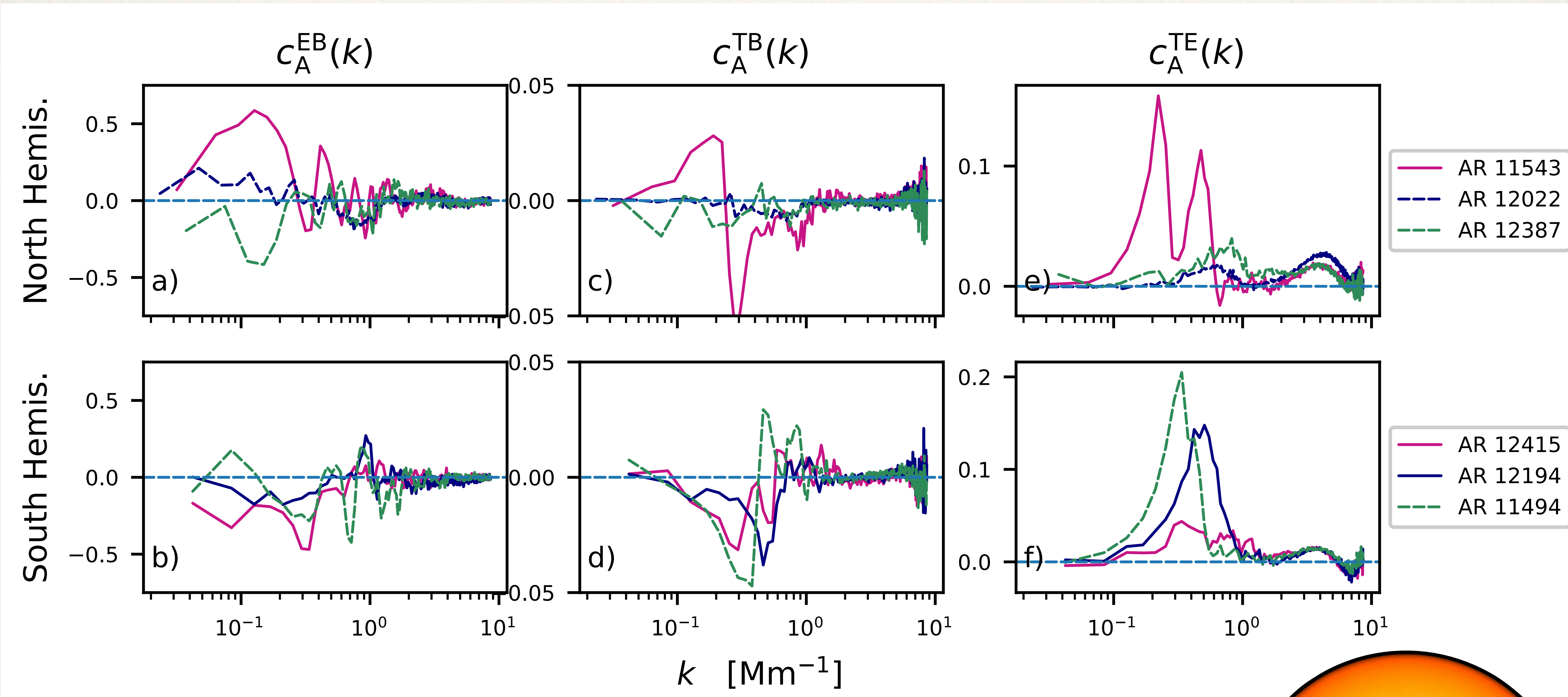


Computed EB correlations from Stokes Q&U at 4 filter positions of HMI and then averaged!

