Helicity2020
Online Talk

2020-12-11 (Friday)
13:00 – 13:30 UTC

Magnetic Helicity Flux across Solar Active Region Photospheres

Hemispheric Sign Preference in Solar Cycle 24

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with

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NWRA
Since 1984

The Sun: Hemispheric Sign Preference

1. A tendency, but not a rule!

- Left-handed helical structures in the northern hemisphere
- Right-handed in the southern hemisphere

2. Observed in different kinds of physical quantities

- Magnetic/current/kinetic helicity
- Force-free-field parameter alpha
- Morphological properties (shape, chirality/handedness)
- …

3. Various features in/from the magnetized solar atmosphere

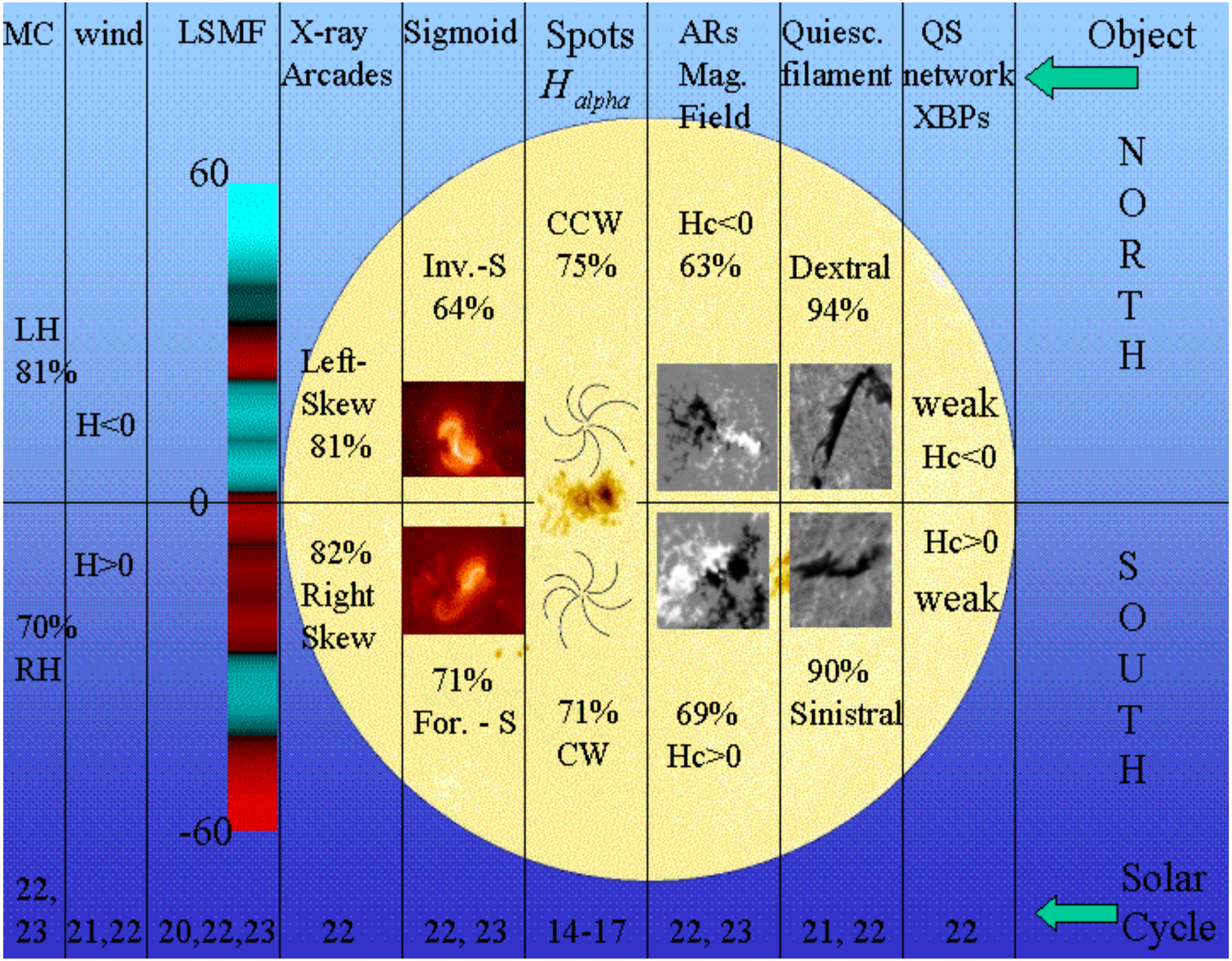
- Sunspots, filaments, coronal loops, CMEs
- Quiet-Sun networks, bright points
- Solar winds, interplanetary CMEs
- …

4. Independent of the solar cycle

Hemispheric Sign Preference (HSP) of Helicity (1)

HSP: 60~80%

(Image credit: Pevtsov 2002)



Hemispheric Sign Preference (HSP) of Helicity (2)

(Table from Wang 2013)

HSP: 60~80%

Percentage of Features Obeying the Hemispheric Helicity/Chirality Rule

Reference	Type of Feature	Method	Sample Size	Hemispheric Bias f_{hem} [a] (%)
Hale (1925)	Hα sunspot whorls	Visual inspection	51	82
Richardson (1941)	Hα sunspot whorls	Visual inspection	141	72
Pevtsov et al. (2003a)	Hα sunspot whorls	Visual inspection	128	62
Rust & Kumar (1996)	X-ray sigmoids	Visual inspection	80[b]	80
Canfield & Pevtsov (1999)	X-ray sigmoids	Visual inspection	182	64
Lim & Chae (2009)	X-ray sigmoids	Visual inspection	45	87
Martin et al. (1994)	Quiescent filaments	Visual (Hα barbs)	73	82
Pevtsov et al. (2003b)	Quiescent filaments	Visual (Hα barbs)	1436	83
Lim & Chae (2009)	Intermediate filaments	Visual (Hα barbs)	45	84
Martin et al. (1994)	Active-region filaments	Visual (Hα barbs)	31	55
Pevtsov et al. (2003b)	Active-region filaments	Visual (Hα barbs)	838	76
Bernasconi et al. (2005)	All filaments	Automated detection (Hα barbs)	658	68
Yeates et al. (2007)	All filaments	Visual (Hα barbs)	123	82
Pevtsov et al. (1995)	Active regions	Vector (α_{best})	69	72
Abramenko et al. (1997)	Active regions	Vector (current helicity imbalance)	40	82.5
Bao & Zhang (1998)	Active regions	Vector (current helicity imbalance)	422	82
Longcope et al. (1998)	Active regions	Vector (α_{best})	203	65
Pevtsov et al. (2001)	Active regions	Vector (α_{best})	263	66
Hagino & Sakurai (2005)	Active regions	Vector (α_{av})	240	60
Zhang (2006)	Active regions	Vector (α_{best})	331	62

Proposed Physical Mechanisms for the HSP

- What is the source and where it happens?

