The Alfven Transition Zone observed by the Parker Solar Probe in Young Solar Wind – Global Properties and Model Comparisons

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Solar corona vs solar wind – where is the boundary?

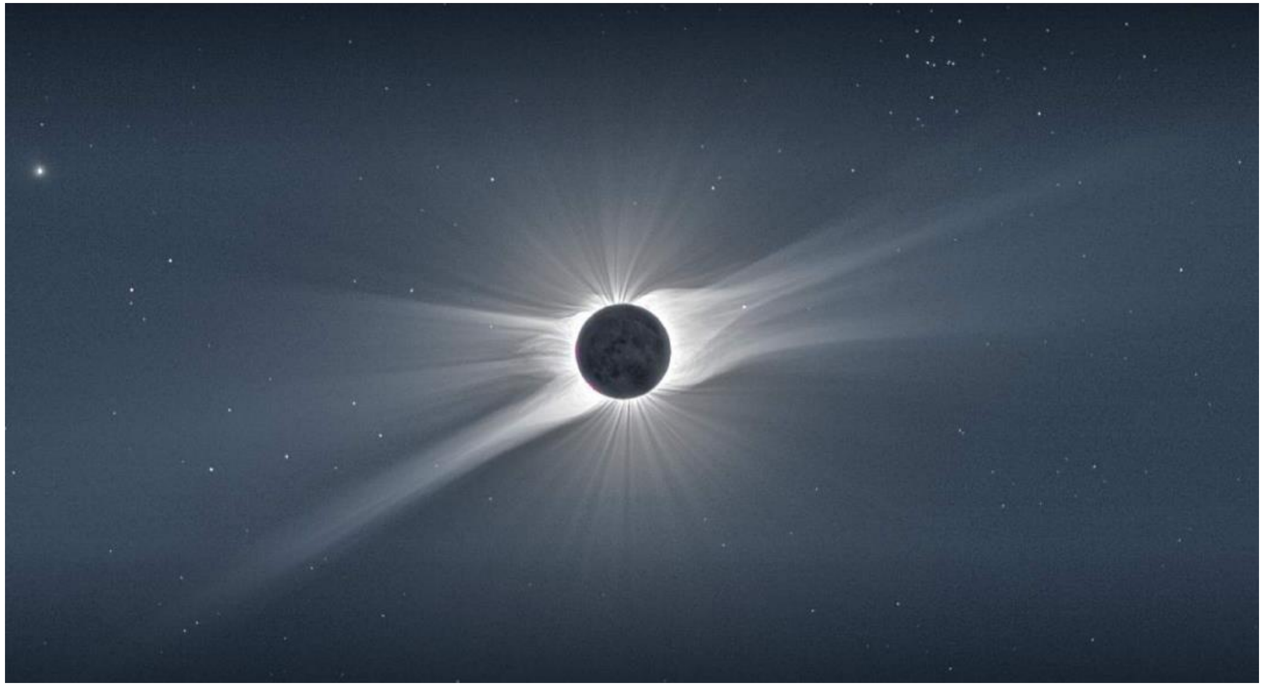


Image credit: Dr. Steve Cranmer

Critical points/surfaces -

- Flow becomes supersonic at the sonic surface
- Super-Alfvenic at Alfven surface
- $\beta = 1$ surface; magnetosonic surface
- PUNCH Science WG1C: What are the evolving physical processes of the Alfven surface?

Outline

- Introduction and overview of Alfvén surface
- Some global properties – PSP vs Model
- Sunward and anti-Sunward Alfven modes around Alfven surface

