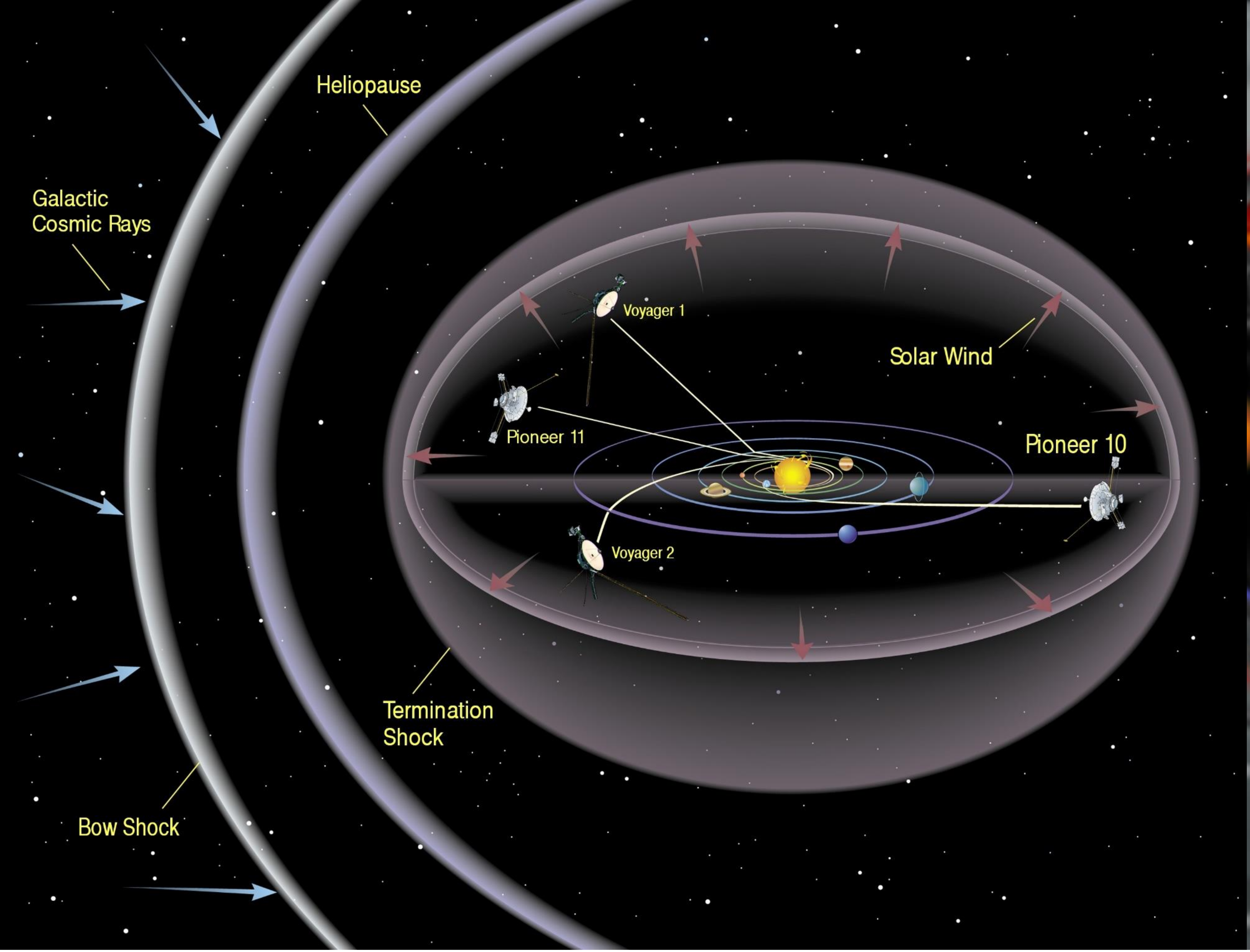
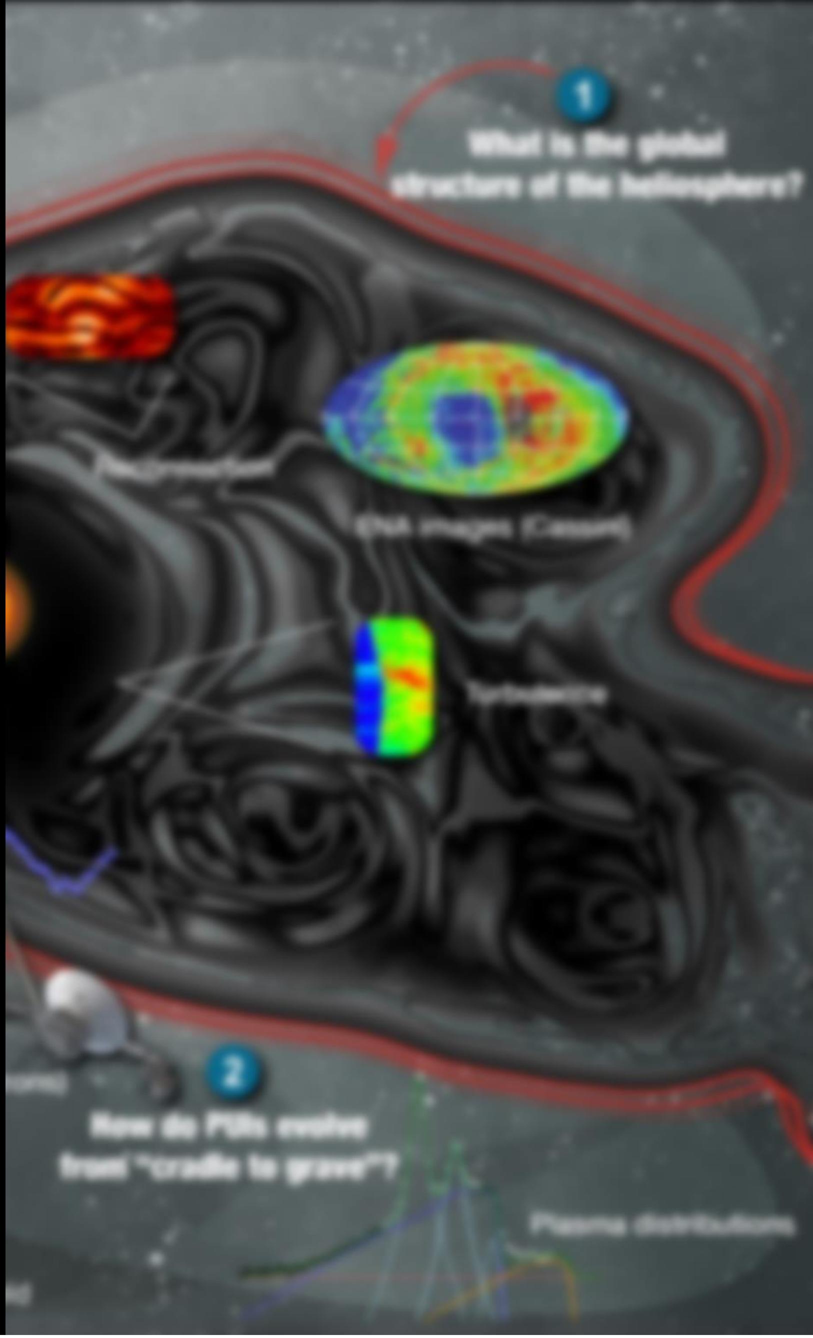
Revisiting the winding angle of the heliospheric magnetic field: investigating the influence of turbulence