(Refer to Bao+2002, and reference therein)

Source	Location	Northern Hemisphere	Southern Hemisphere
Differential rotation	Photosphere	−	+
	Convection zone	+	−
Coriolis force	Photosphere	+	−
	Convection zone	−	+
α-effect	Convection zone	+	−
	Overshoot region (tachocline)	−	+
Σ-effect	Convection zone	−	+
Surface flows (e.g., shear flows)	Photosphere	No preference?	No preference?

Motivation and Approach of This Study

1. A combination of various mechanisms may play together to produce the observed HSP.

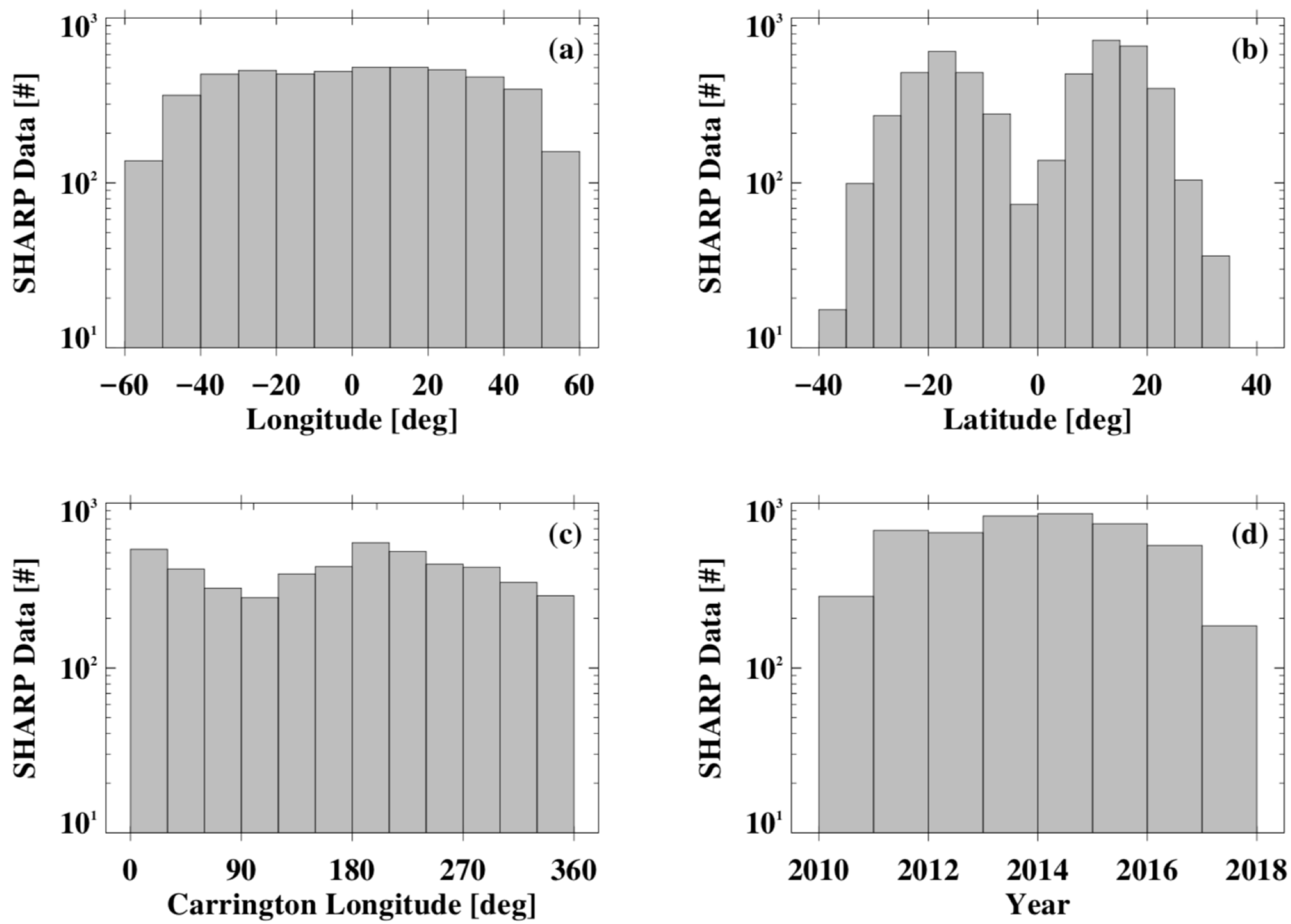
2. Targeted scientific questions
   - What is the major/minor source for the HSP?
   - What will significantly obscure it?

3. The HSP in solar cycle 24
   - Observational data: SDO/HMI vector magnetograms (years 2010−2017)
   - Target: a large number of active region (AR) samples
   - Physical quantity: dH/dt
   - Method used: G_{θ} (Pariat+2005), DAVE4VM (Schuck 2008)

4. Dependence of the HSP with respect to various AR properties

Dataset of HMI Active Region Patches (HARPs)

- A total of 4,802 co-aligned pairs of HARP vector magnetograms at 12-minute separation observed at 00:36 UT and 00:48 UT each day from 2010 to 2017, and within ±60° from the central meridian
- Note that they are NOAA-numbered active regions (ARs) with sunspots.



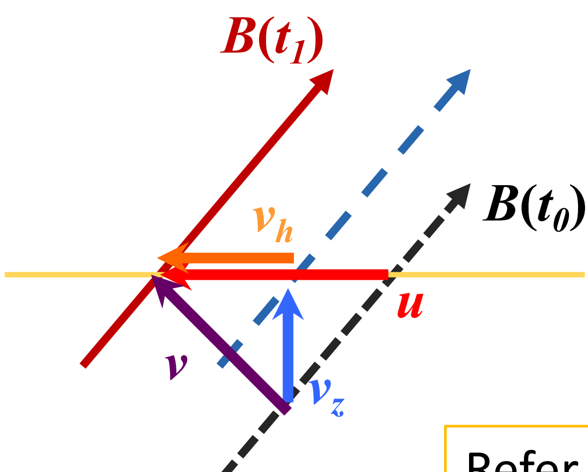
Magnetic Helicity Flux across the Photosphere

- Pariat+2005

$$\frac{\mathrm{d}H}{\mathrm{d}t} = \int_S G_\theta \; \mathrm{d}S$$

$$G_\theta(\boldsymbol{x}, t) = -\frac{B_z}{2\pi} \int_{S'} \left(\frac{\boldsymbol{x} - \boldsymbol{x}'}{|\boldsymbol{x} - \boldsymbol{x}'|^2} \times [\boldsymbol{u} - \boldsymbol{u}'] \right)_z B'_z \; \mathrm{d}S'$$

