Recent ideas about the origin of the solar wind and its turbulence

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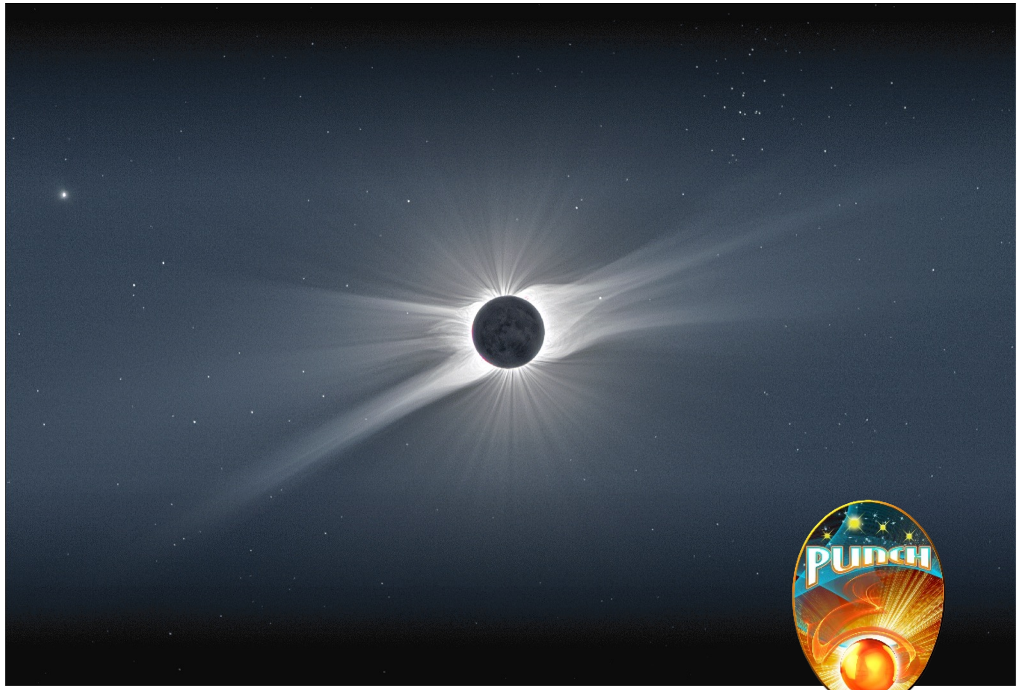
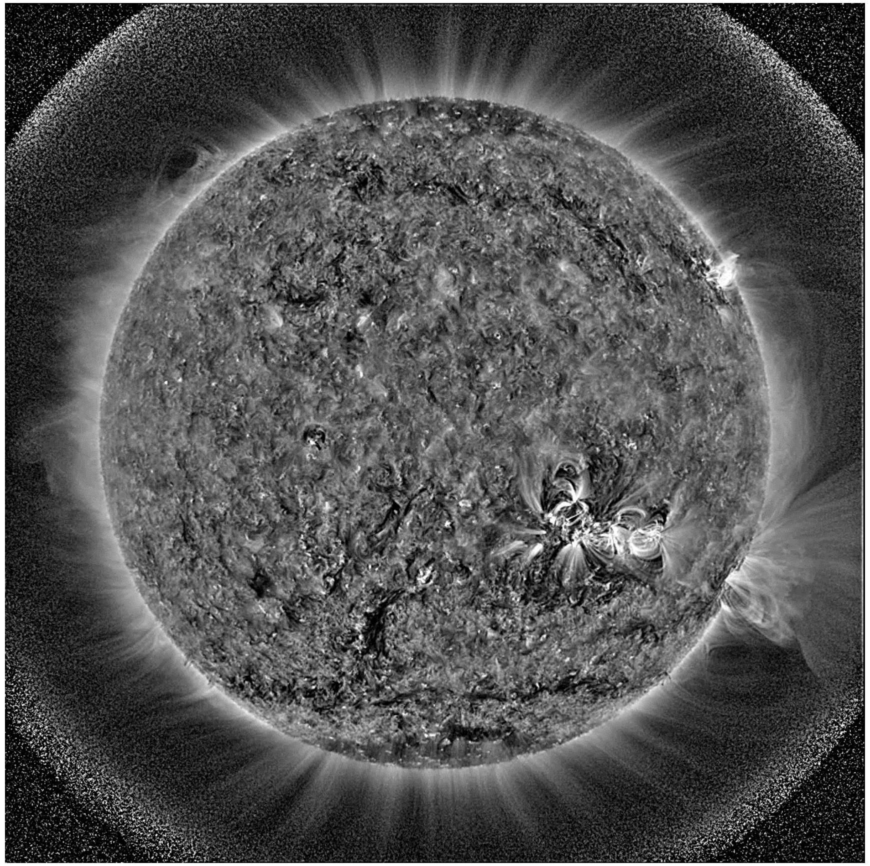
PUNCH 4 Science Meeting
Boulder CO

The corona is structured: PUNCH will measure it!



Indicates PUNCH
can contribute



Courtesy of Steve Cranmer

Recent Parker Solar Probe (PSP) and STEREO observations suggest additional detailed features that may be of importance, several of which will be discussed here:

(1) Presence of 1/f “flicker noise”

(2) Confirmation of the association of the supergranulation scale with organization of the coronal flows and magnetic fields

(3) Differential radial flows exceeding 100km/s in the corona

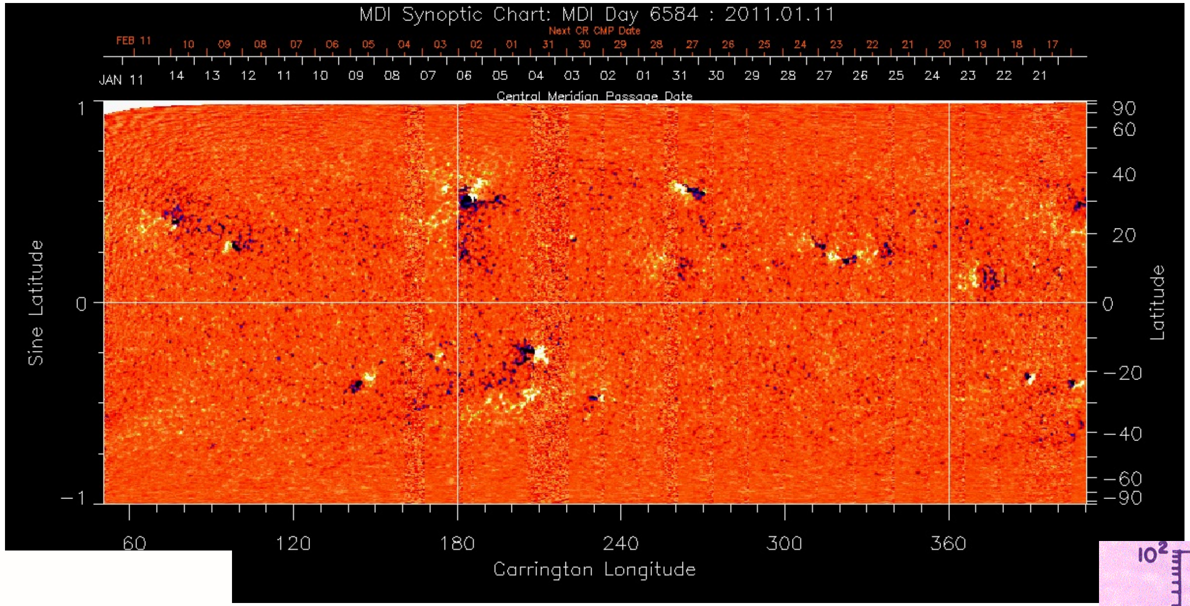
(4) Exploration of low beta sub-Alfvenic corona

(5) The transition between sub- and super-Alfvenic wind, which appears not to be smooth (Chhiber et al, 2022; Cranmer et al 2023).

(6) Turbulence and the question of how the corona is heated and the solar wind is accelerated?

The PUNCH mission can reveal structure in SPACE and TIME, and thus can be expected to further depth to our understanding of these interrelated fundamental heliospheric phenomena.