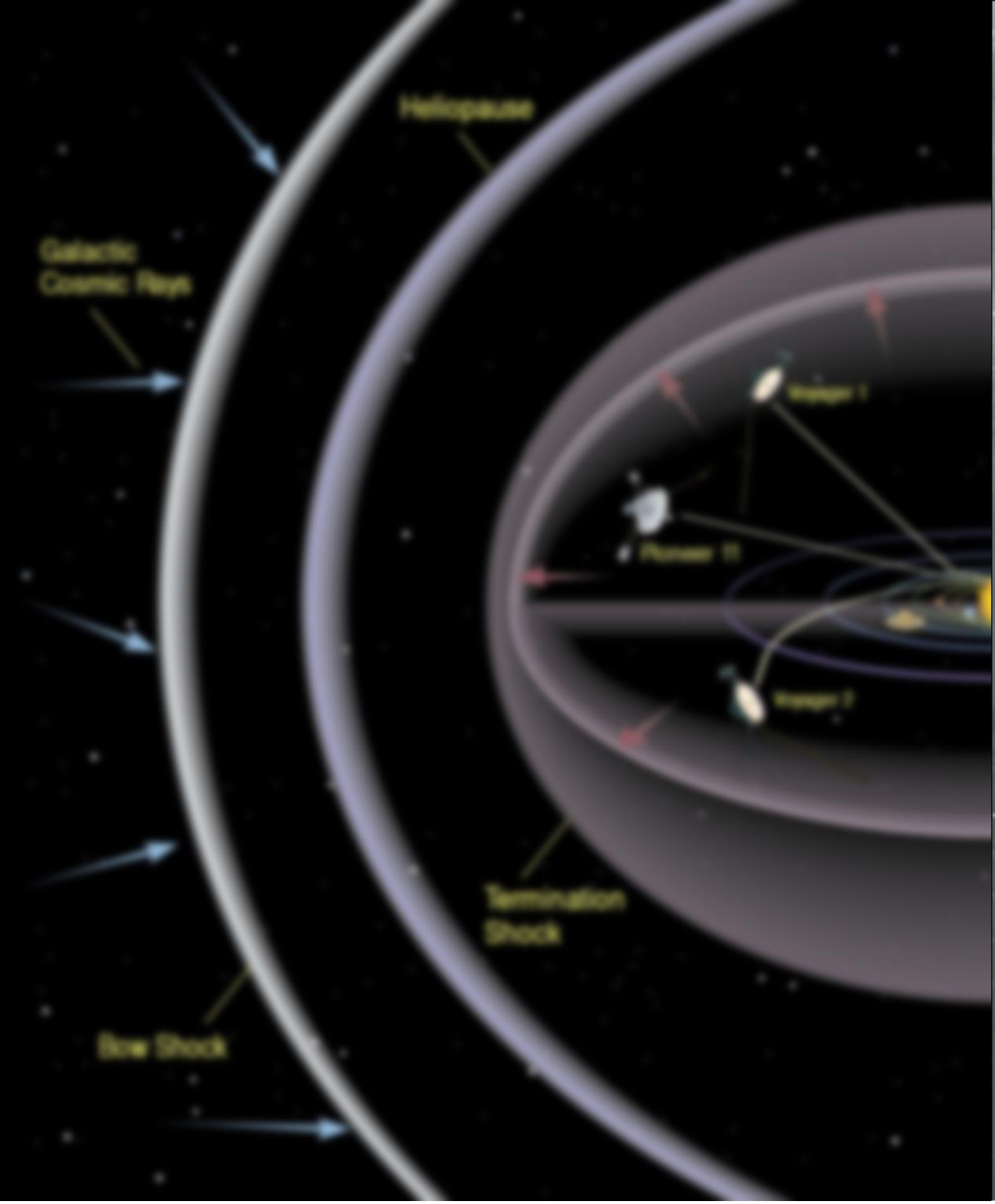
Frans van der Merwe, N.E. Engelbrecht

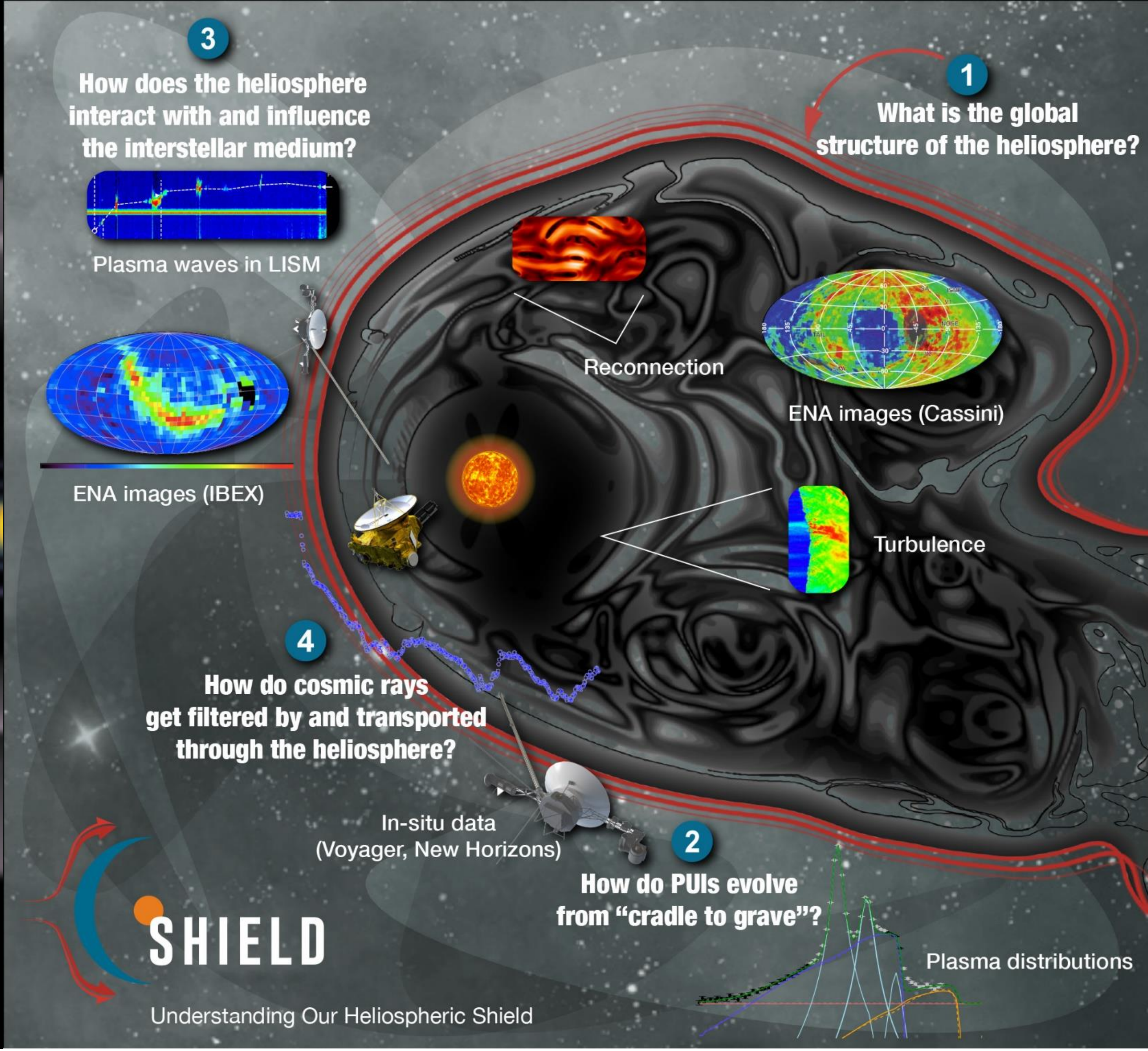
Centre for Space Research

North-West University


Heliopause
Galactic
Cosmic Rays
Voyager 1
Solar Wind
Pioneer 11
Pioneer 10
Voyager 2
Termination
Shock
Bow Shock

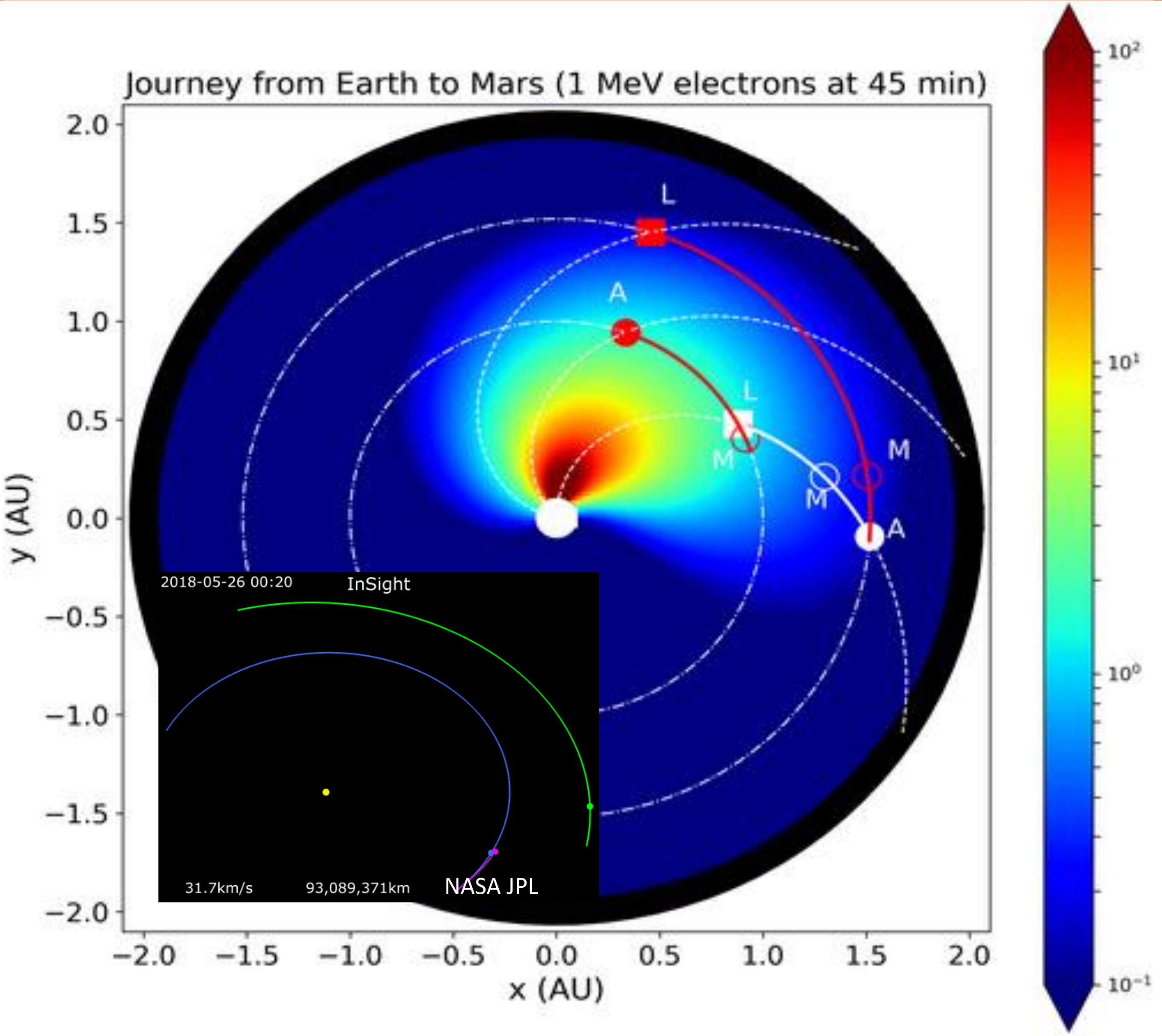





3
How does the heliosphere interact with and influence the interstellar medium?
Plasma waves in LISM
ENA images (IBEX)
Reconnection
ENA images (Cassini)
Turbulence
1
What is the global structure of the heliosphere?
4
How do cosmic rays get filtered by and transported through the heliosphere?
In-situ data (Voyager, New Horizons)
2
How do PUIs evolve from “cradle to grave”?
Plasma distributions
SHIELD
Understanding Our Heliospheric Shield

Why study the winding angle?