- Démoulin & Berger 2003

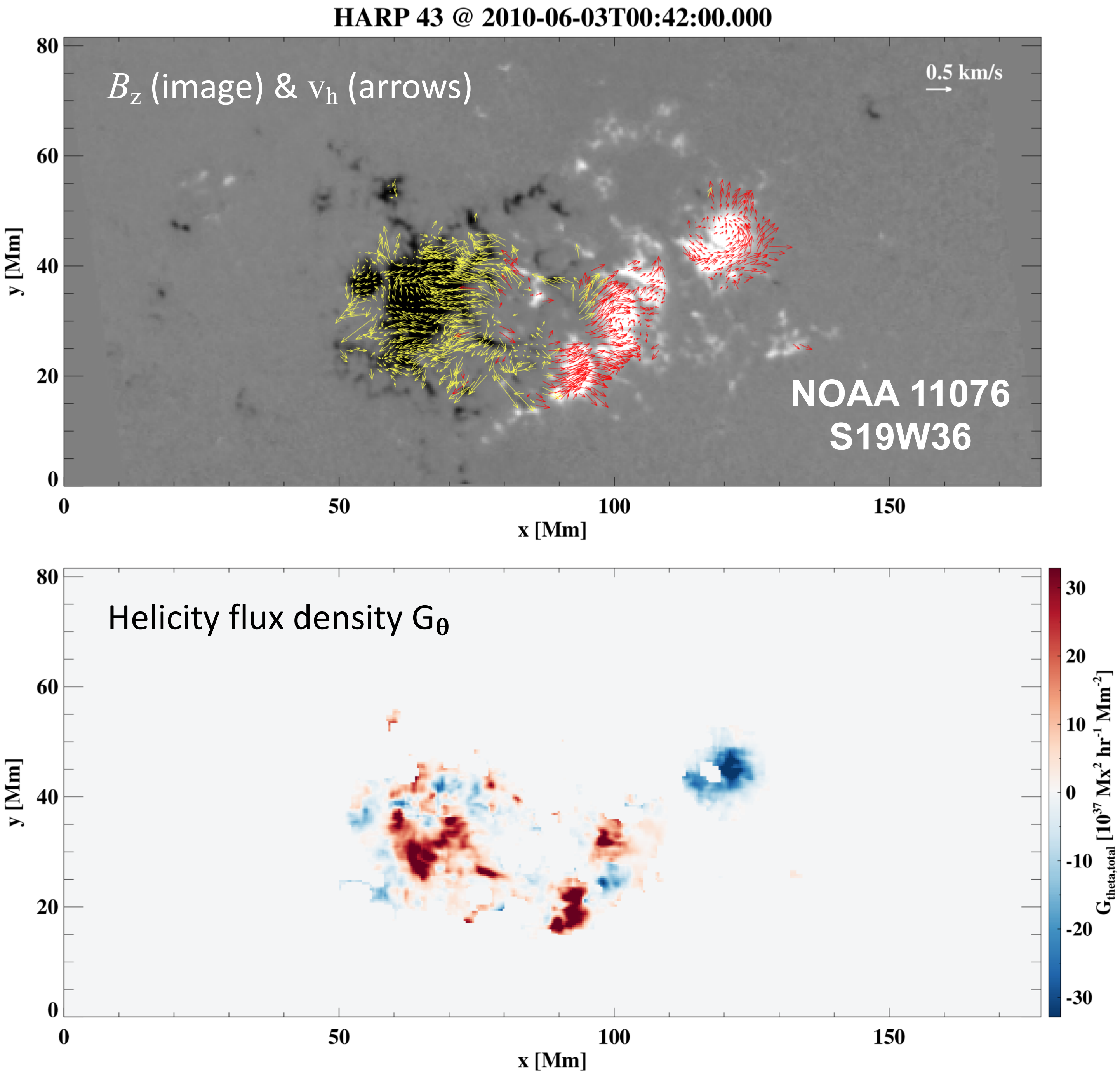


Magnetic field line footpoint velocity $\boldsymbol{u}$

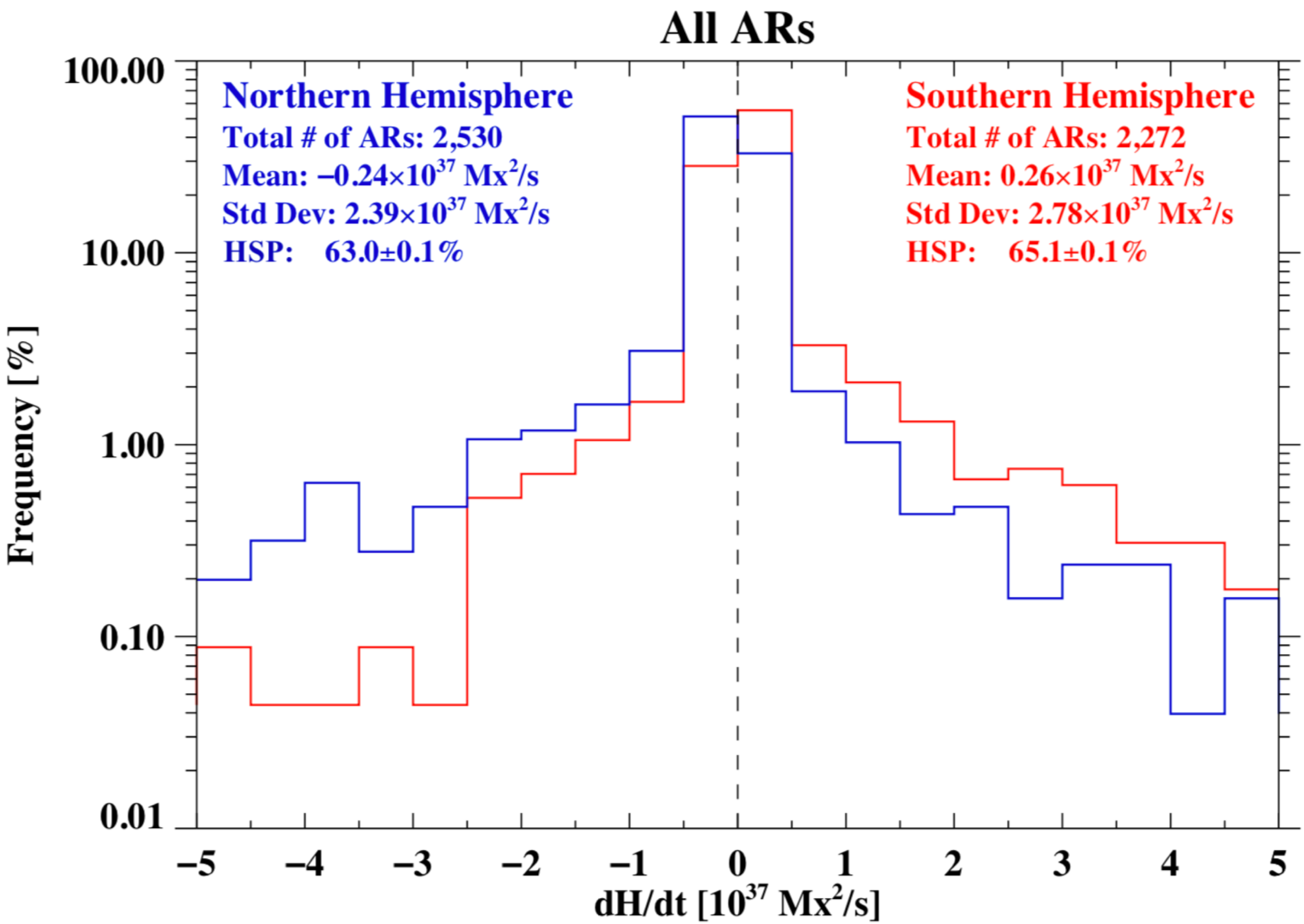
$$\mathbf{u} \equiv \mathbf{v}_h - v_z \frac{\mathbf{B}_h}{B_z}$$