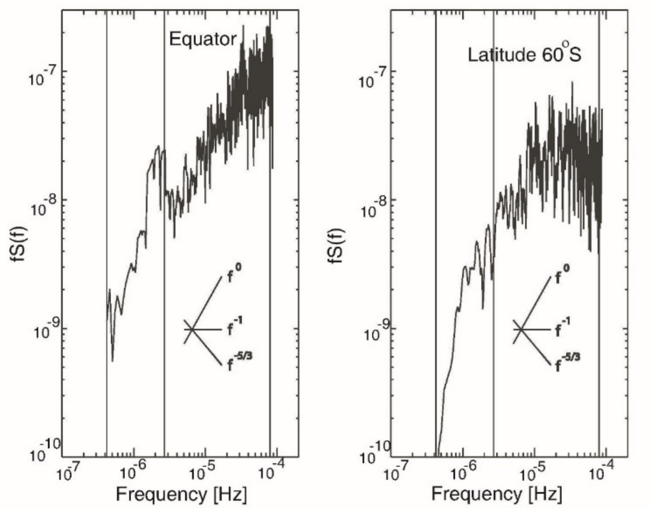
Inner boundary conditions/largest structures



Largest scale Structures: magnetograms

soi.stanford.edu/magnetic/synoptic/eof/plots/

$1/f$ from $2.5\ 10^{-6}$ to $\sim 10^{-4}$ Hz

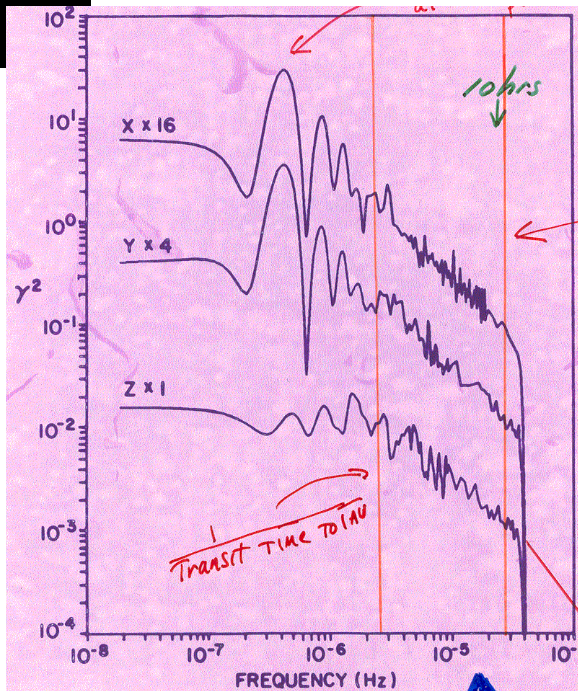


Nakagawa & Levine ApJ (1974)
Also: Matthaeus+ ApJ 657-L121 (2007)

1/f noise:

As observed at 1 AU

WHM & Goldstein, PRL 1986



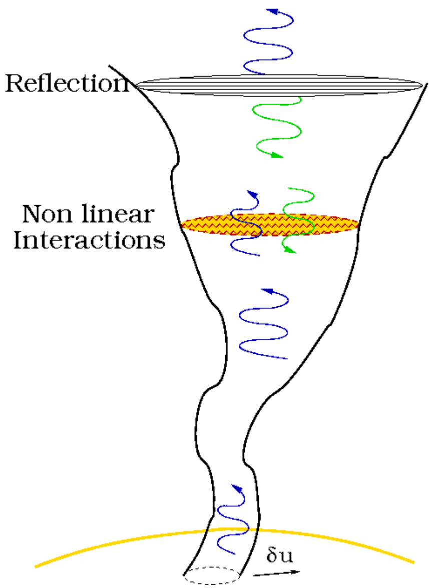
Heating, acceleration and origin of solar wind

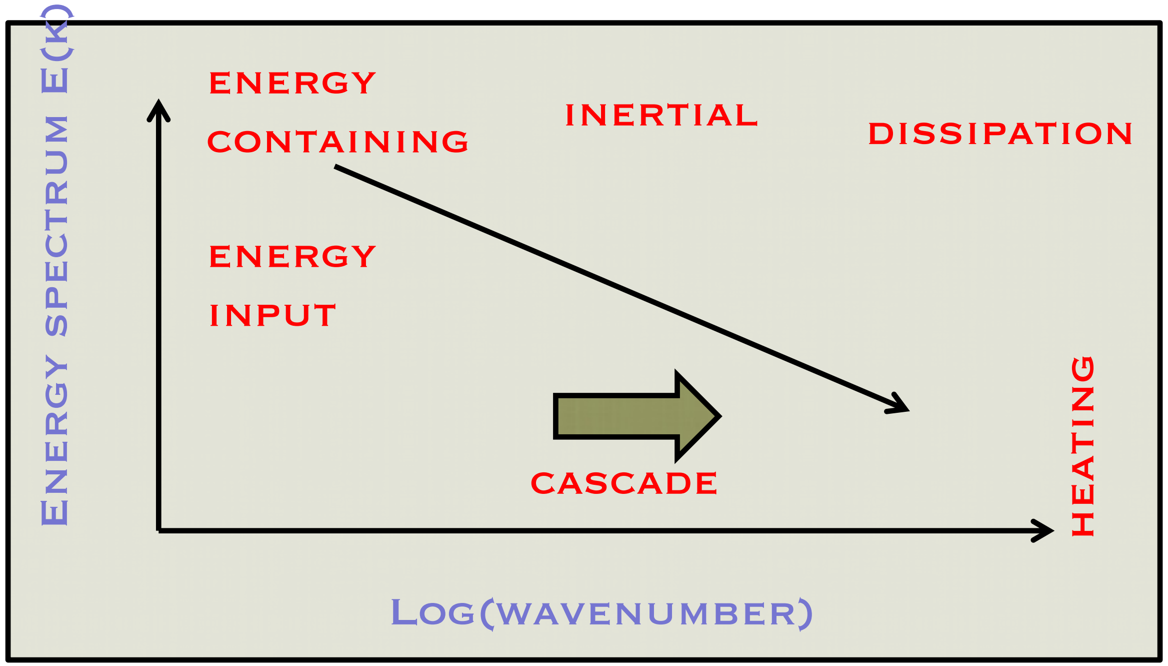
- Turbulence in general driven by gradients

  - **fluctuation /wave input at inner boundary**
    → reflection-driven turbulence
    (quasi-2D)

  - **Magnetic gradients**: reconnection in chromosphere and lower corona
    → component reconnection (common?)
    → neutral point, interchange (rare?)
    → turbulence driven by reconnection

  - **Velocity shears** in stream and microstreams in solar wind
    → shear driven turbulence when $\Delta V > Va$





There is plenty of turbulence: Energy Transfer Rate

Bandyopadhyay et al, ApJS 2020
See also Zhao et al, ApJ 928,L15 (2022)

Elsasser variables $\mathbf{z}^{\pm} = \mathbf{V} \pm \mathbf{B}$ (Magnetic field in Alfven unit)

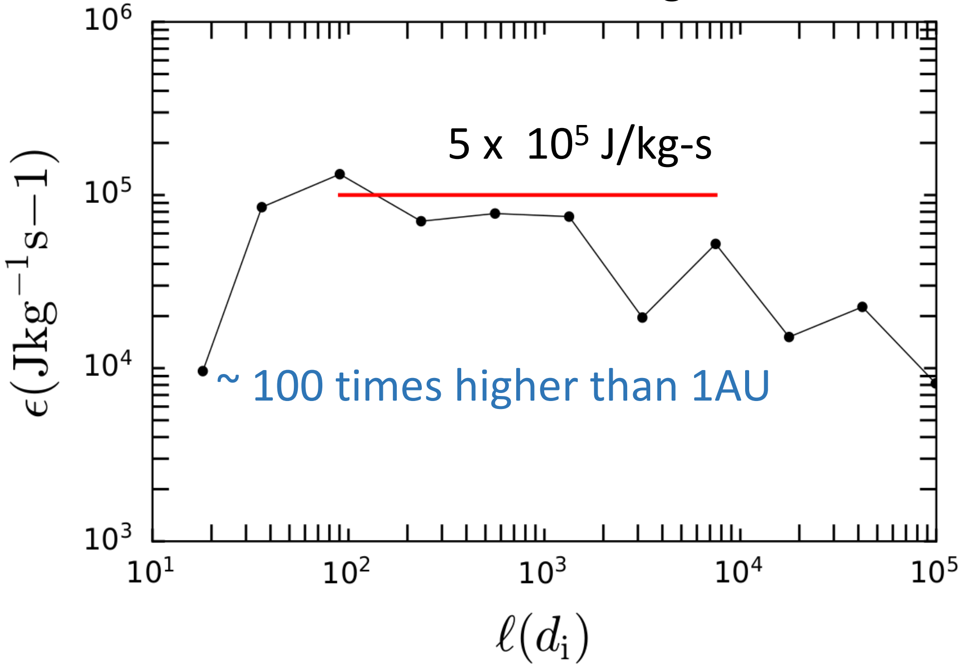
$$Y^{\pm}(\ell) = \langle \hat{\ell} \cdot \Delta \mathbf{Z}^{\mp}(\ell) |\mathbf{Z}^{\pm}(\ell)|^2 \rangle$$

Mixed third order structure function $Y^{\pm}(\ell) = -\frac{4}{3}\epsilon^{\pm}\ell$