- The HMF forms an integral part of our understanding of the Sun, and its geometry plays a key role in the transport of energetic charged particles - **early warning systems for astronauts**
- **Hohmann-Parker effect**, Posner *et al.*, 2013.
- Spacecraft remains close to HMF line connecting Earth/Mars with Sun while in Hohmann transfer orbit



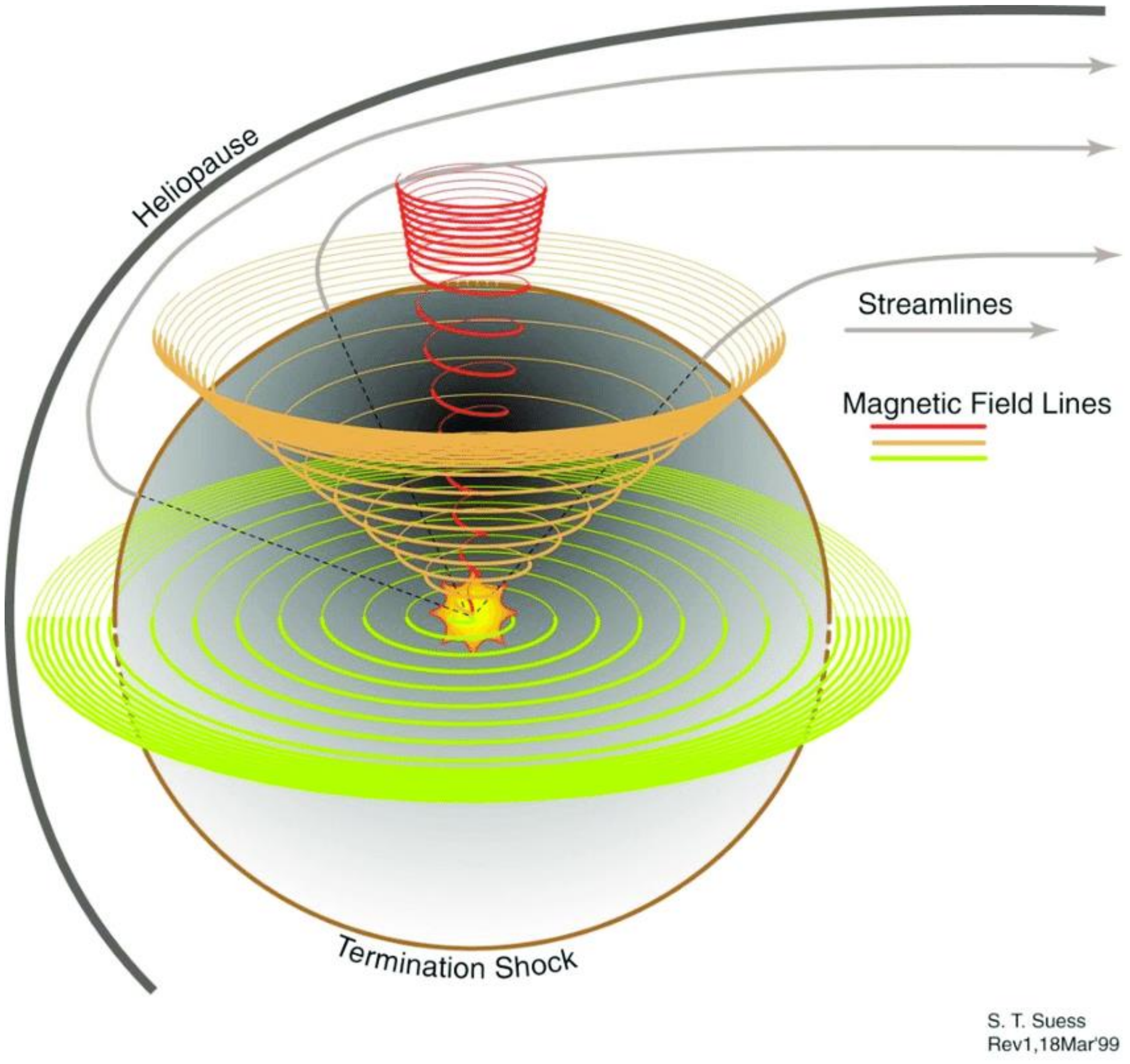
[Posner & Strauss, 2020]

The Parker model of the heliospheric magnetic field

- Assumptions:
- Constant and radially directed solar wind speed
- Constant angular speed of a magnetic footpoint on the source surface
- The magnetic field is frozen into the solar wind

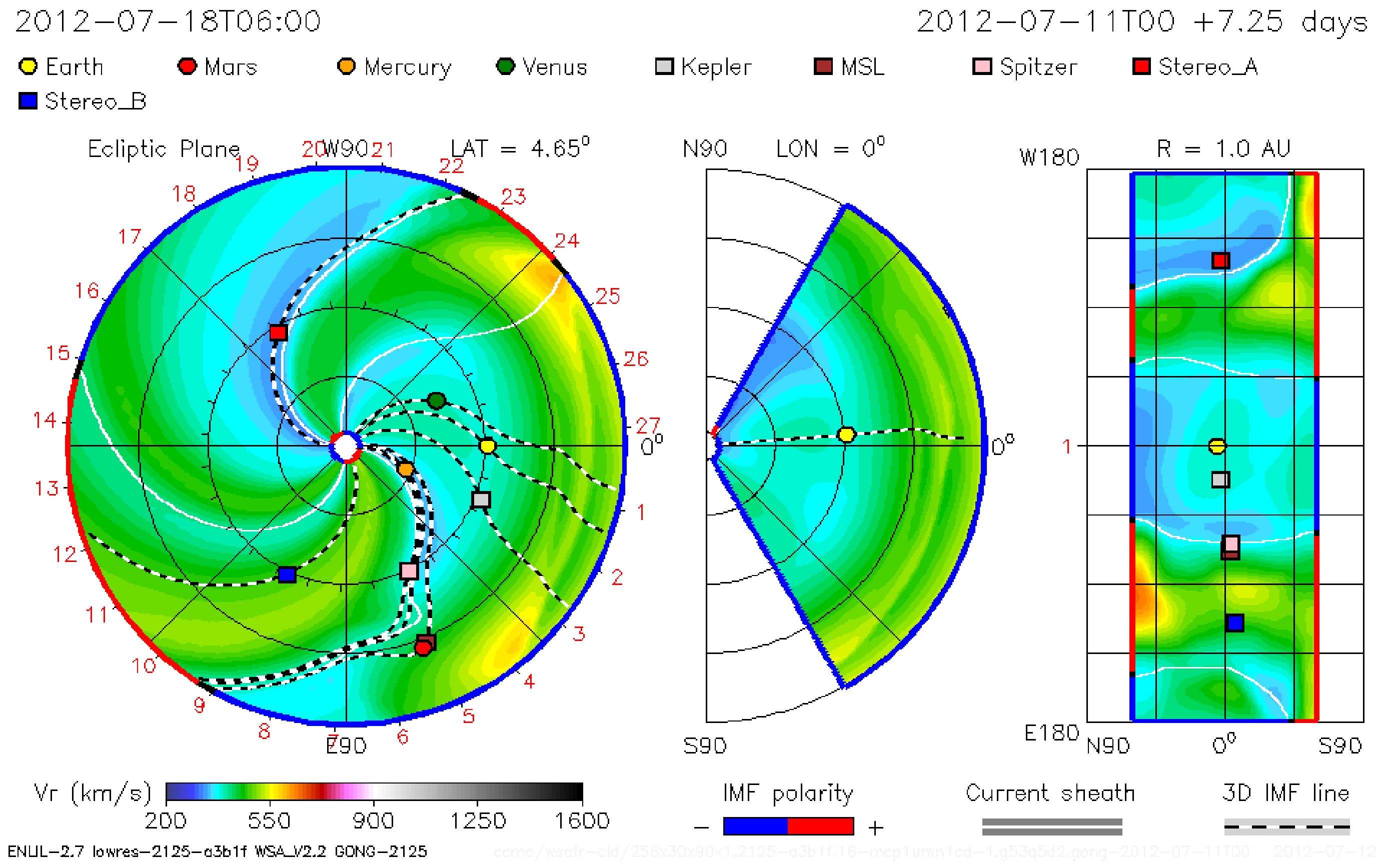
$$\boldsymbol{B}(r) = B_0\left(\frac{r_{ss}}{r}\right)^2 [\,\hat{e}_r - \tan\psi\,\hat{e}_{\phi}]$$