❖ v_h & v_z from DAVE4VM (Schuck 2008)

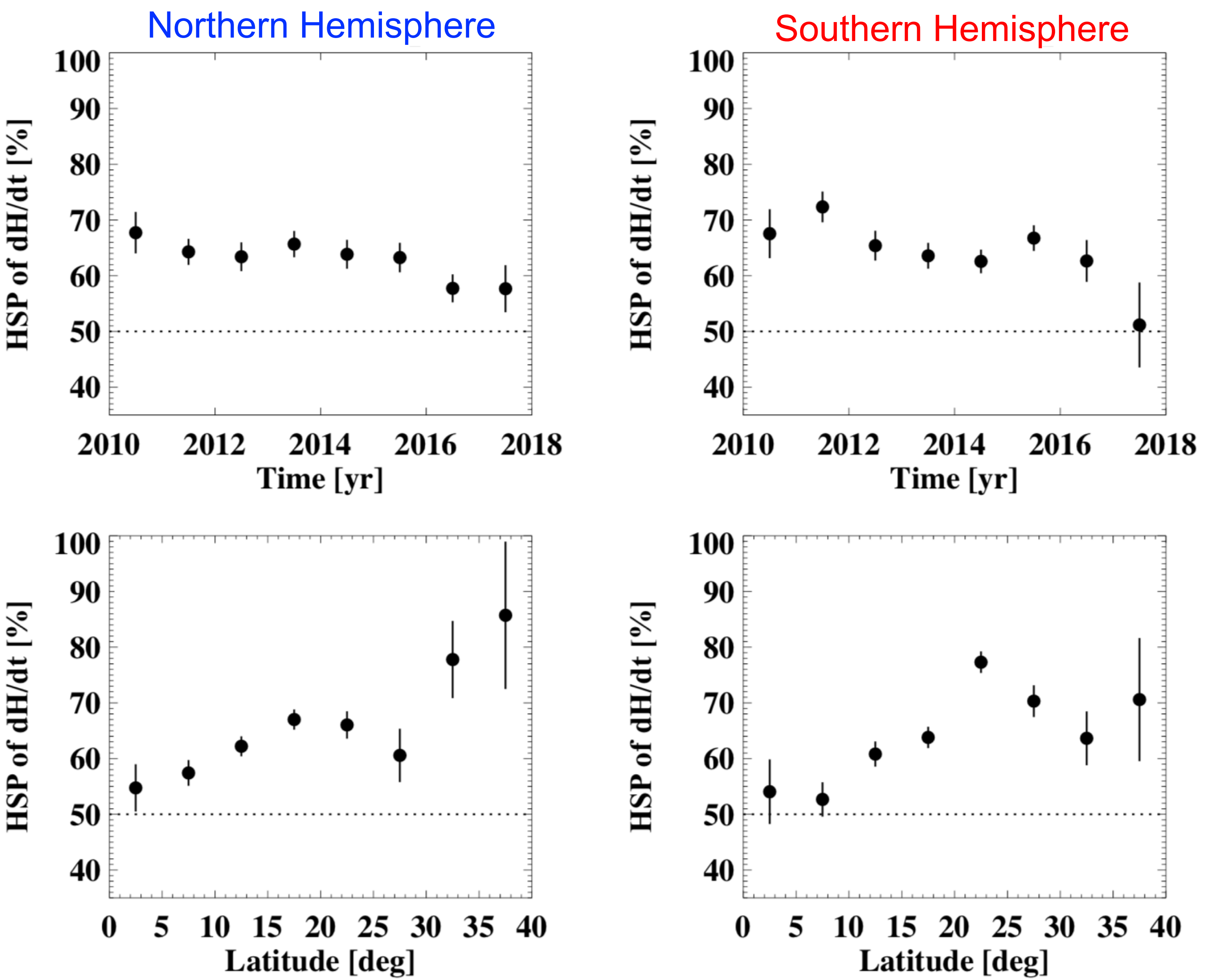
Refer to Park+2020, ApJ, 904, 6


HARP 43 @ 2010-06-03T00:42:00.000
B_z (image) & v_h (arrows)
0.5 km/s
NOAA 11076
S19W36
y [Mm]
x [Mm]
Helicity flux density G_θ
$G_{theta,total}$ [10^{37} Mx^2 hr^{-1} Mm^{-2}]