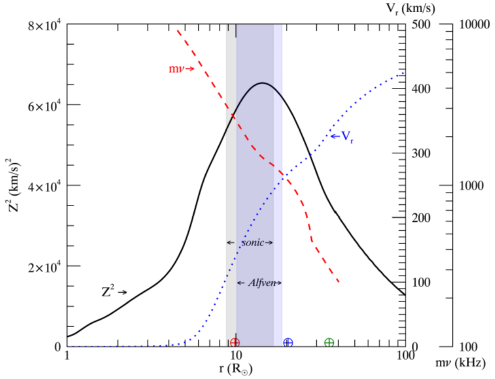
cascade rate

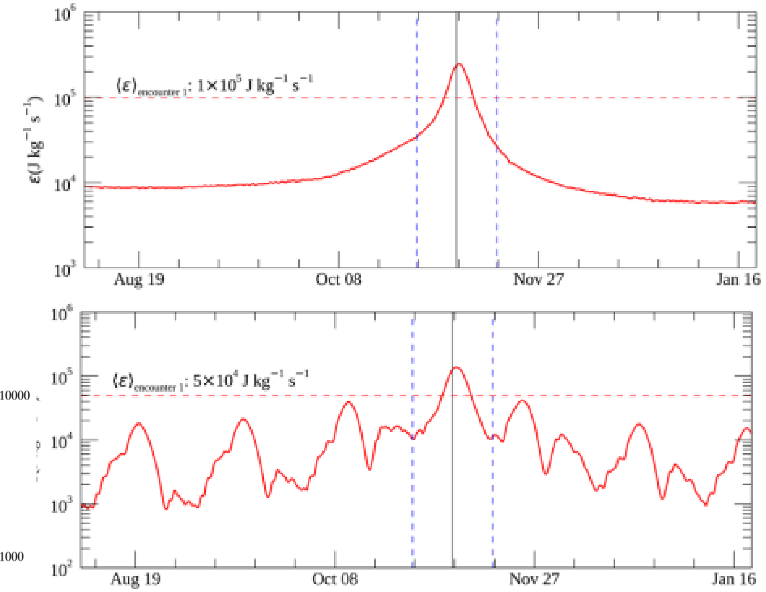
PP98: Politano, H., & Pouquet, A., GRL, (1998a)

Consistent with energy range estimate
at 36 Rs: 2 x 10^5 J/Kg-s



From
Usmanov
Chhiber
Global MHD
simulations

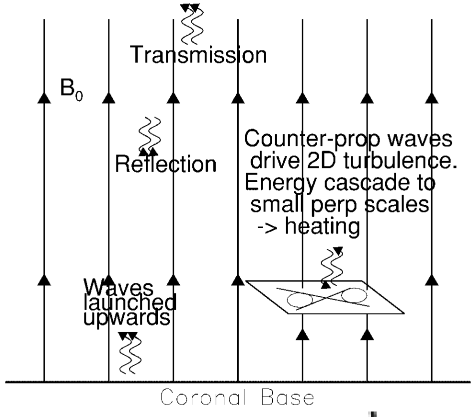




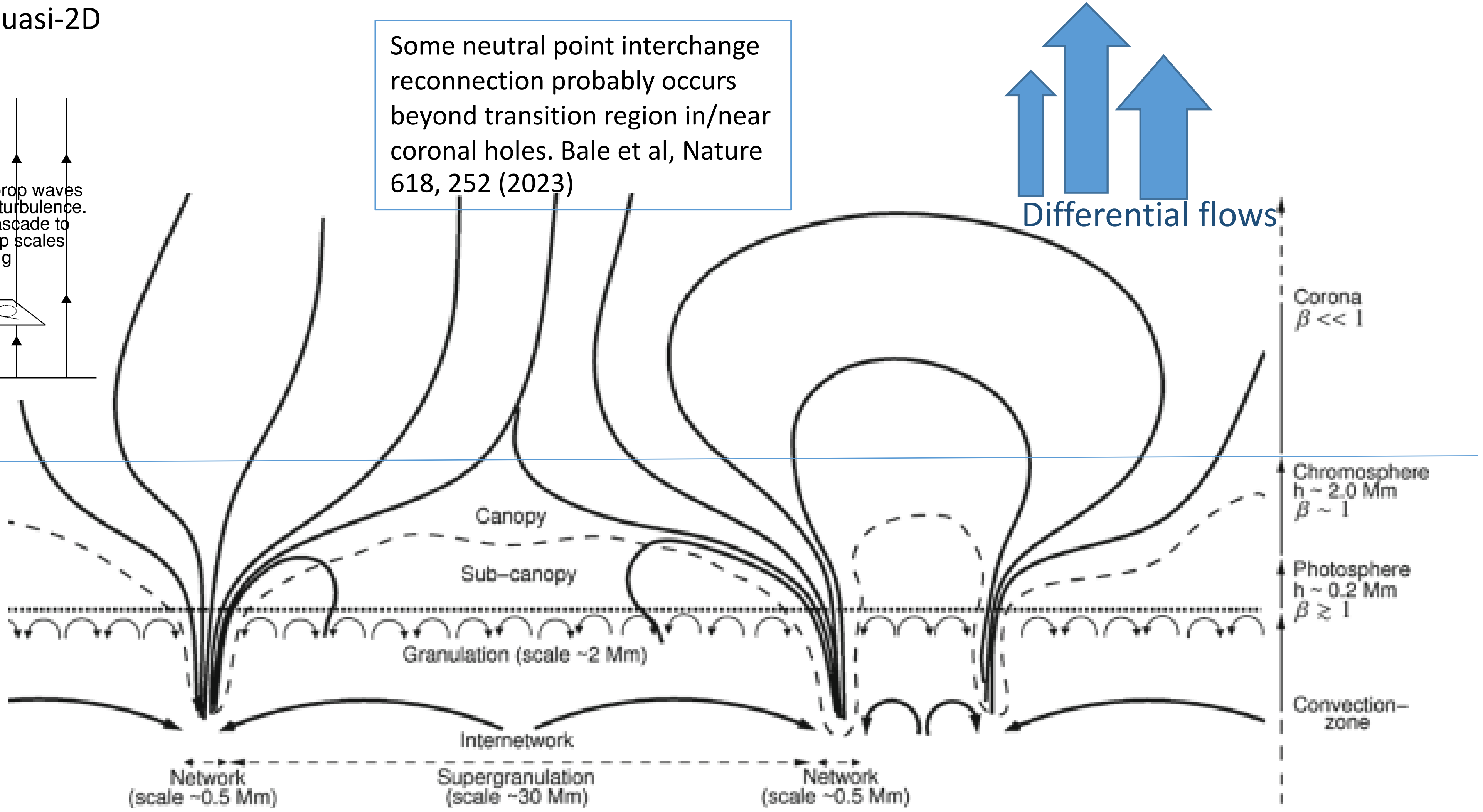
(cf. Sorriso-Valso+2007, MacBride+2008, Stawartz+2009, Osman+2011 … etc)

Energy and nonuniformity: from photosphere to chromoshere to corona

Reflection driven quasi-2D turbulence model



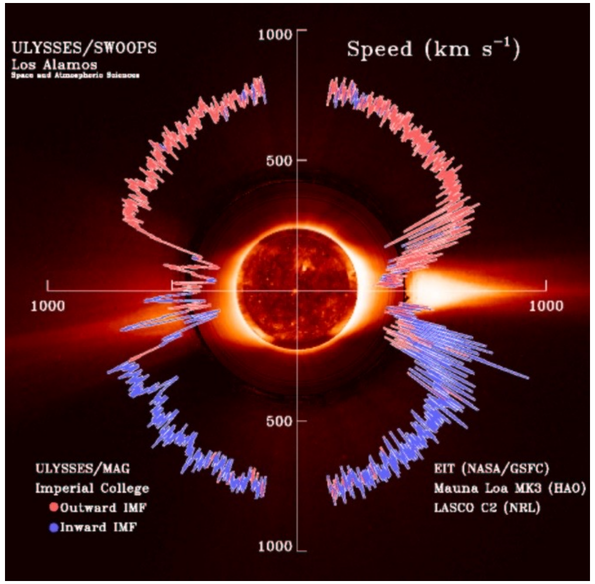
Some neutral point interchange reconnection probably occurs beyond transition region in/near coronal holes. Bale et al, Nature 618, 252 (2023)

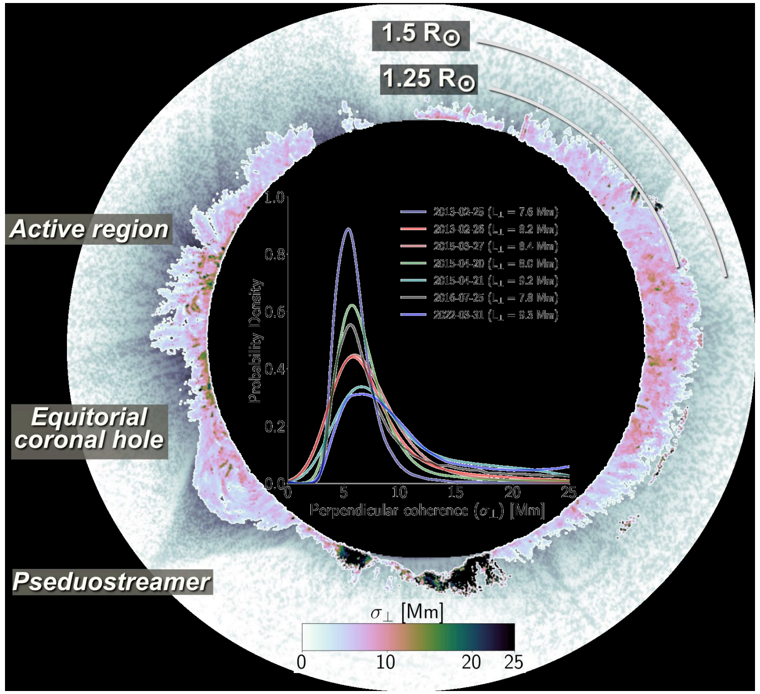


Supergranulation sets the scales !