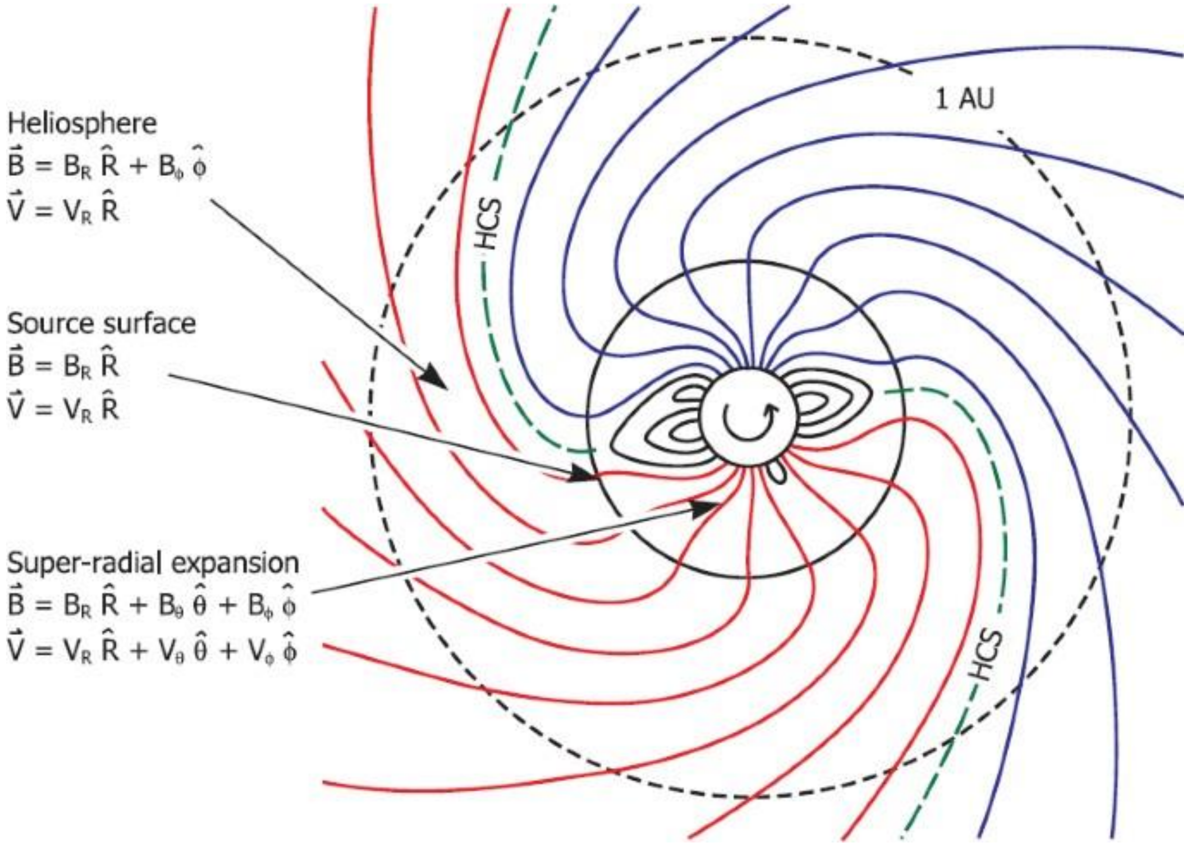
$$\tan\psi = -\frac{B_\phi}{B_r} = \frac{\Omega}{v_{sw}}(r - r_{SS})\sin\theta$$



The Parker model in the ecliptic plane ($\sin\theta = 1$)

HMF +/- important





[Owens and Forsyth, 2013]

The winding angle

- **The 2D winding angle:**

Winding angle of the Parker HMF given by:

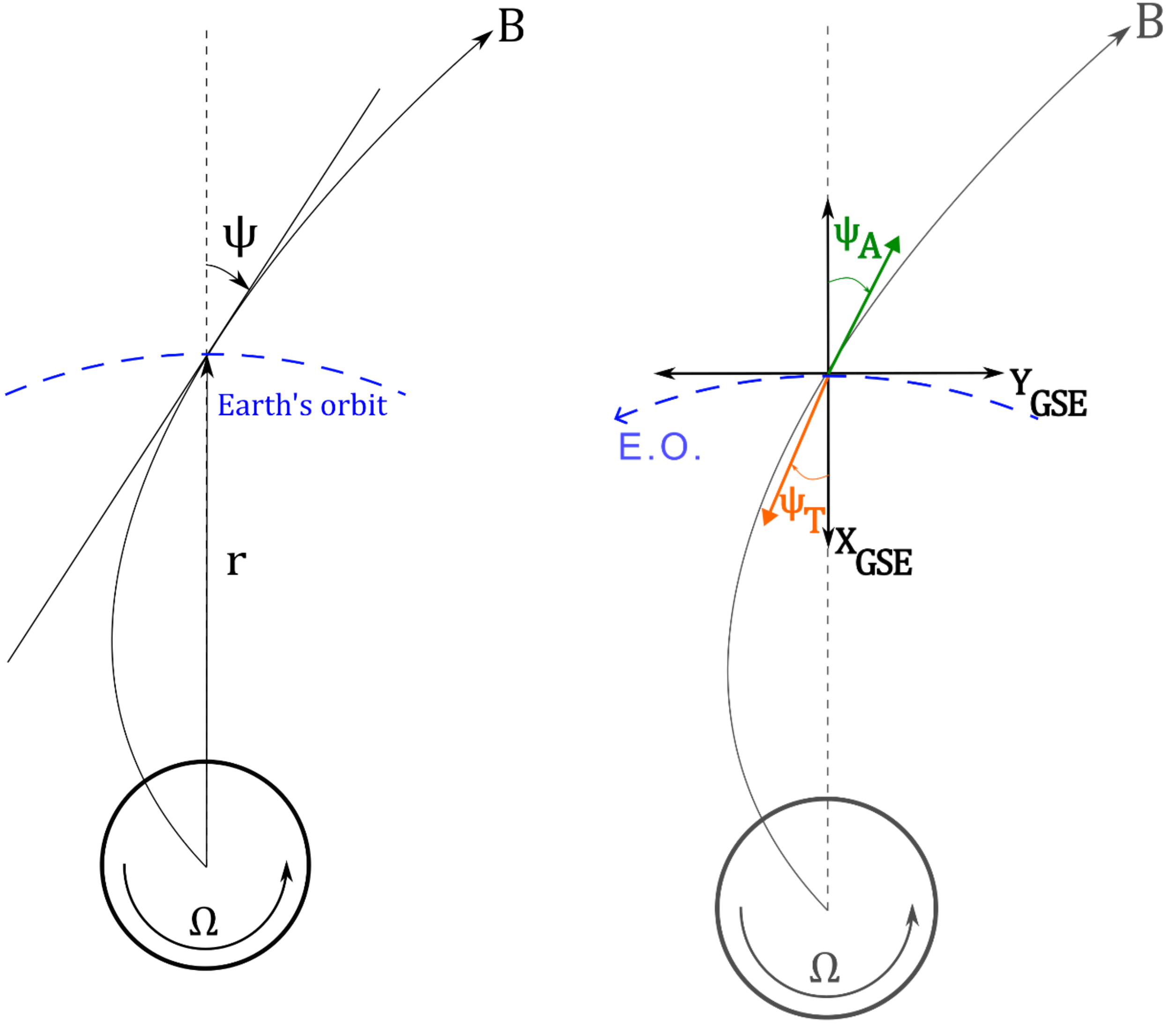
$$\tan\psi_P = -\frac{B_\phi}{B_r} = \frac{\Omega}{v_{sw}}(r - r_{SS})\sin\theta \,,\, \Omega = \frac{2\pi r_\odot}{T}$$

This work Smith & Bieber, 1991

- **The 3D winding angle:**

The HMF is turbulent, and transverse fluctuations at 1 AU imply presence of B_θ component which implies 3D HMF (Burger *et* al. 2008):