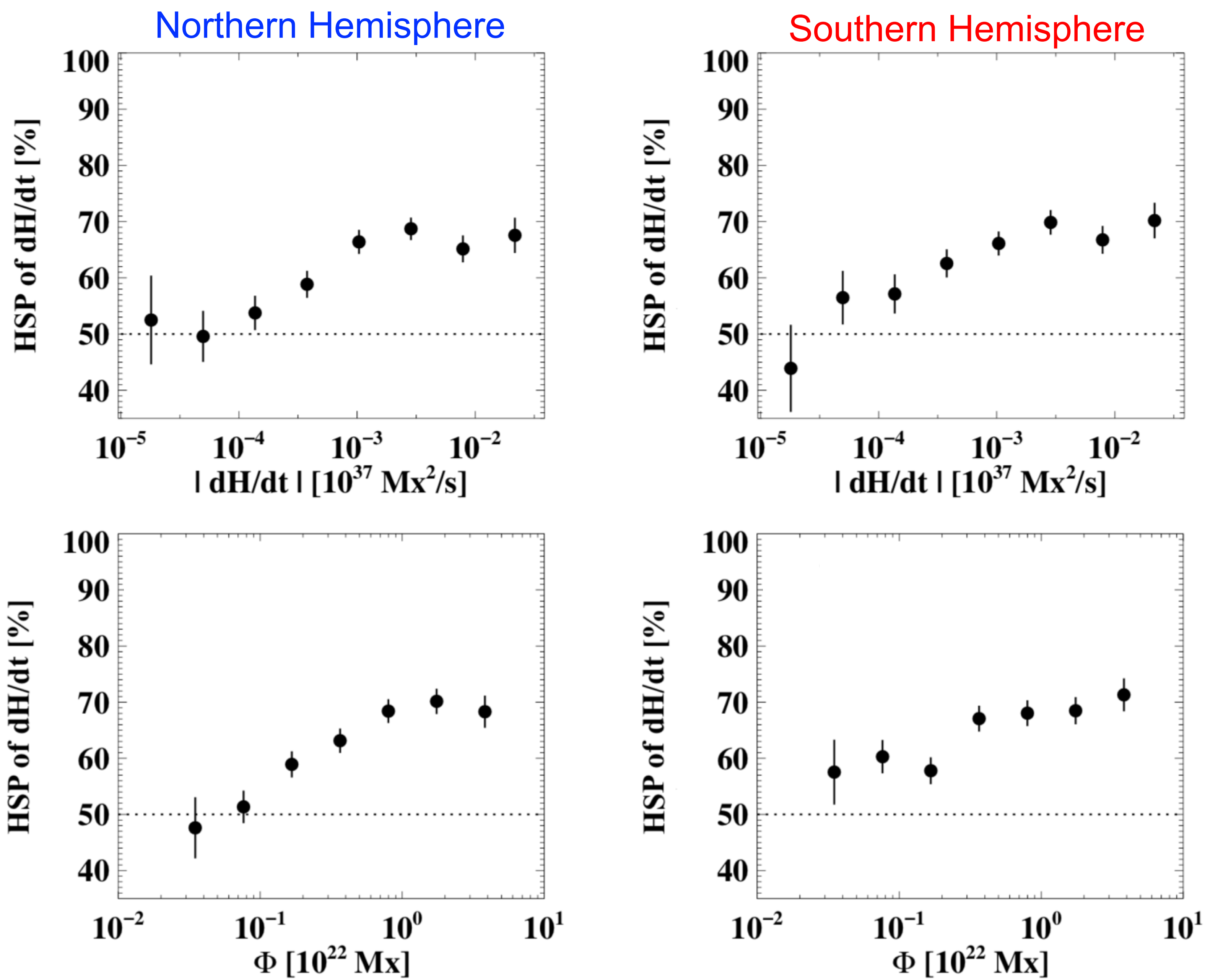
Results: (1) Relative Frequency Distribution of dH/dt



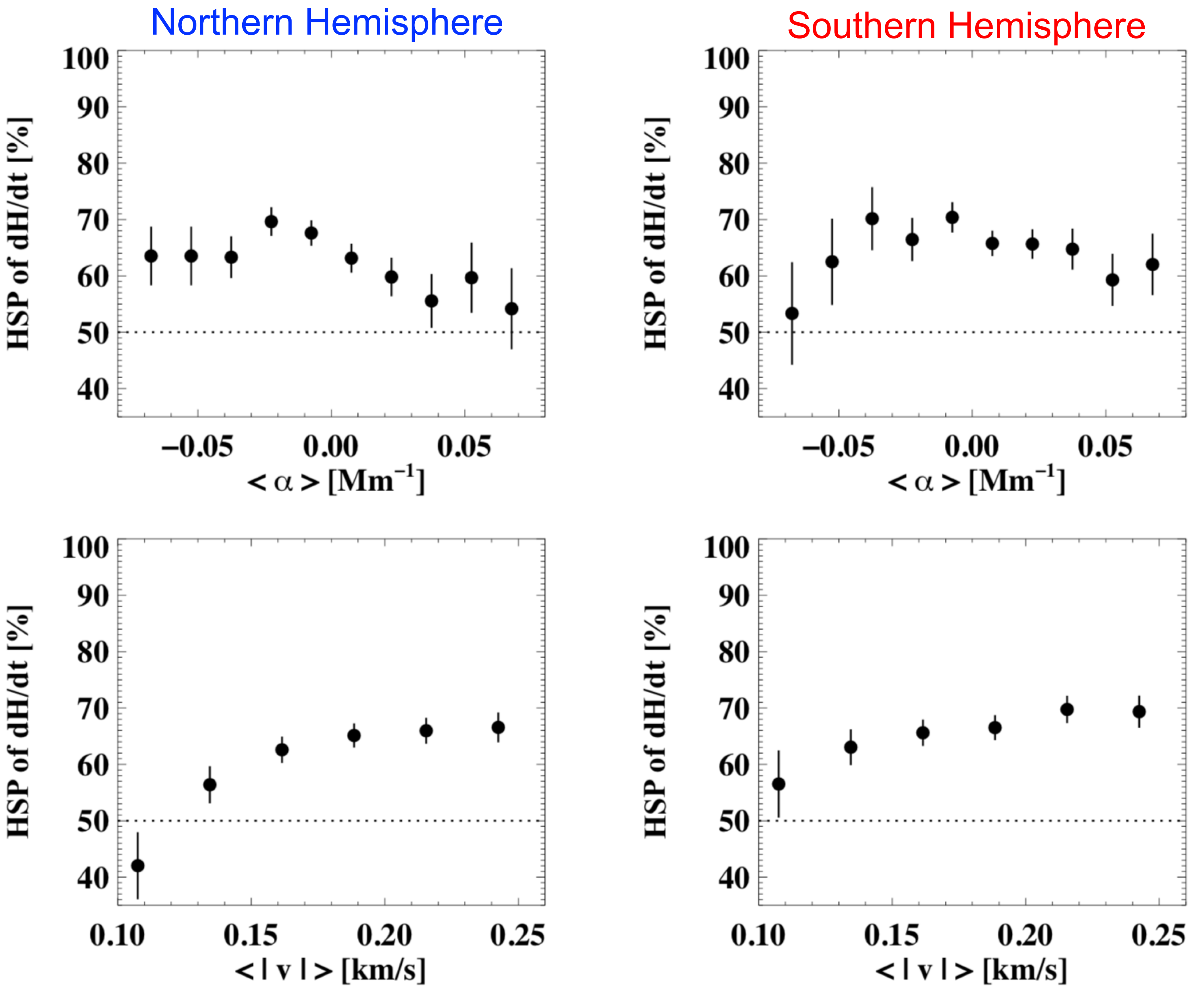
Results: (2) HSP vs Time (Top) & HSP vs Latitude (Bottom)