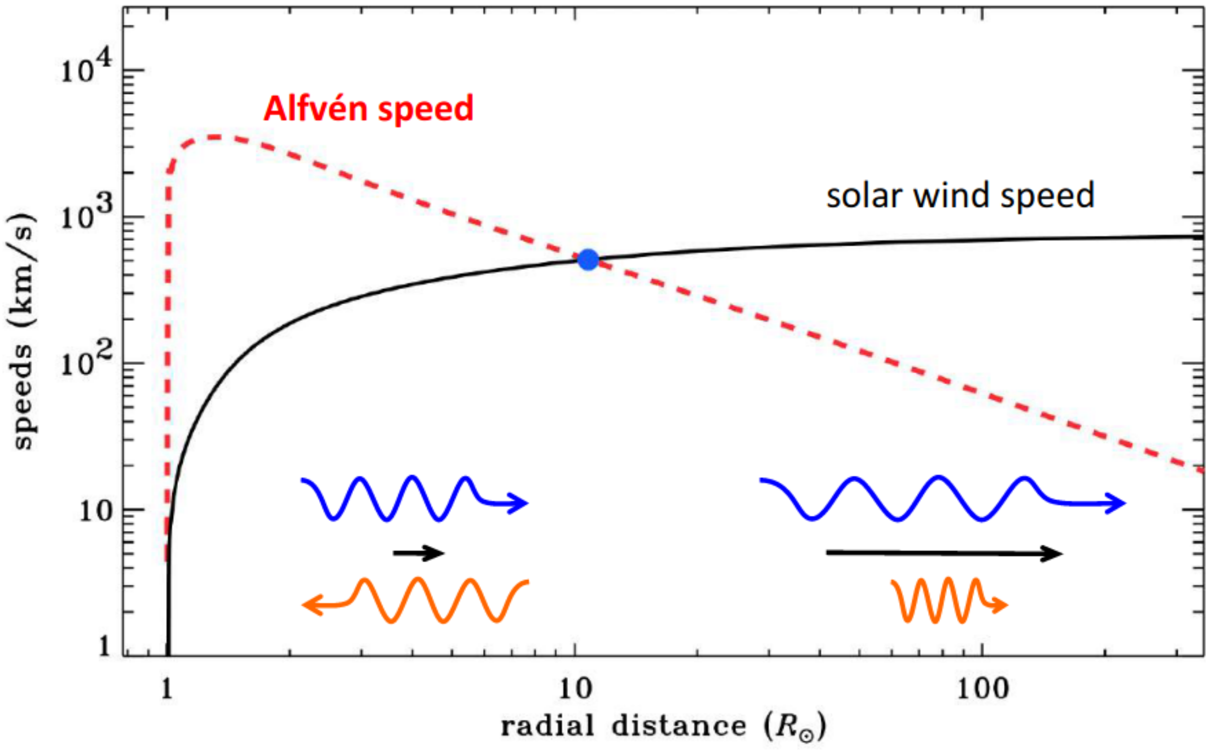
The Alfven "radius"

r_A is distance where $U > V_A$, where
$V_A = \frac{B}{\sqrt{4\pi\rho}}$

- Below r_A, information (waves) can propagate both Sunward & outward.
  Above r_A, the solar wind drags out both inward & outward modes

- Strong transfer of angular momentum from Sun to wind below r_A; Below r_A, magnetic field maintains ~rigid rotation with Sun (Weber & Davis 1967)

- In-situ dynamics like switchback formation and flocculation may “turn on” above r_A (DeForest+ 2016; Ruffolo+ 2020; Pecora+ 2022)