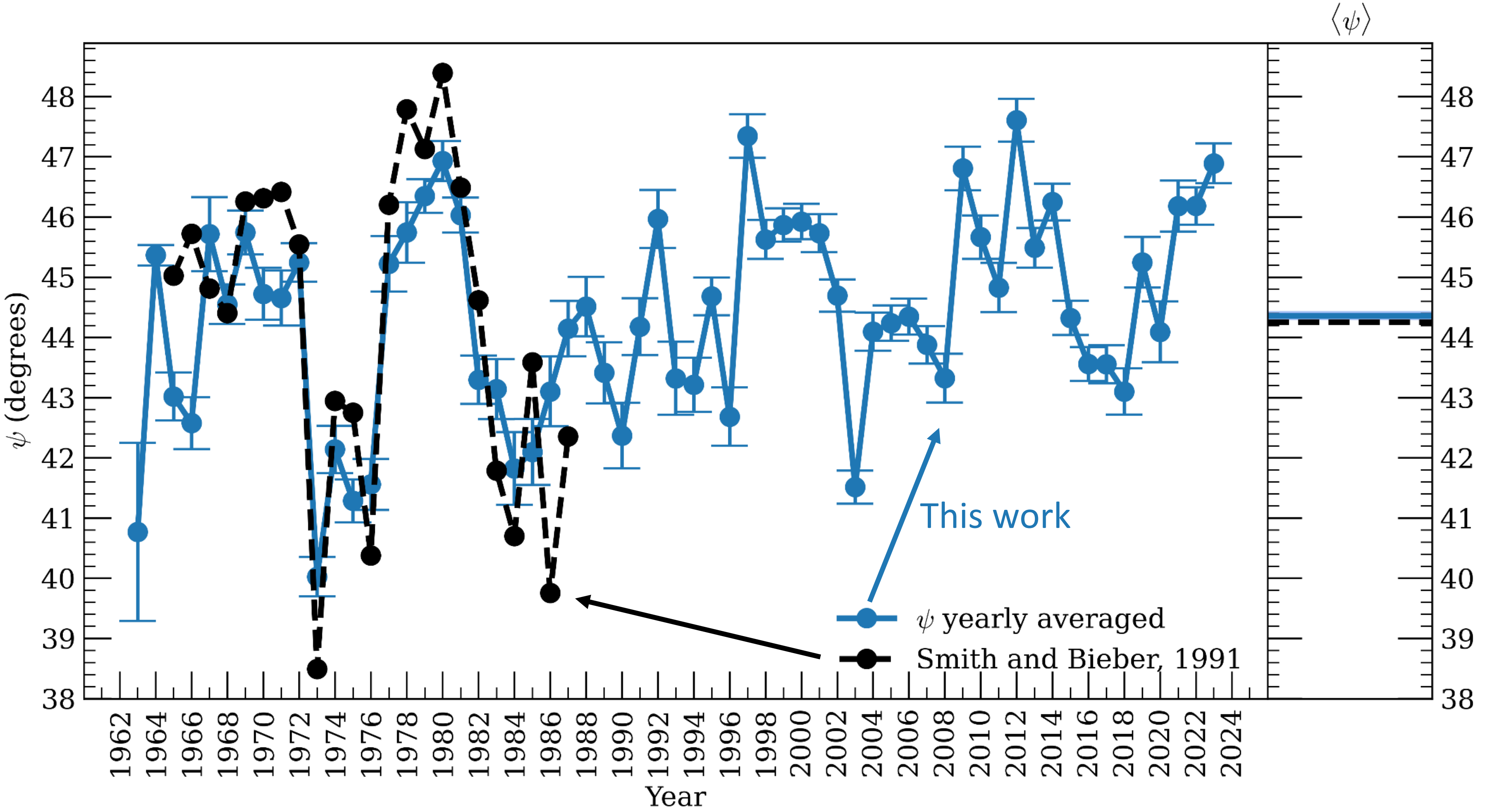
$$\tan\psi_P = -\frac{B_\phi}{\sqrt{B_r^2 + B_\theta^2}}$$



Adapted from Brandt (1970)

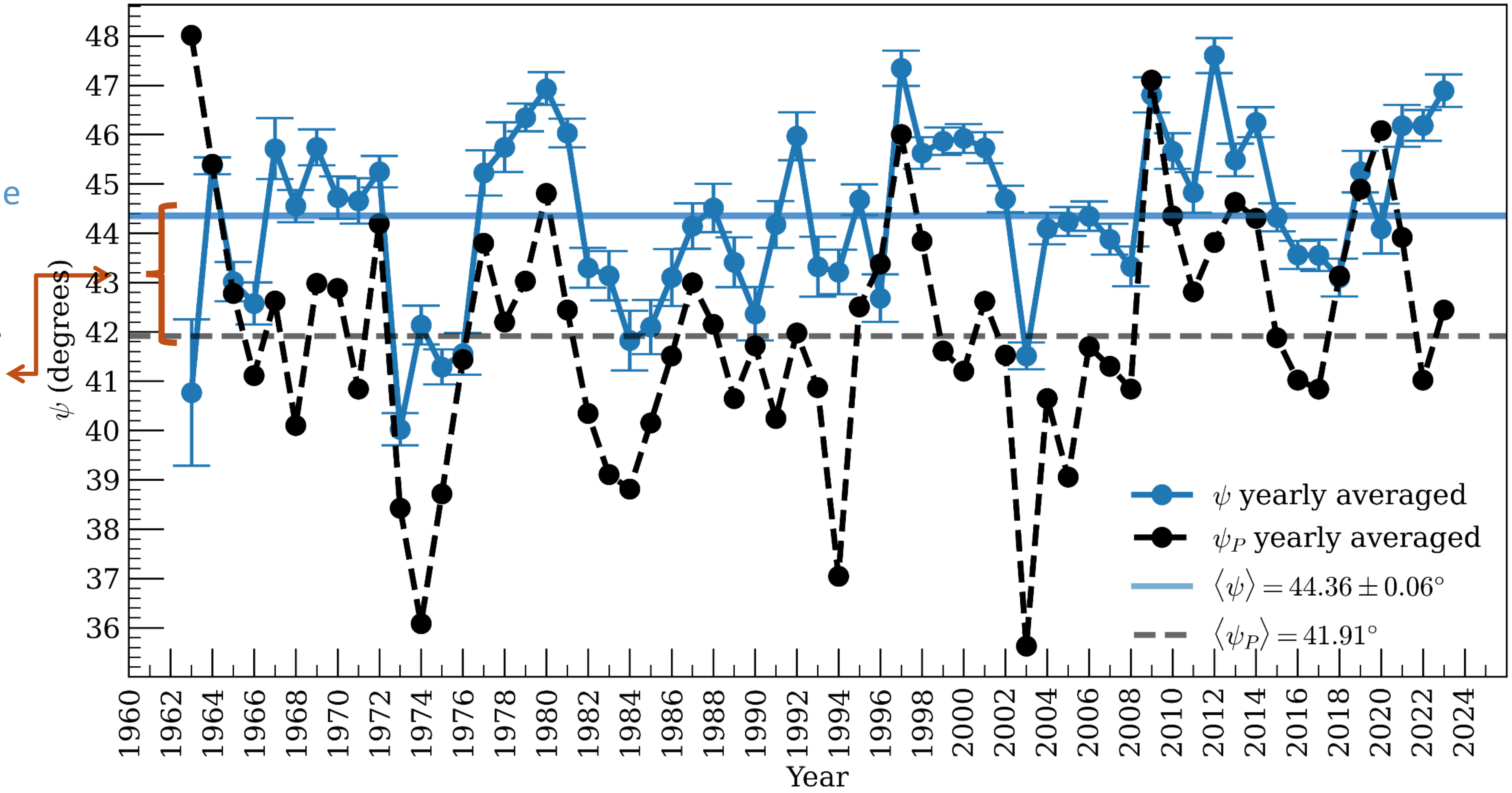
2D winding angle results: SB91 comparison

- GSE: $\tan\psi = -\frac{B_y}{B_x}$,
- 1965-1987: not an exact match to Smith & Bieber (1991), but follows the general trend



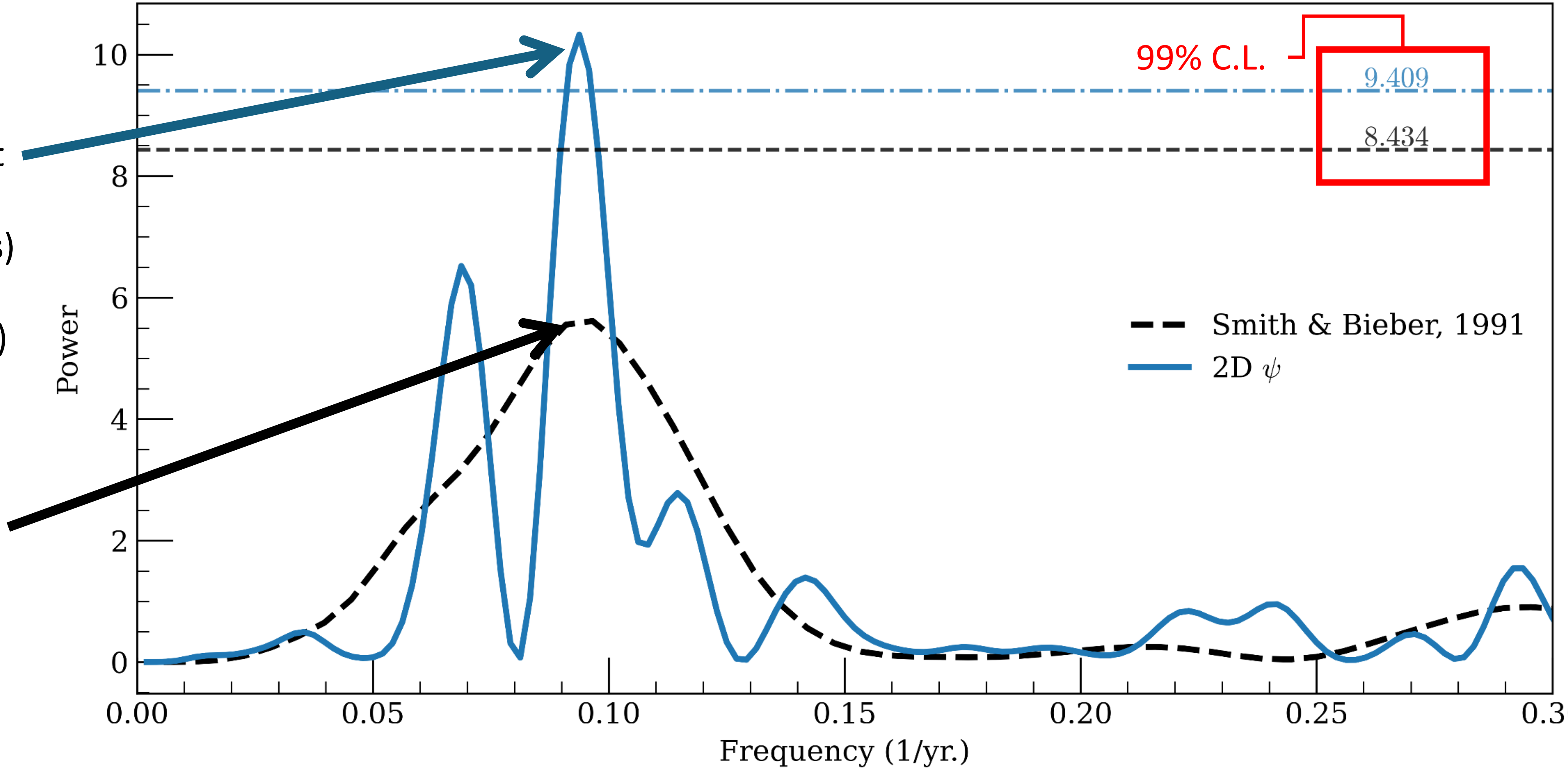
2D winding angle results compared to Parker prediction