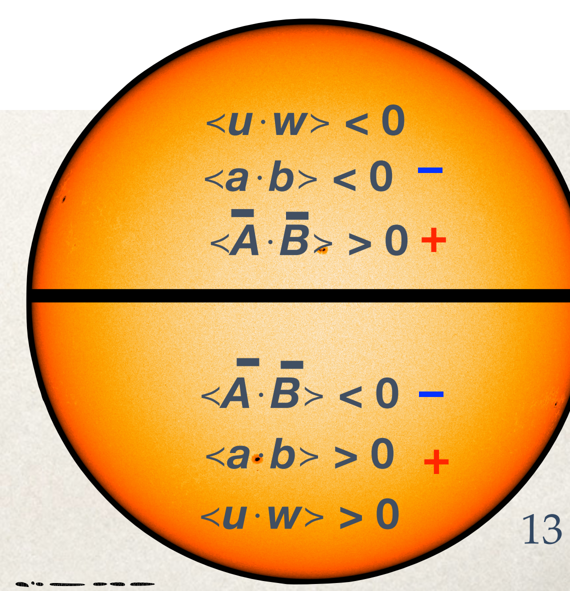




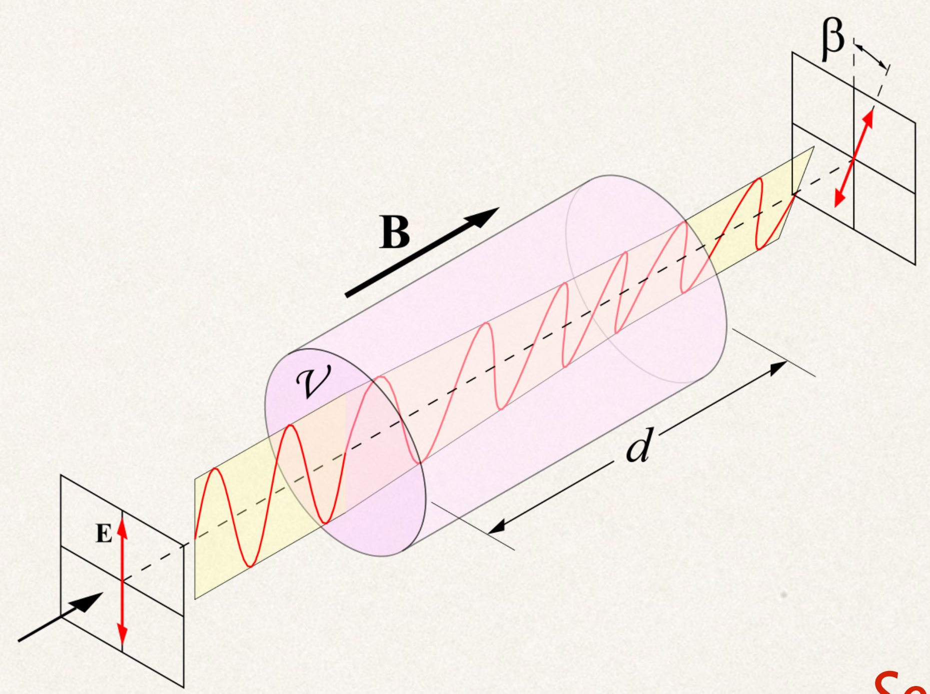
Active regions with reversed (solid) and no preference for sign (dashed)



- Singh et al. (2018) found evidence for the hemispheric sign rule in nearly 75% of the synoptic maps over solar cycle 24