- Ulysses: microstreams (Neugebauer et al. JGR, 100, 23389, 1995)
- Wave & cyclotron driven models based on observations (Thieme, Marsch & Tu, Ann. Geophys, 8, 713 (1990); M&T Solar Phys 1997)

- Transverse Correlation Scale ~ supergranulation scale
  - As used by numerous global models with turbulence (e.g., Usmanov et al, ApJ, 2014, 2018)
  - PSO observations of clusters of switchbacks (Bale et al ApJ 923, 174 (2021)
  - Also recently as computed in Comp/Ucomp datasets (Sharma & Morton; SW 16), 7.8 to 9.3 Mm, at 1.03 to 1.3 Rs



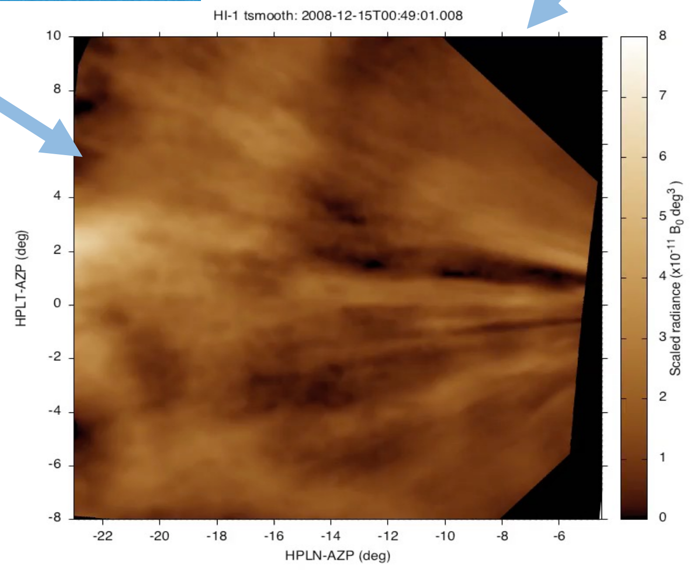


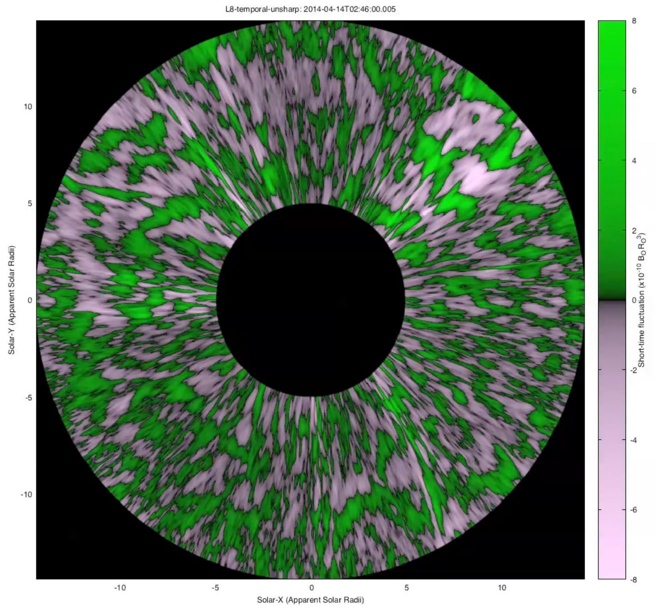
Rahul Sharma & Richard Morton, SW16

Solar wind transition outside the Alfven critical zone

Striated corona

Flocculated solar wind

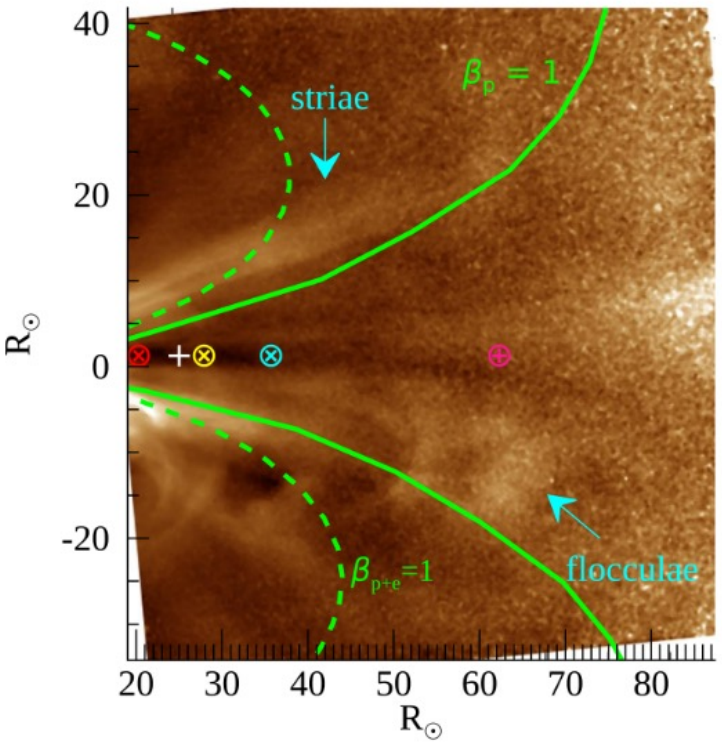




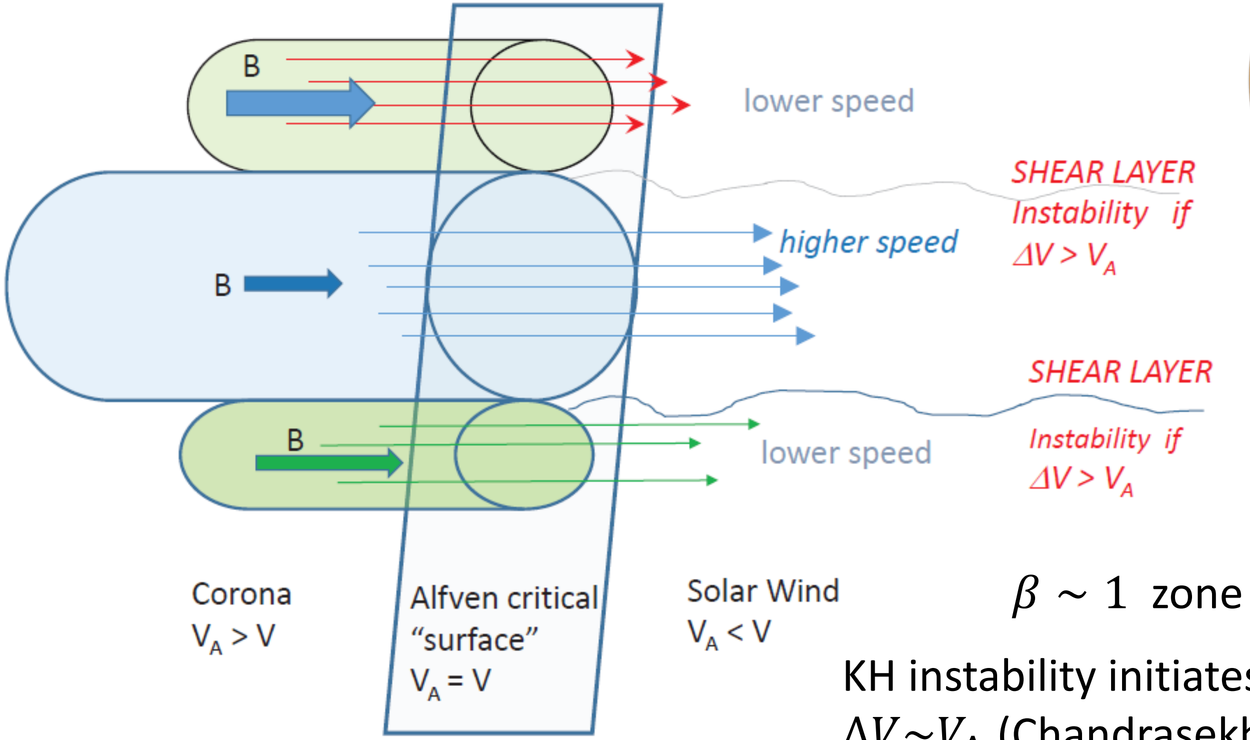
DeForestEA-2016

DeForestEA-2018

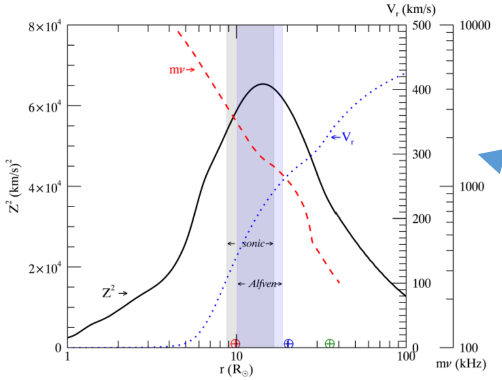
Weakening magnetic field may lead to shear-driven instability above Alfven surface/zone and $\beta = 1$ zone: *enhances SW turbulence*