- Average 2D winding angle $\langle \psi \rangle = 44.36° \pm 0.06°$
- Average winding angle is overwound by $2.45° \pm 0.06°$
- Good agreement with 2.8° of Smith & Bieber (1991)



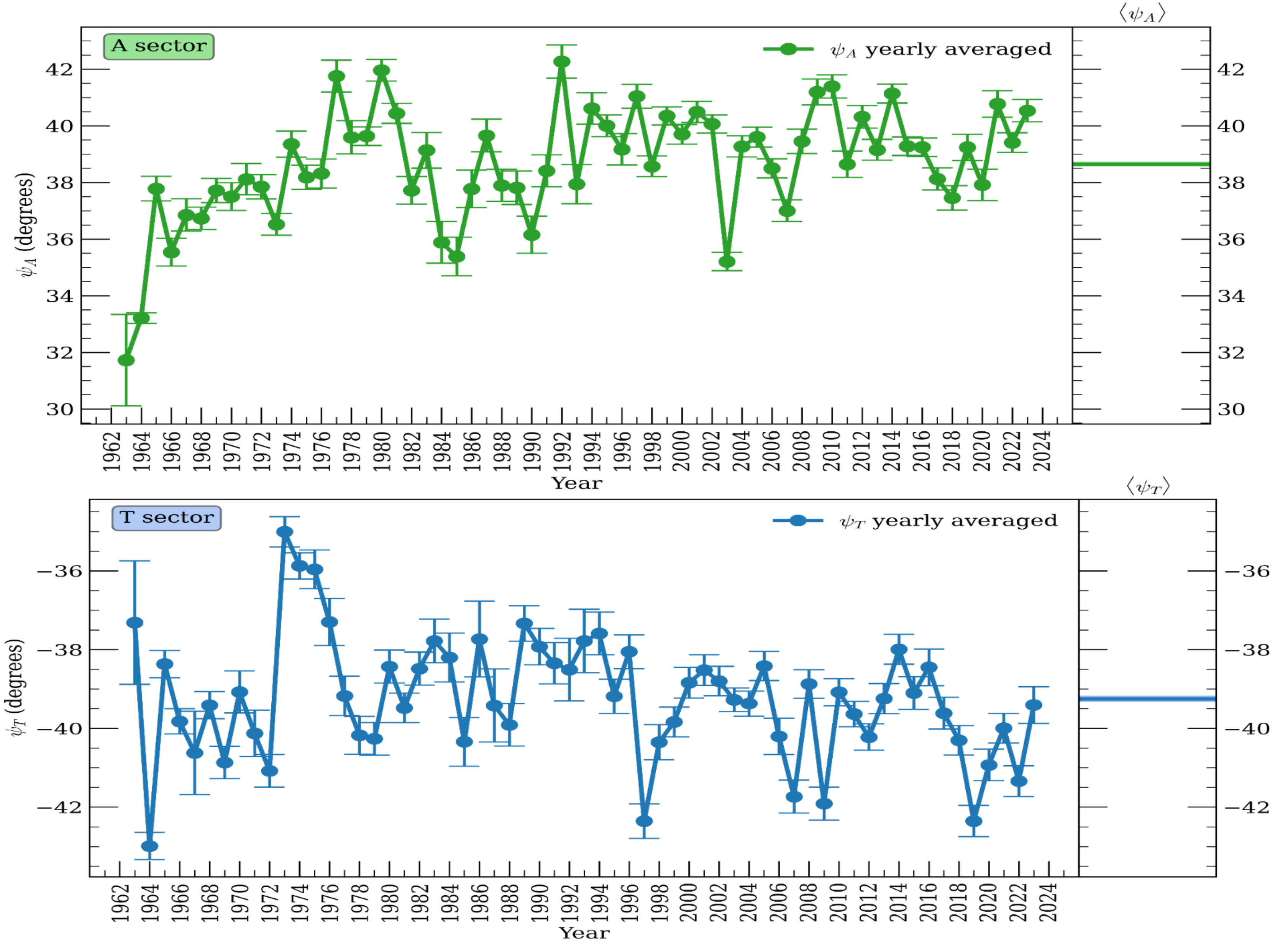
Lomb-Scargle periodogram of 2D winding angle results

- Statistically significant peak at frequency of $0.09 yr.^{-1}$ (**10.7 years**)
- Smith & Bieber (1991) shows no statistically significant 11 or 22 year cycle



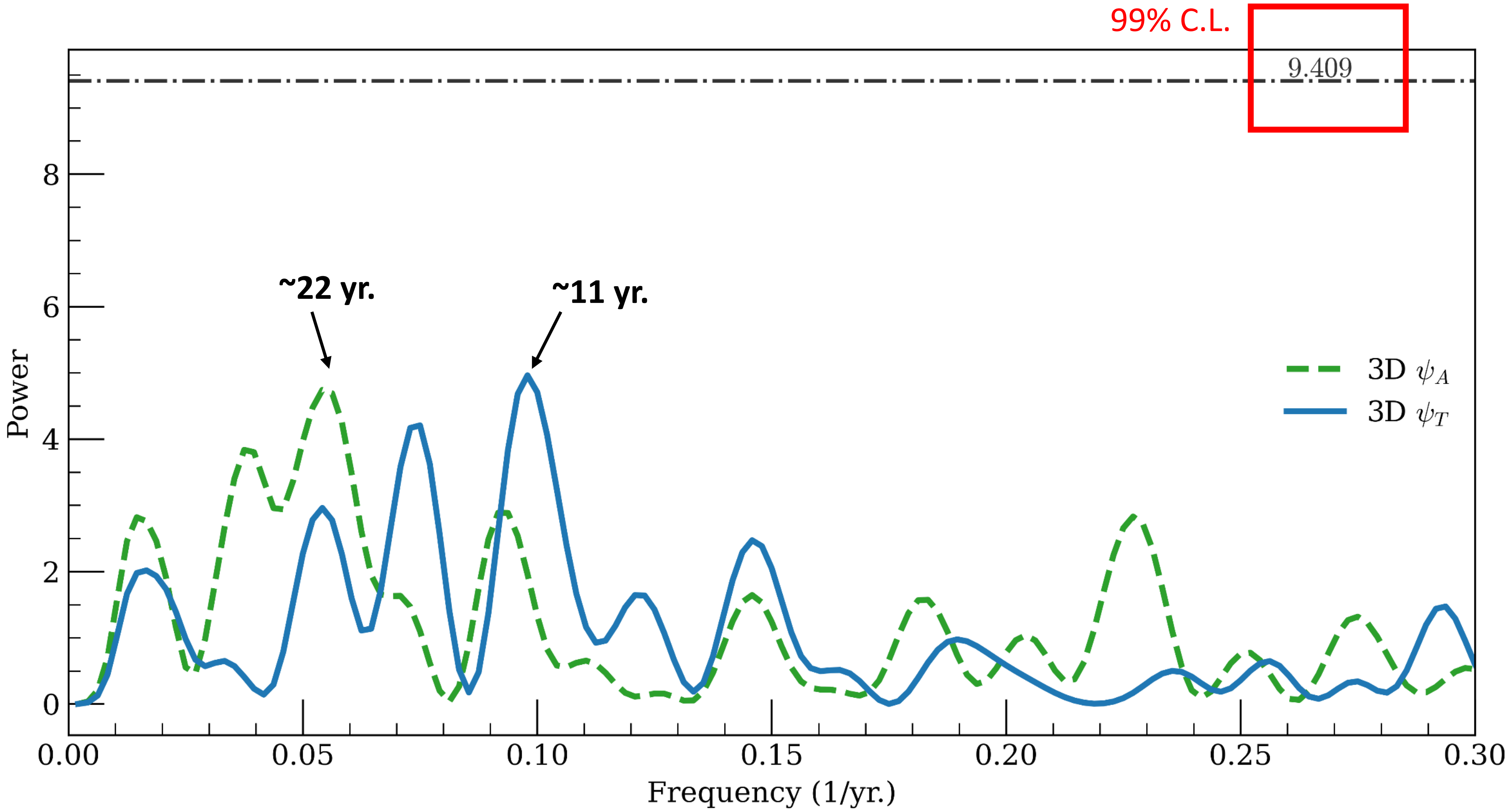
3D winding angle results

- GSE: $\tan\psi = -\frac{B_y}{\sqrt{B_x^2 + B_z^2}}$
- $\langle\psi_A\rangle = 38.65° \pm 0.06°$
- 3D field underwound from Parker prediction by $3.26° \pm 0.06°$
- $\langle\psi_T\rangle = -39.25° \pm 0.07°$, underwound by $2.66° \pm 0.07°$
- ***3D field is underwound by ≈ 3° !!!***