Results: (3) HSP vs |dH/dt| (Top) and HSP vs ϕ (Bottom)



Results: (4) HSP vs < α > (Top) and HSP vs <|v|> (Bottom)



Summary of Observational Findings

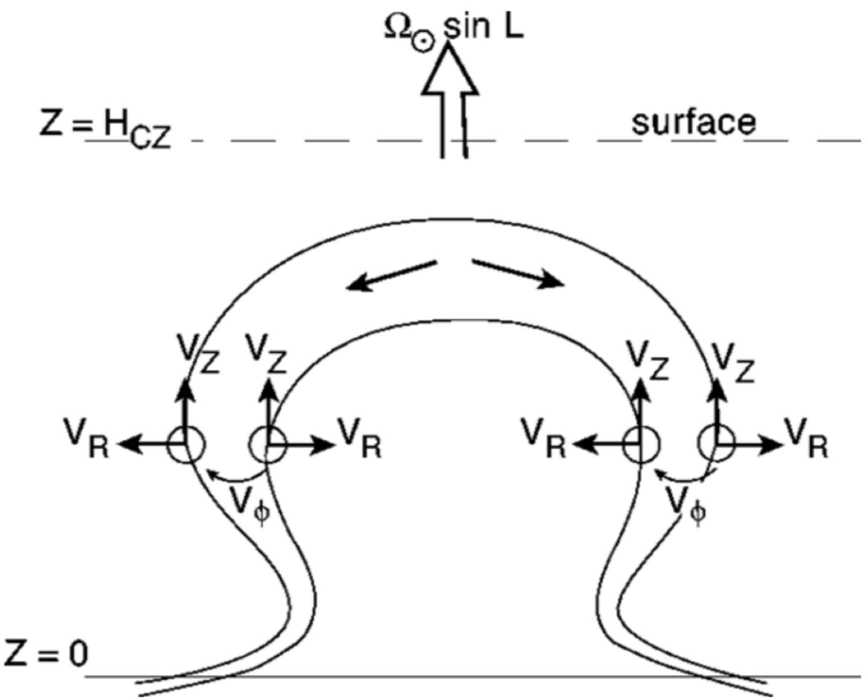
1. The HSP of dH/dt
   - 63% and 65% in the northern and southern hemispheres

2. The HSP increases from 50–60% up to 70–80% in cases where the ARs:
   1) appeared during the inclining phase of the solar cycle, or at higher latitudes;
   2) had larger values of |dH/dt|, the total unsigned magnetic flux, or the average plasma-flow speed;
   3) displayed the same sign between the average force-free parameter and that expected from the HSP (i.e., negative/positive in the northern/southern hemisphere).

Interpretations: (1) Coriolis Force in the Convection Zone
(Including small-scale Σ-effect)

left-handed/right-handed in the northern/southern hemisphere

$$\frac{\text{Coriolis Force}}{m} = 2 V_R \Omega_\odot \sin L$$



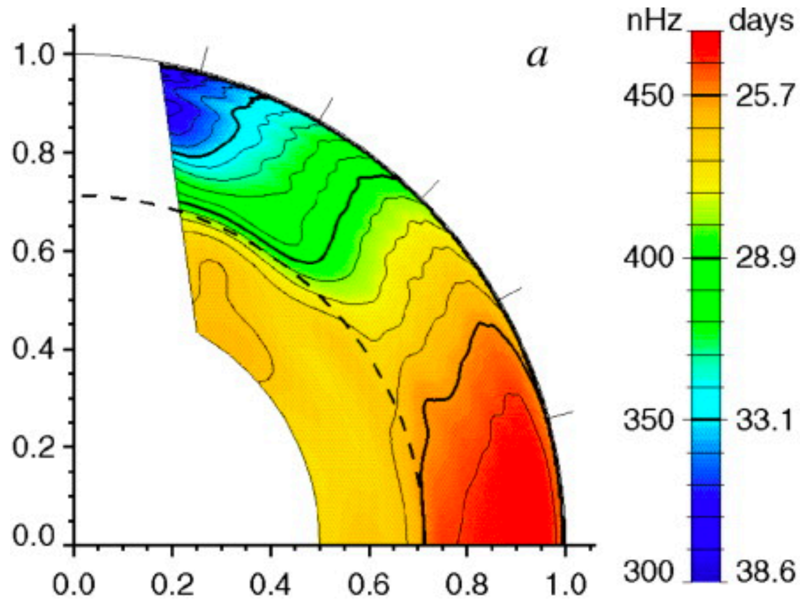
Wang+2013

- The twist with the sign agreeing with the HSP will be more effectively induced by the Coriolis force in cases:
  1) Higher latitude
  2) Larger magnetic flux
     → Larger magnetic pressure
     → Faster expansion

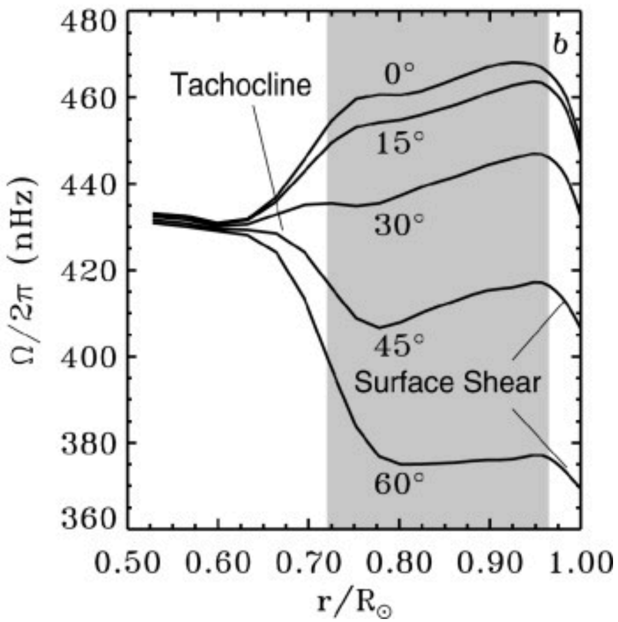
- Good agreement with our observational findings:
  - The HSP of dH/dt is positively correlated with heliographic latitude, Φ, and <|v|>, respectively.