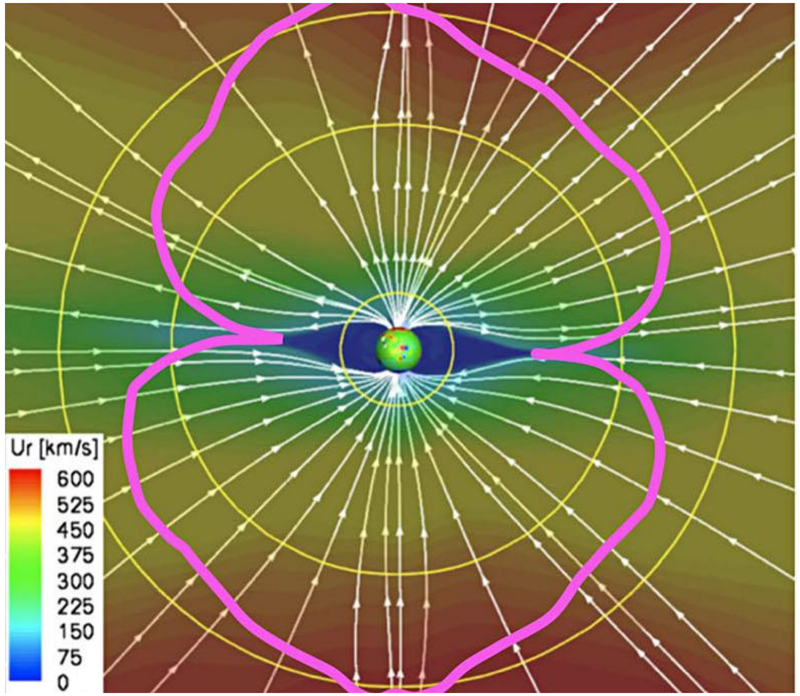


Credit: Dr. Steve Cranmer

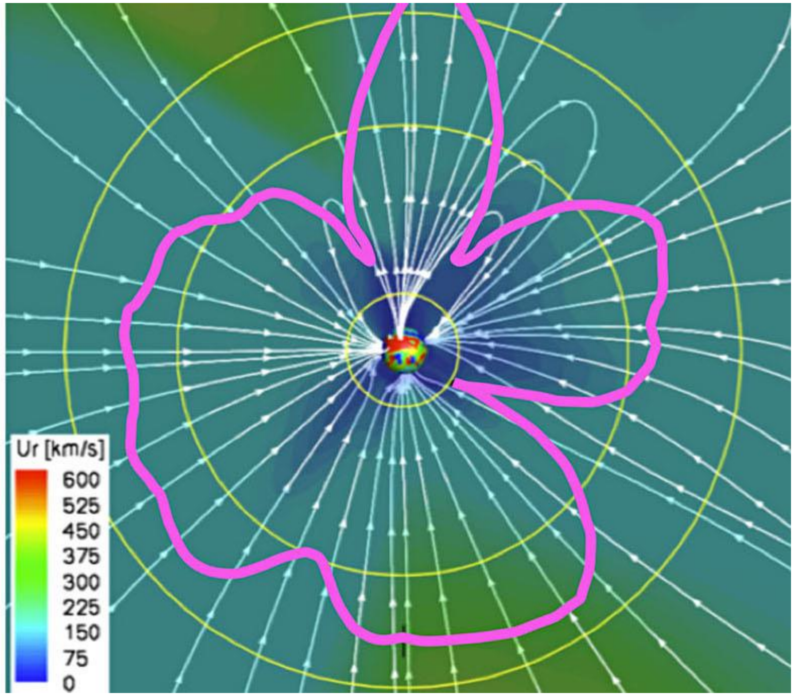
Alfven surface in 3D MHD simulations of global solar wind