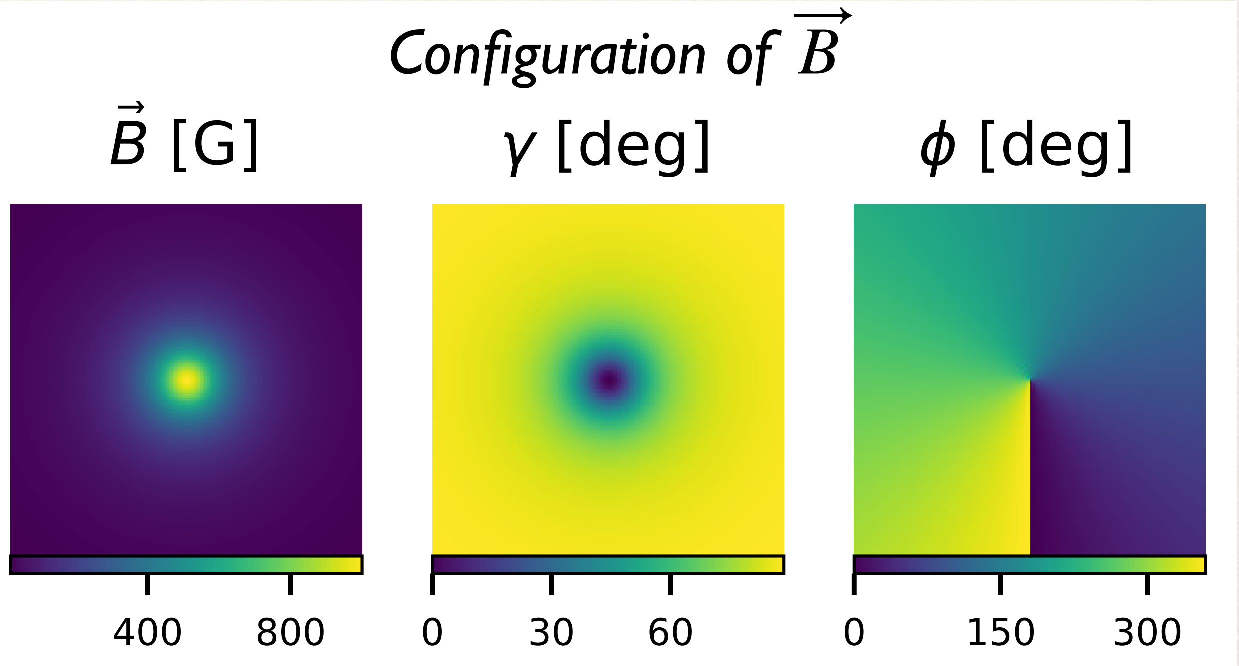


Faraday rotation could play a role : a homogeneous non-helical field could contribute to parity-odd correlations (*Scannapieco & Ferreira 1997*)



Source: wikipedia

Aim: To test if a non-helical magnetic field on the Sun's surface can contribute to significant parity odd C_{A}^{EB} or C_{A}^{TB} correlations purely due to Faraday rotation