DeForest et al. 2016 ApJ
Chhiber et al. 2018 ApJL



KH instability initiates if
$\Delta V \sim V_A$ (Chandrasekhar 1981)

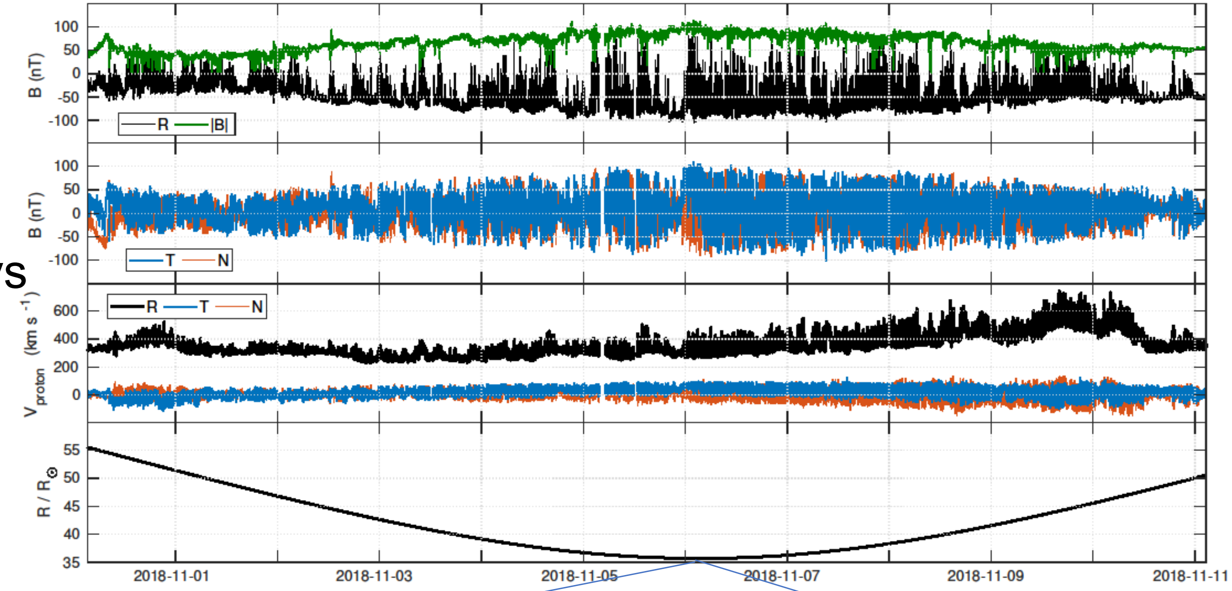


Fluctuations
peak near
Alfven zone

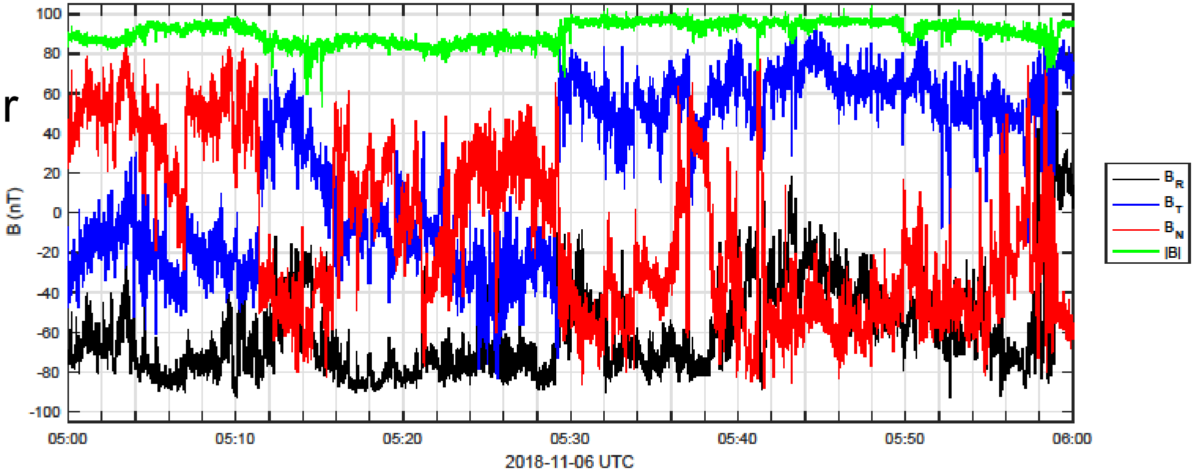
Ruffolo et al, ApJ, 2020

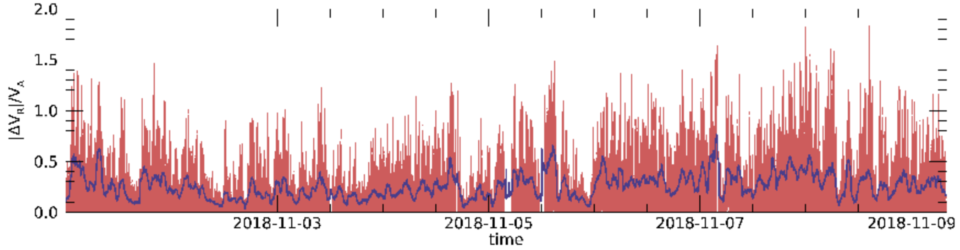
PSP E1

11 days



1 hour



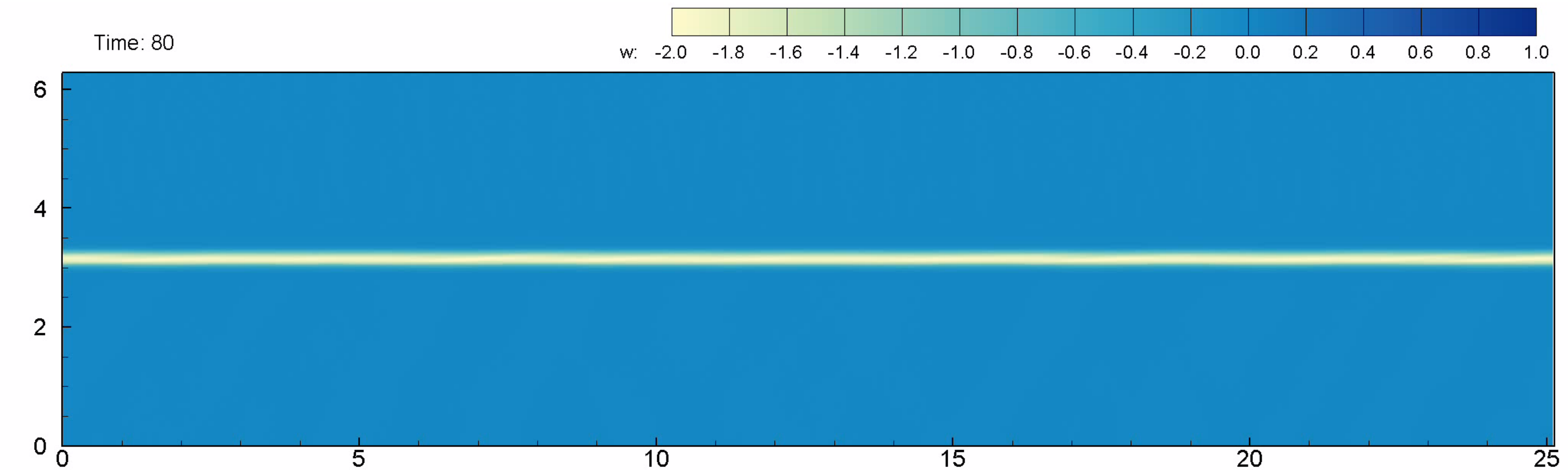


→ *Variation of radial speed at the correlations scale is frequently subject to instability using Chandrasekhar's criterion*