Lomb-Scargle periodogram of 3D winding angle results

- No statistically significant 11 or 22 year periodicities



The influence of turbulence on the winding angle

- The influence of turbulence possibly explains the underwound 3D result due to B_θ influence on 3D winding angle.
- Define 3D HMF $\boldsymbol{B} = B_0\hat{e}_B + \boldsymbol{b} = B_0\hat{e}_B + b_1\hat{e}_1 + b_2\hat{e}_2$
- Construct a basis orthonormal to the Parker HMF such that

$$\boldsymbol{B} = (B_0\cos\psi + b_2\sin\psi)\hat{e}_r + b_1\hat{e}_\theta + (b_2\cos\psi - B_0\sin\psi)\hat{e}_\phi$$

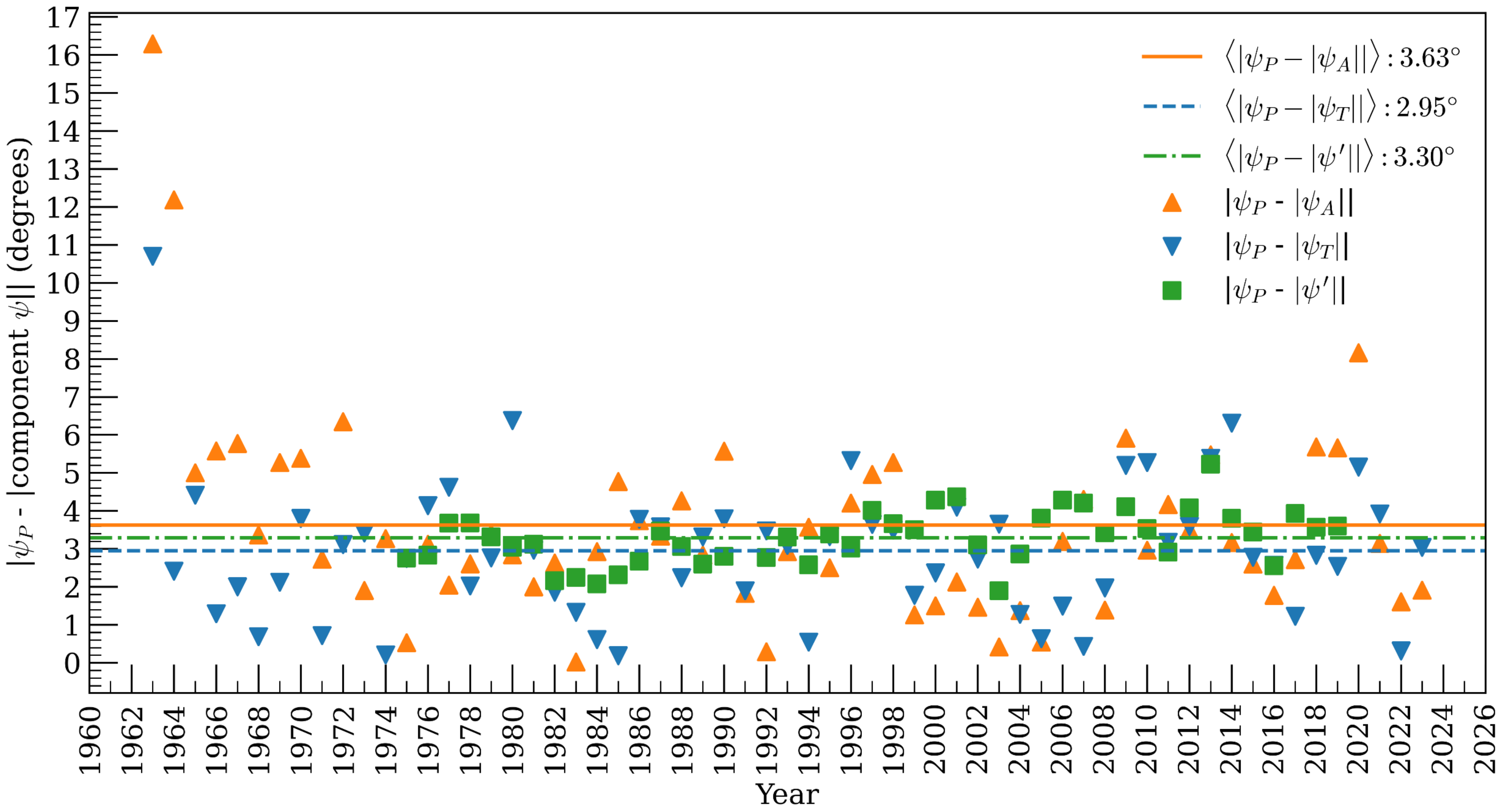
- Assume low strength axisymmetric fluctuations such that $\langle b_1^2\rangle \approx \langle b_2^2\rangle \approx \delta B_1^2$
- The winding angle for the turbulent 3D HMF is then defined by

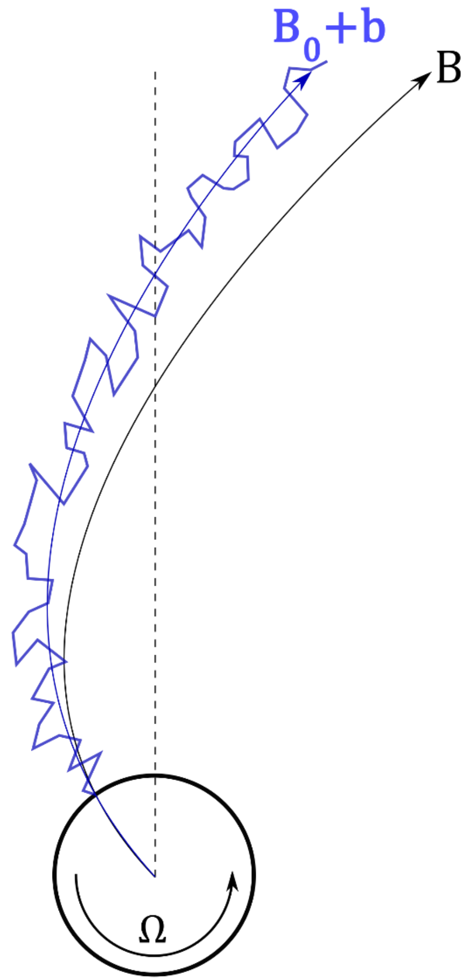
$$\tan\psi' \approx \tan\psi_P\left[1 + \frac{1}{2}\frac{\delta B_1^2}{B_0^2}\left(\frac{1+\sin^2\psi_P}{\cos^2\psi_P}\right)\right]^{-\frac{1}{2}}$$

$-\frac{B_\phi}{B_r}$

Magnetic variance (Burger, Nel and Engelbrecht, 2022)