Interpretations: (2) Differential Rotation in the CZ

Schou+1998



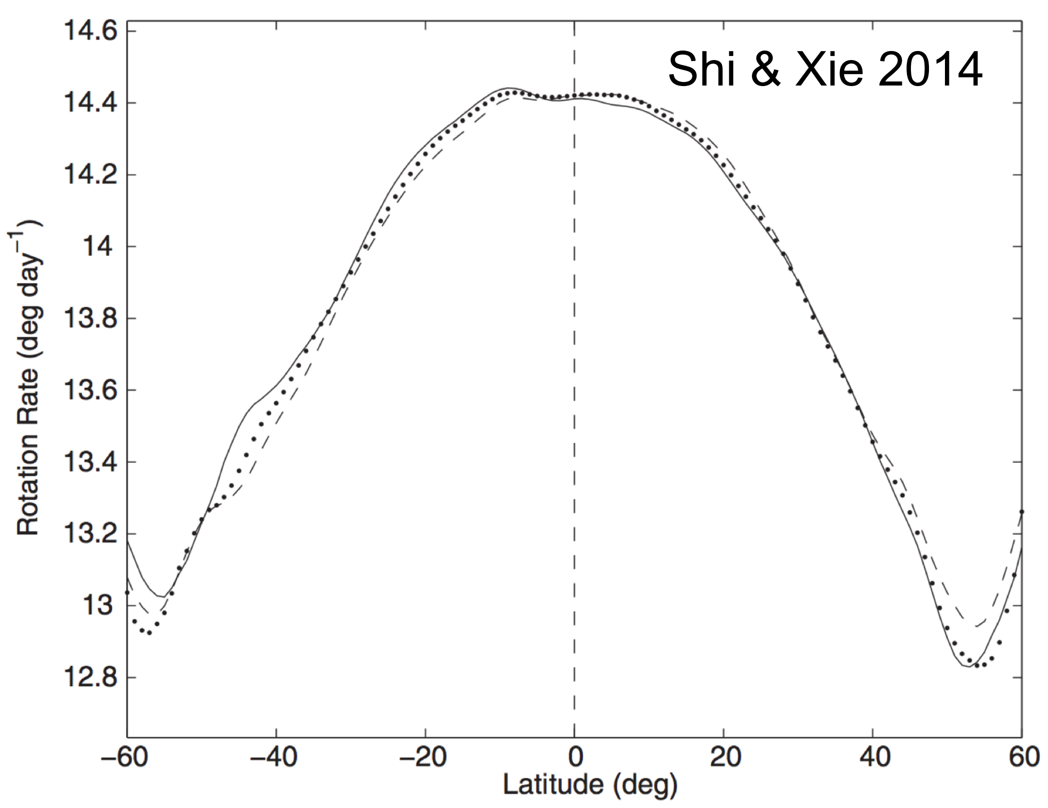
Howe+2000



- A negative contribution to the HSP by a shearing action of differential rotation on a rising Ω-shaped flux tube with a tilt in the CZ.
  1) Larger differential rotation at a higher latitude (Schou+1998; Howe+2000)
  2) Strong, large-scale magnetic fields at the base of the convection zone (Fan & Fang 2014,2016)
     → More enhanced outward Reynolds stress
     → Larger differential rotation

- Disagreement with our observational findings

Interpretations: (3) Differential Rotation on the Surface



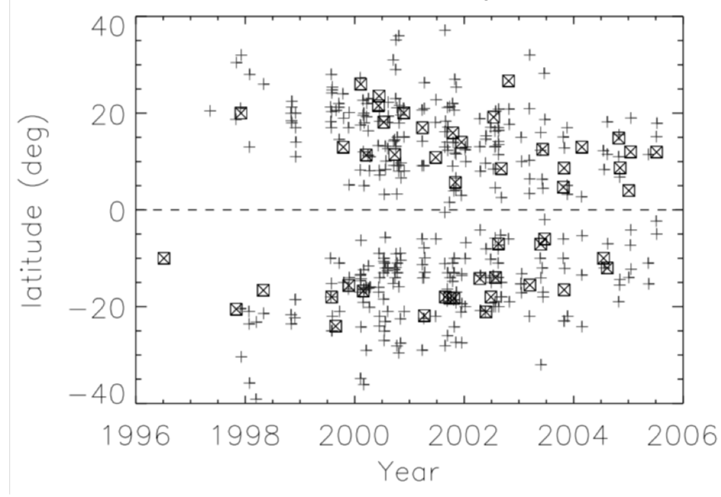
- The differential rotation on the surface will lead to the enhancement of the HSP:
  - Twisting the footpoints of emerged magnetic fields
  - Shearing a bipolar sunspot pair of an emerged Ω-shaped flux tube.

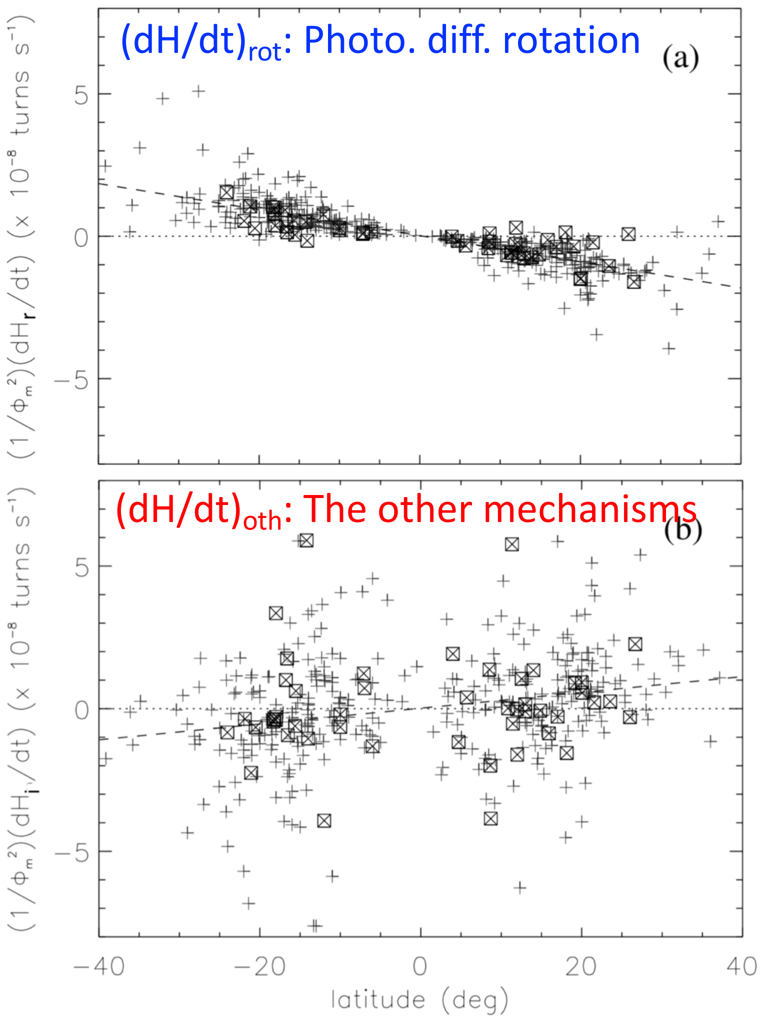
- The HSP can be strengthened by a larger surface differential rotation observed at a higher latitude (Shi & Xie 2014; Lamb 2017).
  - This agrees with our observations!