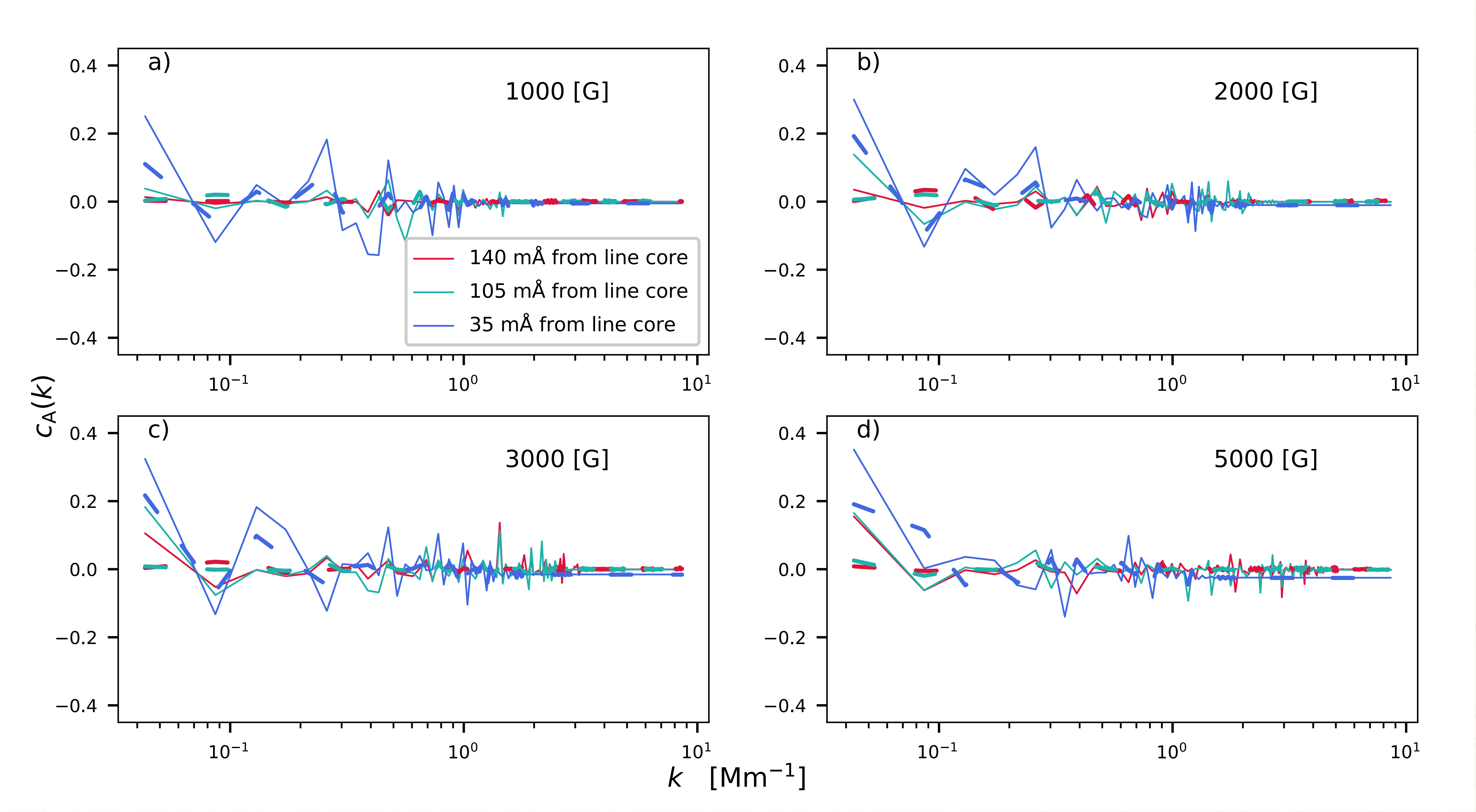


1. Simple model of solar atmosphere
2. Solve the radiative transfer equation for polarised light i.e.

$$\frac{\mathrm{d}\mathbf{I}}{\mathrm{d}\tau_{\mathrm{c}}} = \mathbf{K}(\mathbf{I} - \mathbf{S})$$

3. Synthesise spectra, compute *E* and *B* from Stokes Q and U and check for any significant parity odd correlations arising purely due to Faraday rotation

Contributions of Faraday effect from a non-helical field seem negligible!



Conclusions

- EB decomposition of linear polarisation is a promising proxy for magnetic helicity for solar observations
- It can be used to infer the sign of H_m directly from polarisation without having to reconstruct $\overrightarrow{B}$
- A next step is to include the information Stokes V in this approach (if it's even feasible)

Appendix

See Zaldarriaga & Seljak 1997

$$(Q \pm iU)' = e^{\mp 2i\phi}(Q \pm iU)(\hat{\vec{n}}) \; ,$$

$$(Q \pm iU)(\hat{\vec{n}}) = \sum_{lm} a_{lm}^{\pm 2} \; {}_{\pm 2}Y_{lm}(\hat{\vec{n}}) \; ,$$

With $a_{lm}^{E} = -(a_{lm}^{2} + a_{lm}^{-2})/2 \; , a_{lm}^{B} = i(a_{lm}^{2} - a_{lm}^{-2})/2 \; ,$ *redefine above equation*

We work within the confines of the small scale limit i.e.

$$ {}_{2}Y_{lm} = \left[\frac{(l-2)!}{(l+2)!}\right]^{1/2} \eth^{2} Y_{lm} \longrightarrow \frac{1}{2\pi}\frac{1}{l^{2}} \eth^{2} e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \; ,$$

$$ {}_{-2}Y_{lm} = \left[\frac{(l-2)!}{(l+2)!}\right]^{1/2} \bar{\eth}^{2} Y_{lm} \longrightarrow \frac{1}{2\pi}\frac{1}{l^{2}} \bar{\eth}^{2} e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \; ,$$

And invoking the definition of the spin-up and down operators:

$$(\tilde{E} + i\tilde{B}) = (\hat{k}_x - i\hat{k}_y)^2(\tilde{Q} + i\tilde{U})$$