Large-scale variability – solar-source related; solar activity effects

Solar min



17.5 Rsun



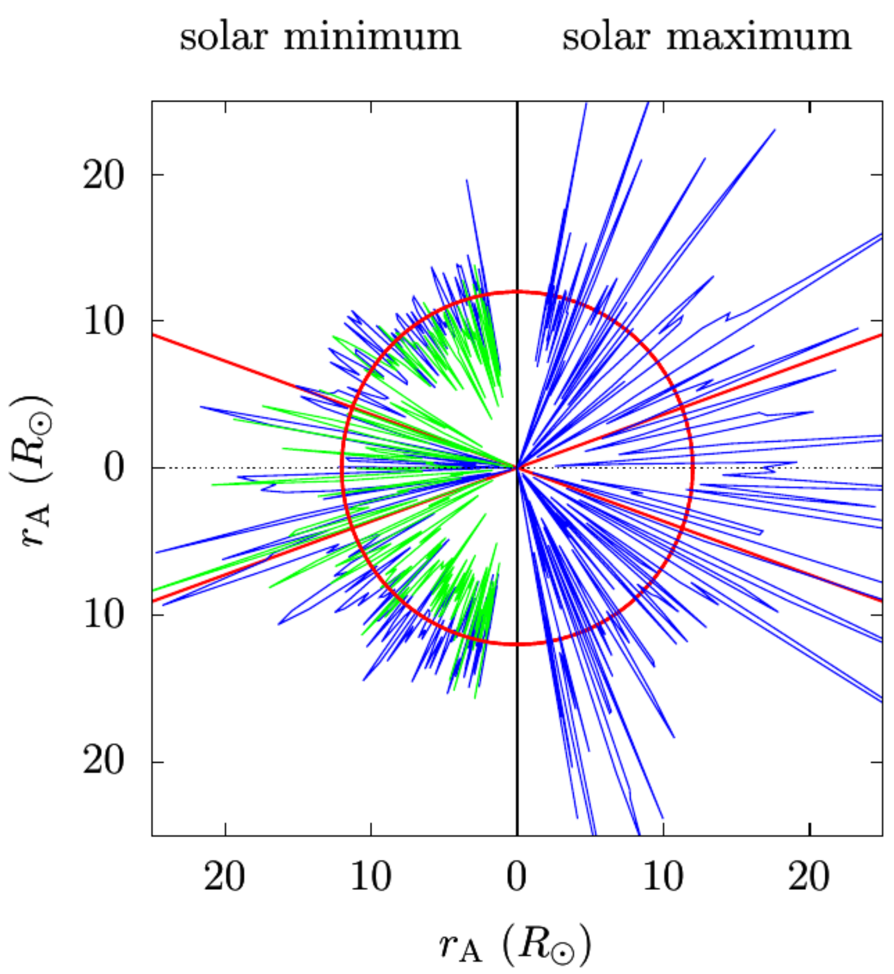