(3) Differential Rotation on the Surface

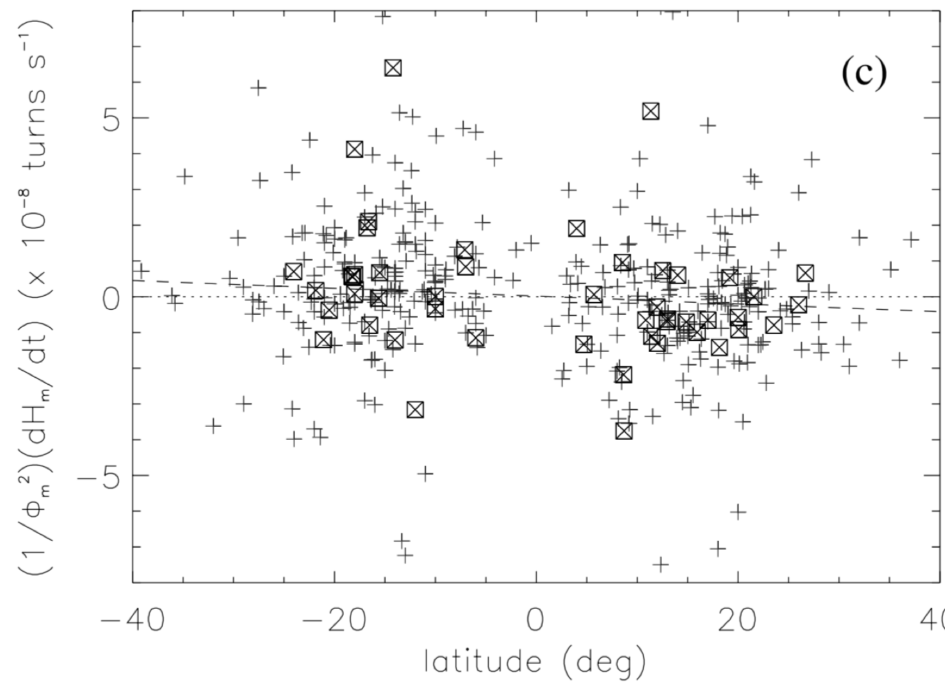
- LaBonte+2007
  - dH/dt for 393 ARs in cycle 23
  - $(dH/dt)_{oth}$: $(dH/dt)_{rot}$ = ~5.4 : 1
  - HSP: 57% in the north and 60% in the south

393 AR samples

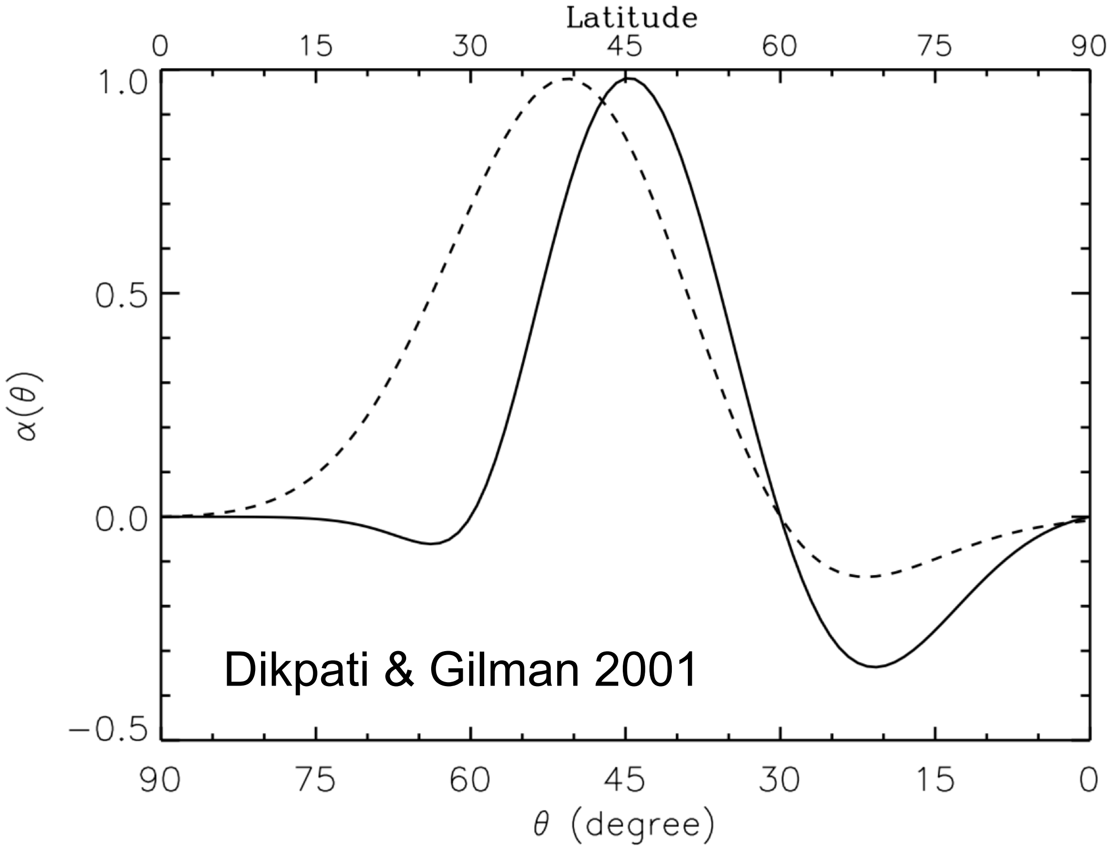




$dH/dt = (dH/dt)_{rot} + (dH/dt)_{oth}$



Interpretations: (4) α-effect at the base of the CZ



- The tachocline α-effect of flux-transport dynamos (e.g., Gilman & Charbonneau 1999; Dikpati & Gilman 2001):
  - Generating a twisted flux tube of which helicity sign follows the HSP
  - The tachocline α-effect is much larger at latitudes of ∼30°–50°.
  - A higher HSP is expected at higher latitudes.
  - This agrees with our observations!

One-sentence Conclusion and Challenges

- Our observational findings support ***the enhancement of the HSP*** mainly by the Coriolis force acting on an expanding flux tube through the convection zone, as well as the differential rotation on the surface and the tachocline α-effect of a flux-transport dynamo.

- Can state-of-the-art solar convective dynamo simulations help us?
  - To validate the observed HSP trends
  - To better understand the relative important of the different processes responsible for the HSP