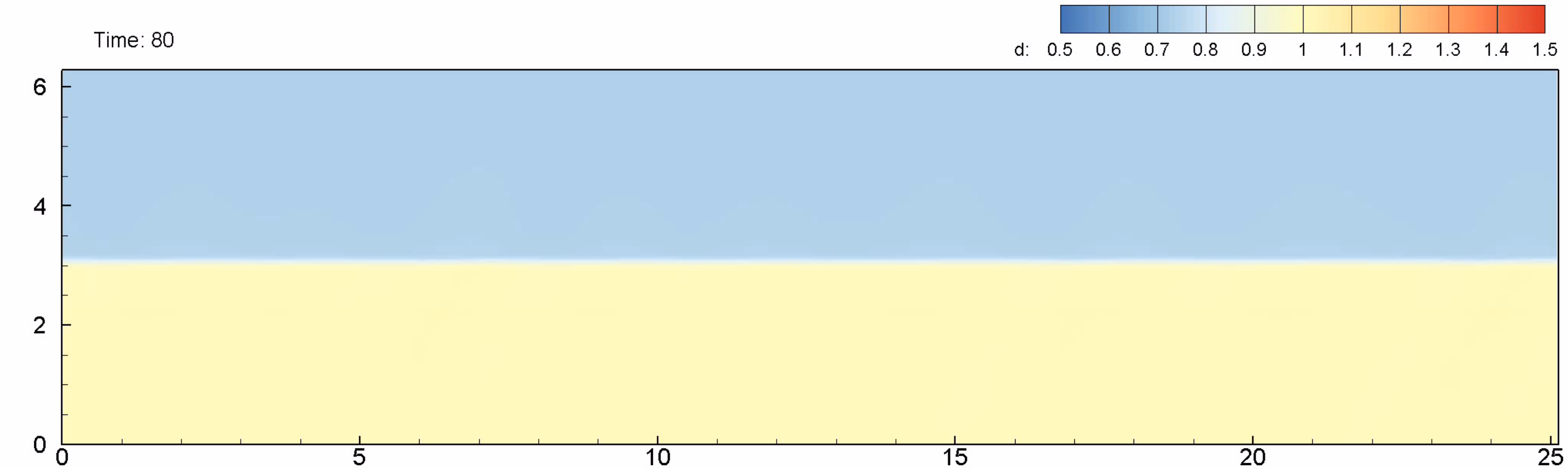
MHD mixing layer – super Alfvenic shear

Simulation by Yan Yang
See similar Solar Orbiter observations in Kieokaew et al A&A 656 A12 (2021)

vorticity



density



Entering coronal plasma

There is some evidence that PSP is beginning to see samples of "classical coronal plasma" in sub-Alfvenic solar wind

For example:

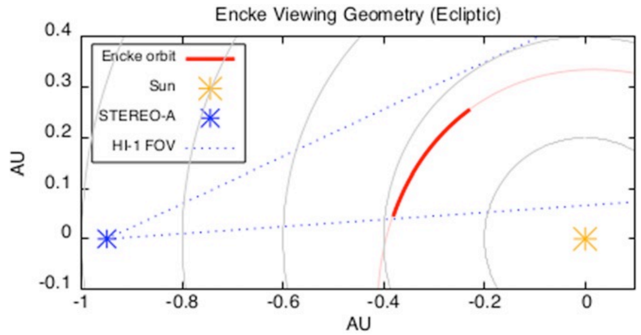
- Lower turbulence amplitude
- Greater variance anisotropy
- Less – or No – switchbacks
- Lower density fluctuation level (?)
- Systematic differences in correlation lengths and times.
- Differences in 3rd order cascade rates

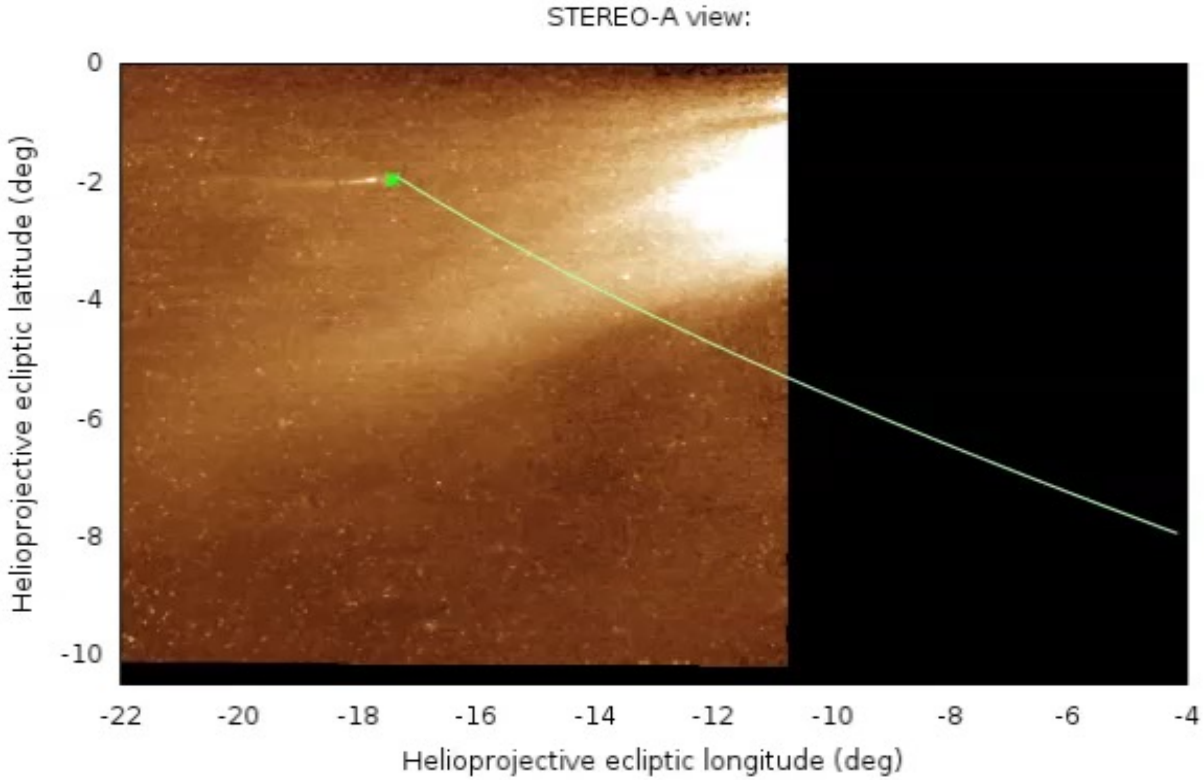
More like Reduced MHD !

Bandyopadhyay et al, ApJL 926, L1 (2022)
Zhao et al, ApJL 928, L15 (2022)
Zank et al ApJ (2022)
Pecora et al, ApJL 945, L20 (2023)

Turbulence tracking from imaging

Stereo imaging analysis of solar wind &
Comet Enke by Craig DeForest





Quantitative analysis from images →

DeForest et al, ApJ, 812, 108 (2015)
DeForest et al, ApJ, 828, 66 (2016)

Summary:

(1) Presence of 1/f "flicker noise" observed by OMNI, ISSE, ACE, Ulysses, MDI, UVCS and now PSP

(2) Confirmation of the association of the supergranulation scale with organization of the coronal flows and magnetic fields, which has long been recognized based on both remote sensing of solar images and in situ observations of microstreams (Neugebauer et al, 1995);

(3) Differential radial flows exceeding 100km/s in the corona, an energy source that is transported upwards in the magnetically controlled corona (DeForest et al, 2016, 2018), may represent a source of augmented turbulence beyond the critical Alfven region (Ruffolo et al, 2020);

(4) Assumptions concerning the nature of the low beta sub-Alfvenic corona are now being confirmed directly by PSP (Bandyopadhyay et al, 2022; Zhao et al, 2022) ;

(5) The transition between sub- and super-Alfvenic wind, which appears not to be smooth, may even be fragmented (Chhiber et al, 2022; Cranmer et al 2023).

(6) Have we made progress on understanding how the corona is heated and the solar wind is accelerated?

- Turbulence is strong and measured everywhere. Turbulence driven models are alive and well.
- How about neutral point interchange reconnection?