17.5 Rsun

Solar max

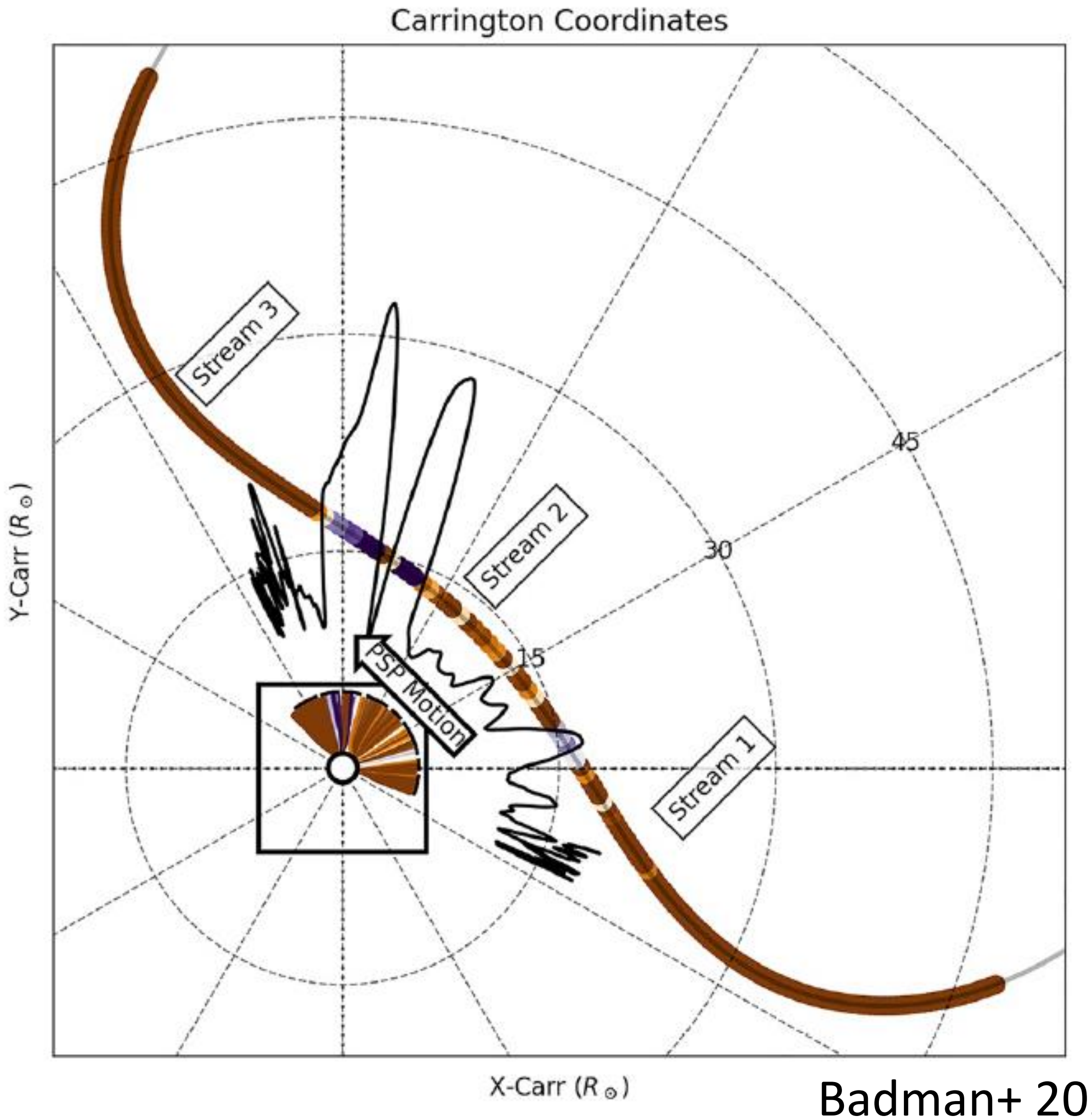
Meridional planes (Cohen 2015; PUNCH website)