The influence of turbulence on the winding angle



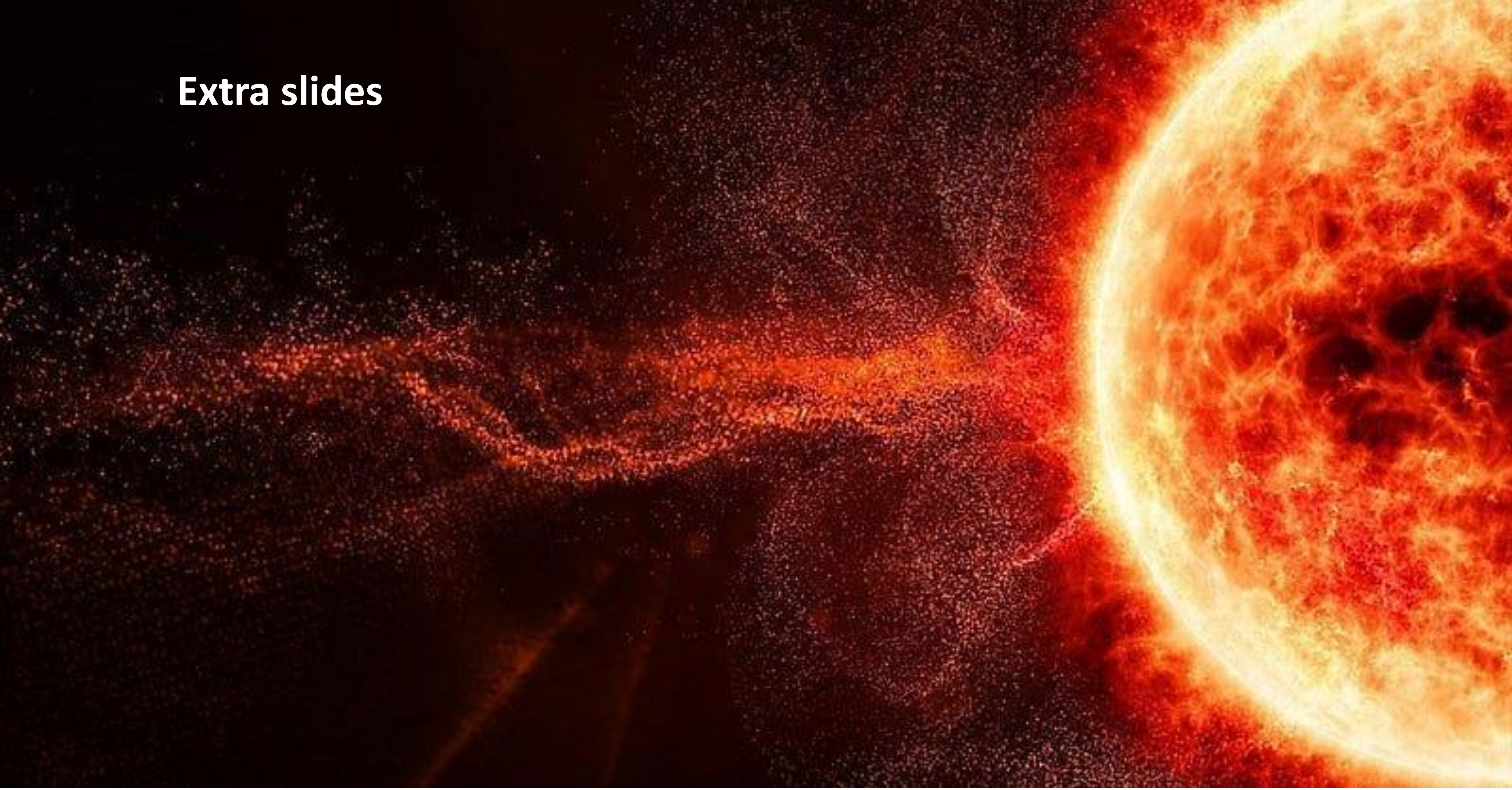


Summary and outlook

- The current analysis provides results in reasonable agreement with Smith & Bieber (1991): **2D winding angle is overwound in general**. This result also agrees with subsequent studies of the effect of the averaging interval on the winding angle, e.g. Isaacs *et al.* (2015)
- Lomb-Scargle analysis of Smith & Bieber (1991) results does not show a significant 11-year, nor a 22-year periodicity. This analysis of 60 years of data show a **statistically significant 11-year periodicity for the 2D winding angle**.
- However, analysing the winding angle due to the **3D field** leads to a slightly **underwound** field, by ≈ 3°, with **no statistically significant 11 year periodicity**.
- The **underwinding** can, in principle, be explained through a simple model taking into account **turbulent fluctuations transverse to the Parker HMF** - reasonable prediction for the degree of underwinding.
- Over-/underwound HMF renders early warning system less effective.

Thanks, any questions?

Extra slides



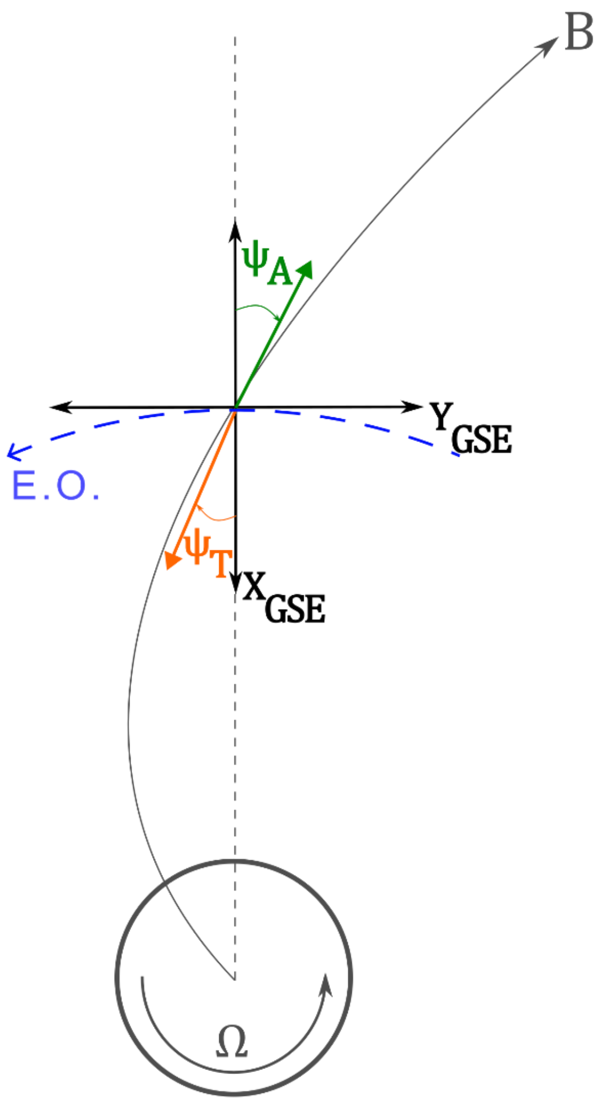
Sources

- Brandt, J. 1970. *Introduction to the Solar Wind*. Astronomy and astrophysics series. W. H. Freeman.
- Burger, R.A., Nel, A.E., Engelbrecht, N.E. 2022. *Spectral properties of the N component of the heliospheric magnetic field from IMP and ACE observations for 1973-2020.* Astrophys. J. 926, 128.
- Burger, R., Krüger, T., Hitge, M. & Engelbrecht, N. 2008. *A Fisk-Parker hybrid heliospheric magnetic field with a solar-cycle dependence*. The Astrophysical Journal, 674(1):511.
- By Phoenix7777 - Own workData source: HORIZONS System, JPL, NASA, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=71080434
- Engelbrecht, N.E., Effenberger, F., Florinski, V. *et al.* Theory of Cosmic Ray Transport in the Heliosphere. *Space Sci Rev* 218, 33 (2022). https://doi.org/10.1007/s11214-022-00896-1
- Engelbrecht, N. & Herbst, Konstantin & Strauss, R. & Scherer, Klaus & Light, Juandre & Moloto, Katlego. (2024). *On the Comprehensive 3D Modeling of the Radiation Environment of Proxima Centauri b: A New Constraint on Habitability?.* The Astrophysical Journal. 964. 10.3847/1538-4357/ad2ade.
- Isaacs, J.J., Tessein, J.A. & Matthaeus, W.H. 2015. *Systematic averaging interval effects on solar wind statistics*. Journal of Geophysical Research: Space Physics, 120(2):868-879. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/2014JA020661.
- Owens, M.J., Forsyth, R.J. The Heliospheric Magnetic Field. *Living Rev. Sol. Phys.* 10, 5 (2013). https://doi.org/10.12942/lrsp-2013-5
- Parker, E.N. 1958. *Dynamics of the Interplanetary Gas and Magnetic Fields*. The Astrophysical Journal, 128:664.
- A. Posner, D. Odstrĉil, P. MacNeice, L. Rastaetter, C. Zeitlin, B. Heber, H. Elliott, R.A. Frahm, J.J.E. Hayes, T.T. von Rosenvinge, E.R. Christian, J.P. Andrews, R. Beaujean, S. Böttcher, D.E. Brinza, M.A. Bullock, S. Burmeister, F.A. Cucinotta, B. Ehresmann, M. Epperly, D. Grinspoon, J. Guo, D.M. Hassler, M.-H. Kim, J. Köhler, O. Kortmann, C. Martin Garcia, R. Müller-Mellin, K. Neal, S.C.R. Rafkin, G. Reitz, L. Seimetz, K.D. Smith, Y. Tyler, E. Weigle, R.F. Wimmer-Schweingruber, The Hohmann–Parker effect measured by the Mars Science Laboratory on the transfer from Earth to Mars: Consequences and opportunities, Planetary and Space Science, Volume 89, 2013, Pages 127-139, ISSN 0032-0633, https://doi.org/10.1016/j.pss.2013.09.013.
- O. Porth, M. J. Vorster, M. Lyutikov, N. E. Engelbrecht, Diffusion in pulsar wind nebulae: an investigation using magnetohydrodynamic and particle transport models, *Monthly Notices of the Royal Astronomical Society*, Volume 460, Issue 4, 21 August 2016, Pages 4135–4149, https://doi.org/10.1093/mnras/stw1152
- Smith, C.W. & Bieber, J.W. 1991. *Solar cycle variation of the interplanetary magnetic field spiral*. The Astrophysical Journal, 370(1):435-441. MAG ID: 2087812249.

Data analysis

- Hourly averaged data set (1963-2023) NASA OMNIWeb LRO data set. Parameters used in GSE coordinates: HMF x, y, z components in units of nT, and the plasma flow speed v_{sw} in km/s.
- Sector designation (B and v): based on the sign of the magnetic field components as in the figure where T and A denote the toward and away sectors
  3D designation: same as 2D with B_z having any sign.
- Substituting $B_r = -B_x, B_\phi = -B_y$, and $B_\theta = B_z$, yields the winding angle definitions in GSE coordinates:

$$\tan\psi = -\frac{B_y}{B_x}, \quad \tan\psi = -\frac{B_y}{\sqrt{B_x^2 + B_z^2}}$$



Data analysis (continued)

- The winding angles are binned into 27 day bins with the restriction that 15% of a bin must contain useful $\boldsymbol{B}$ field measurements, otherwise it is discarded along with the corresponding bin of solar wind data.

- Toward and away winding angles (and solar wind speeds) are averaged separately, then the average of the two sector averages is calculated (Smith & Bieber, 1991):

$$\langle\psi\rangle = \frac{\langle\psi_T\rangle + \langle\psi_A\rangle}{2}, \qquad \langle v_{sw}\rangle = \frac{\langle v_{sw_T}\rangle + \langle v_{sw_A}\rangle}{2}$$

- Periodicities: Lomb-Scargle periodograms for 11-year or 22-year cycles; PAST