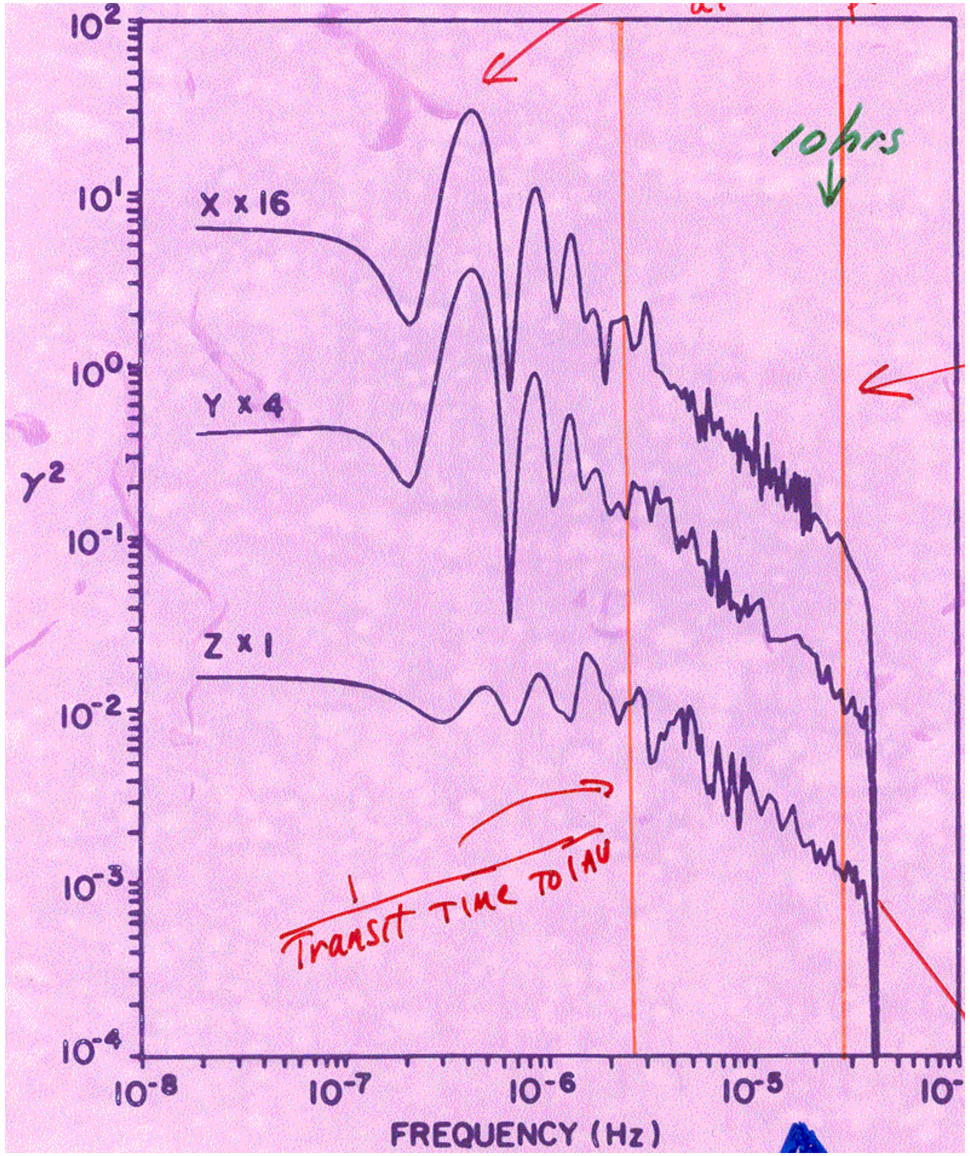
→The PUNCH mission can reveal structure in SPACE and TIME, and thus can be expected to further depth to our understanding of these interrelated fundamental heliospheric phenomena.

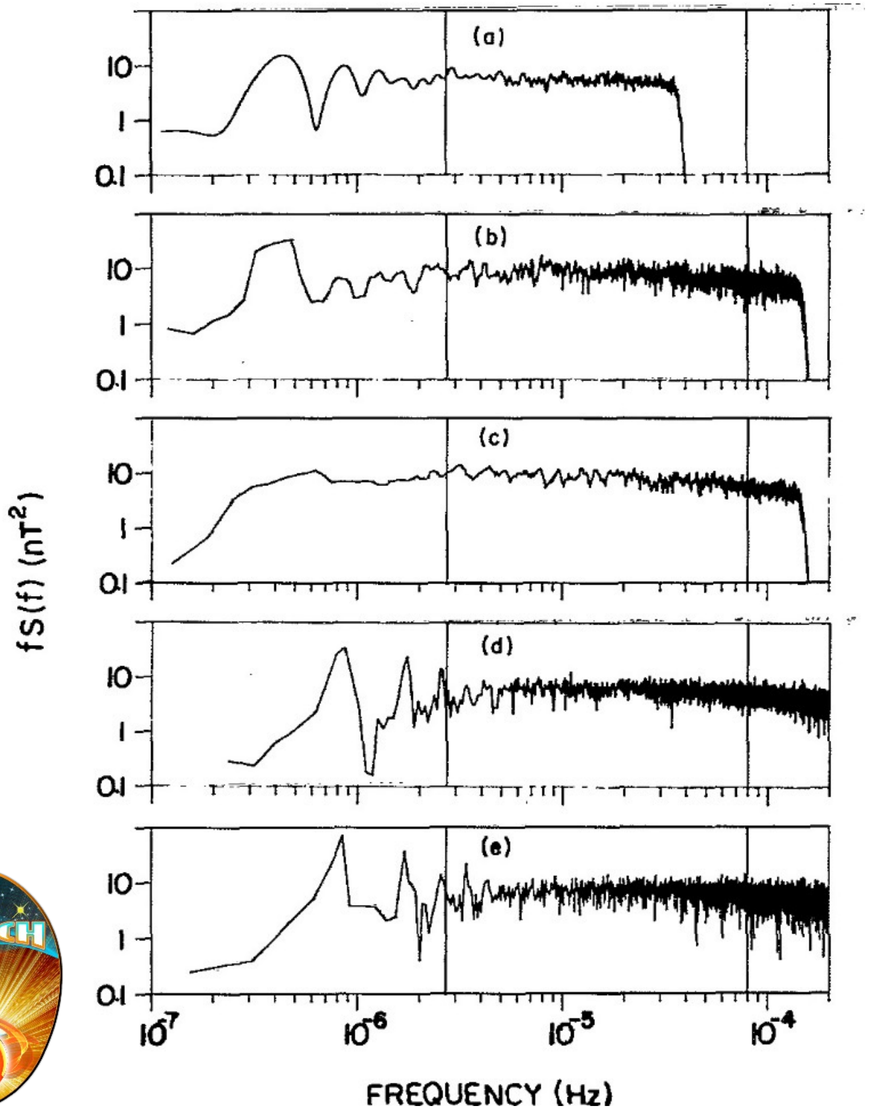
end

1/f Low frequency magnetic spectrum in SW

WHM & Goldstein PRL 1986

1/f from 2.5 10^{-6} to ~ 10^{-4} Hz





ISEE3 214d 1978

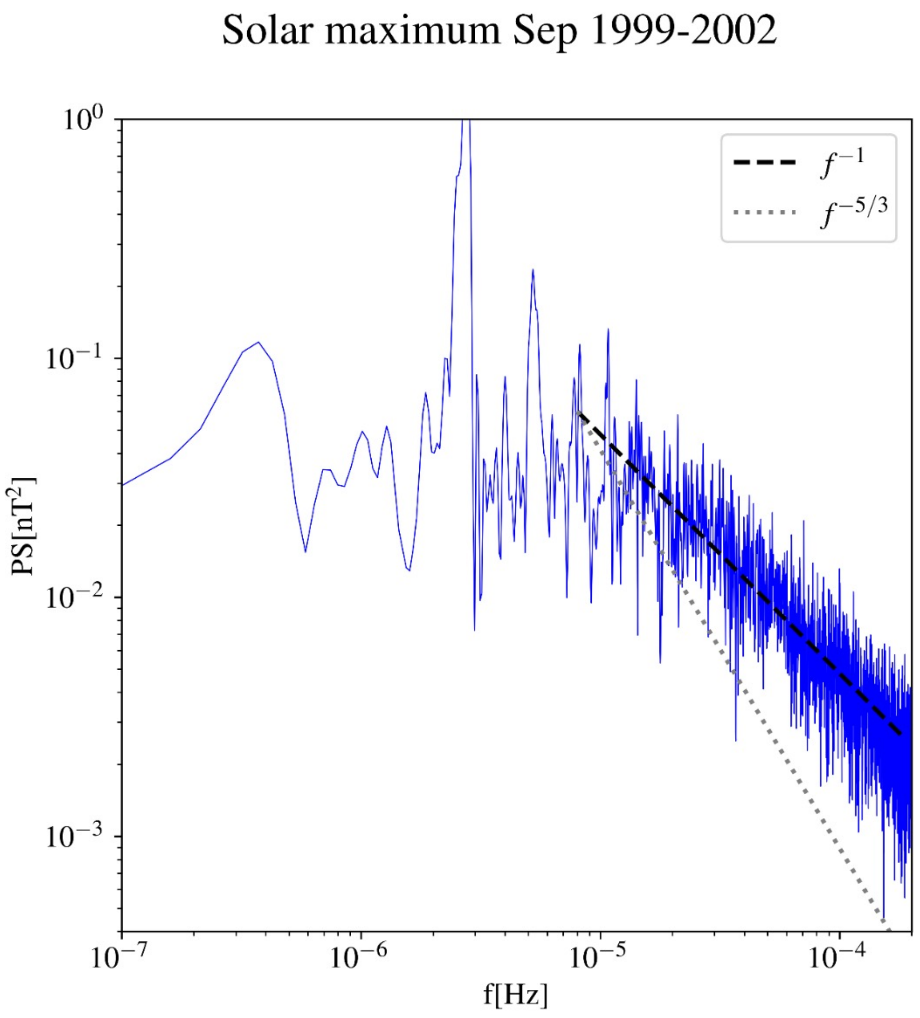
ISEE3 184d 1979

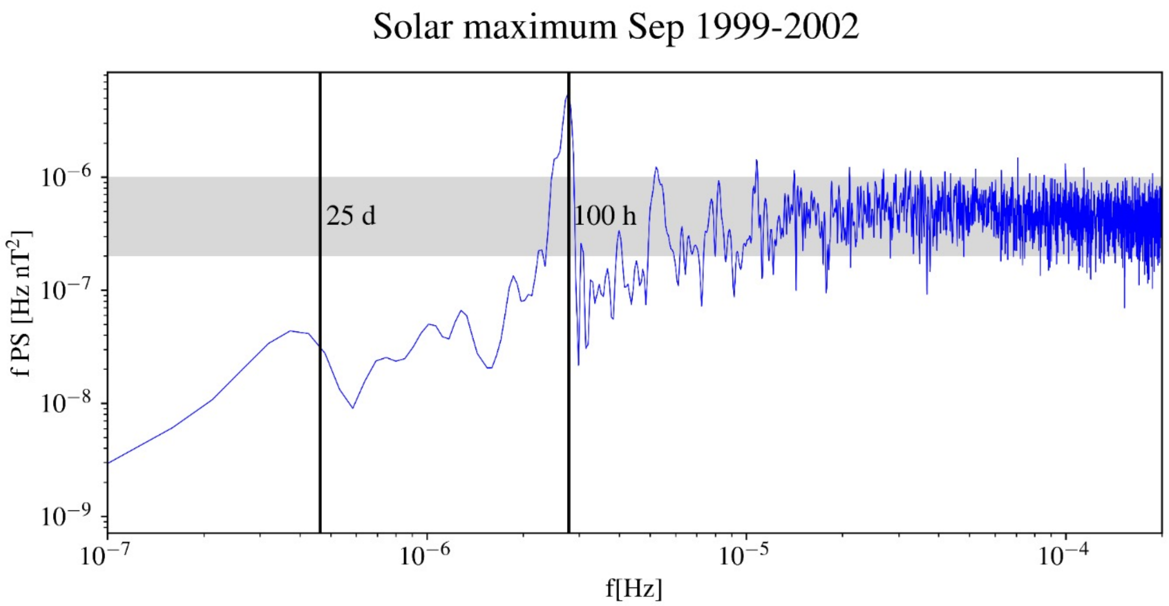
IMP 621d 1968-1969

OMNI 1964-1974

OMNI 1974-1984

OMNI mag data: long interval 1999-2002

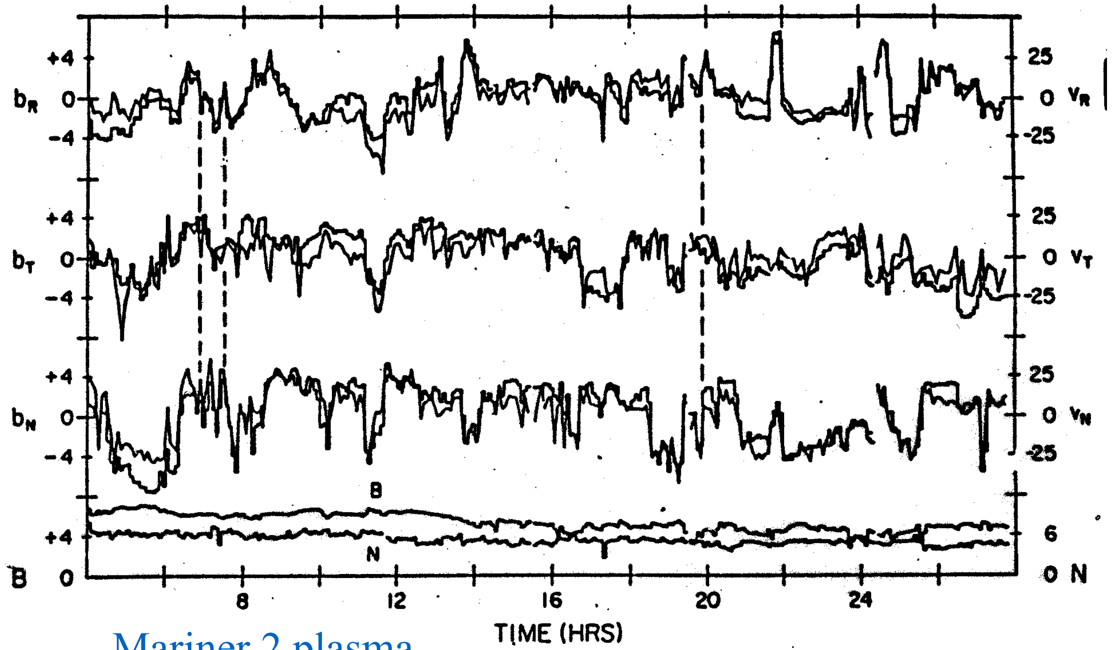




New analysis by F Pecora

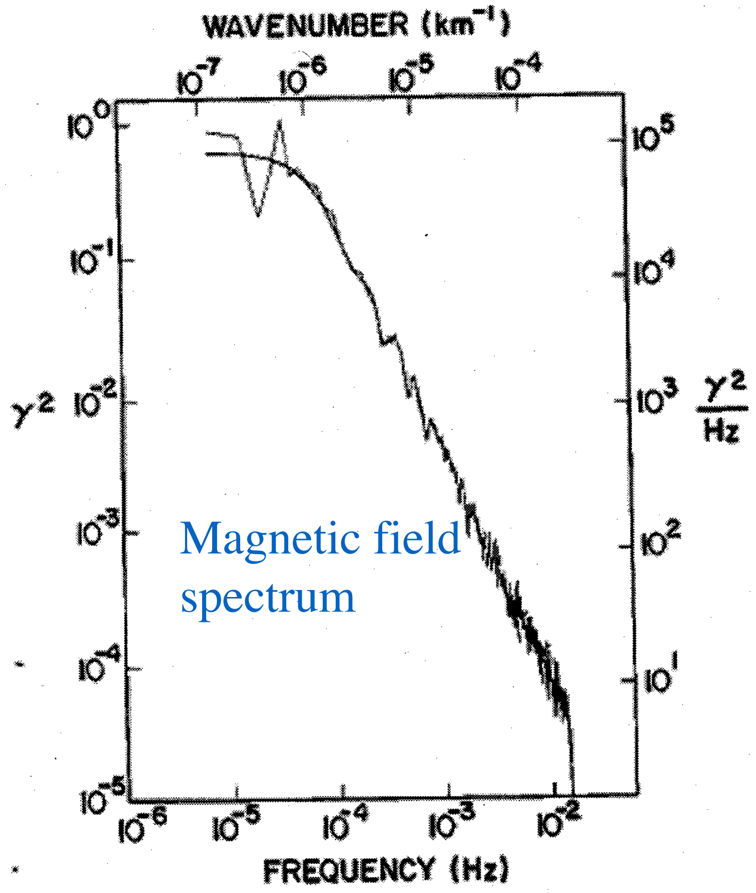
Solar wind: indications of both turbulence and wave-like properties:

- Powerlaws
- “Alfvenic fluctuations”



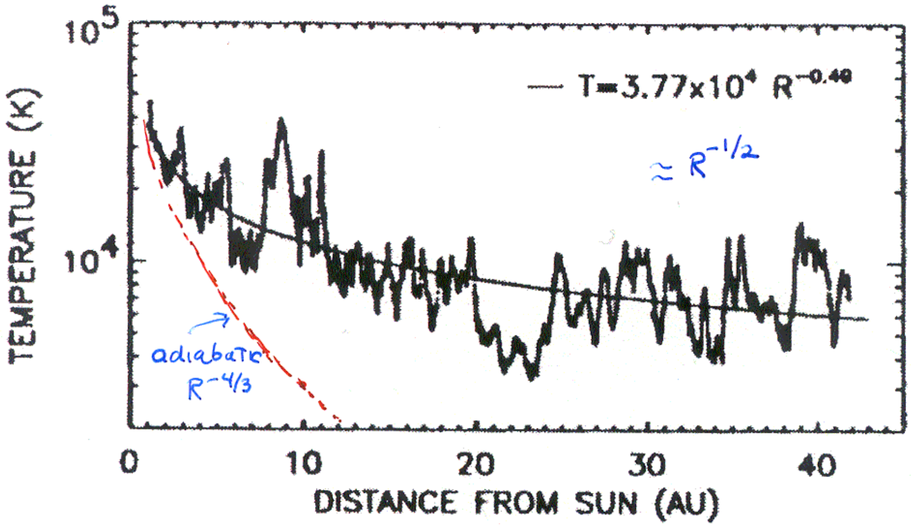
Mariner 2 plasma and magnetic field data

Belcher and Davis, JGR, 1972



SW at 2.8 AU: Matthaeus and Goldstein

Something is heating the solar wind in the outer heliosphere (> 1 AU)



Voyager proton temperatures

Richardson et al, GRL, 1995