Corrugated Alfven surface - Recent in situ observations

Verscharen+ 2021; *Ulysses*



Variability in heliolatitude

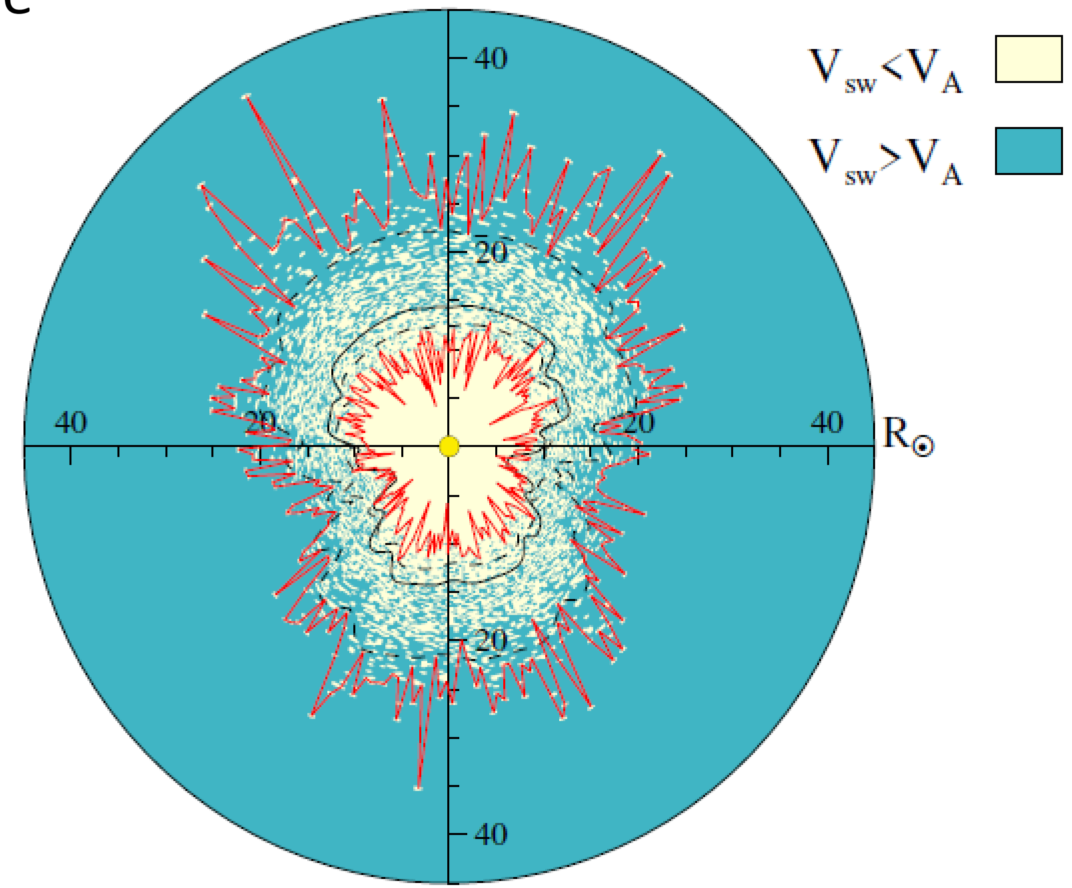


Badman+ 2023; *PSP*

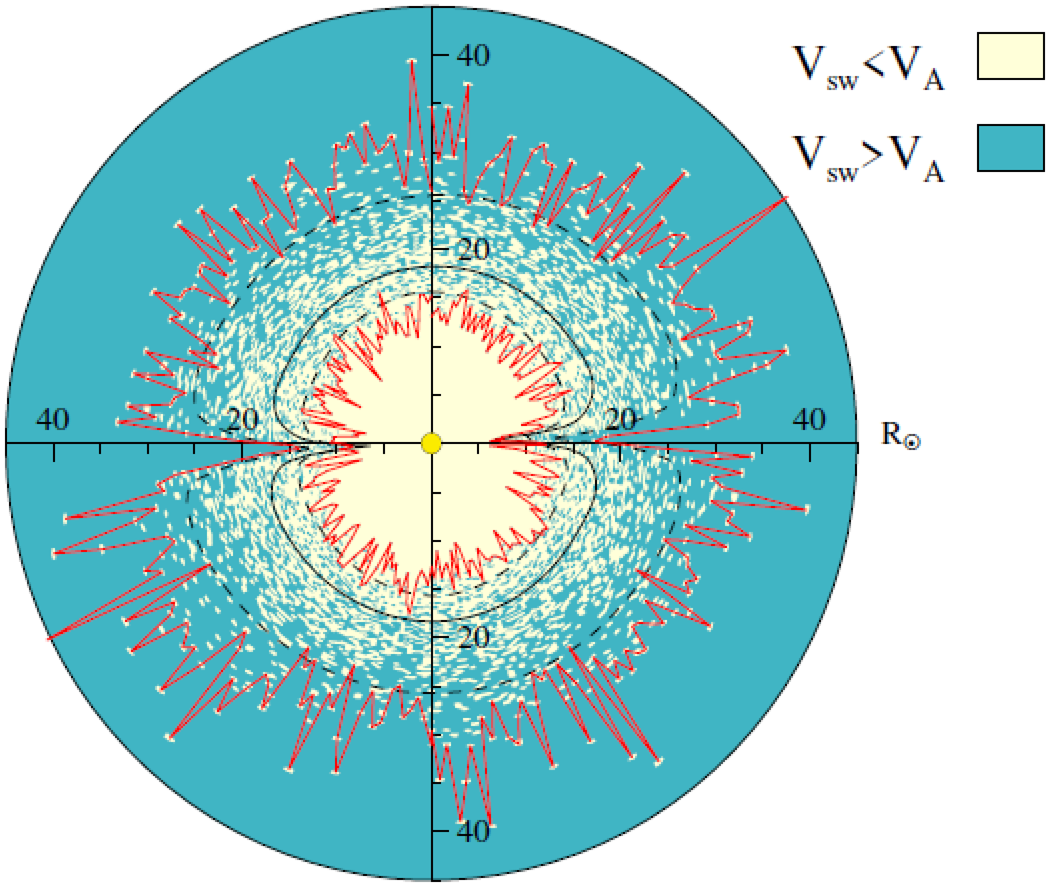
Variability in heliolongitude

Fragmented Alfven zone from global model + turbulence

Solar equatorial plane



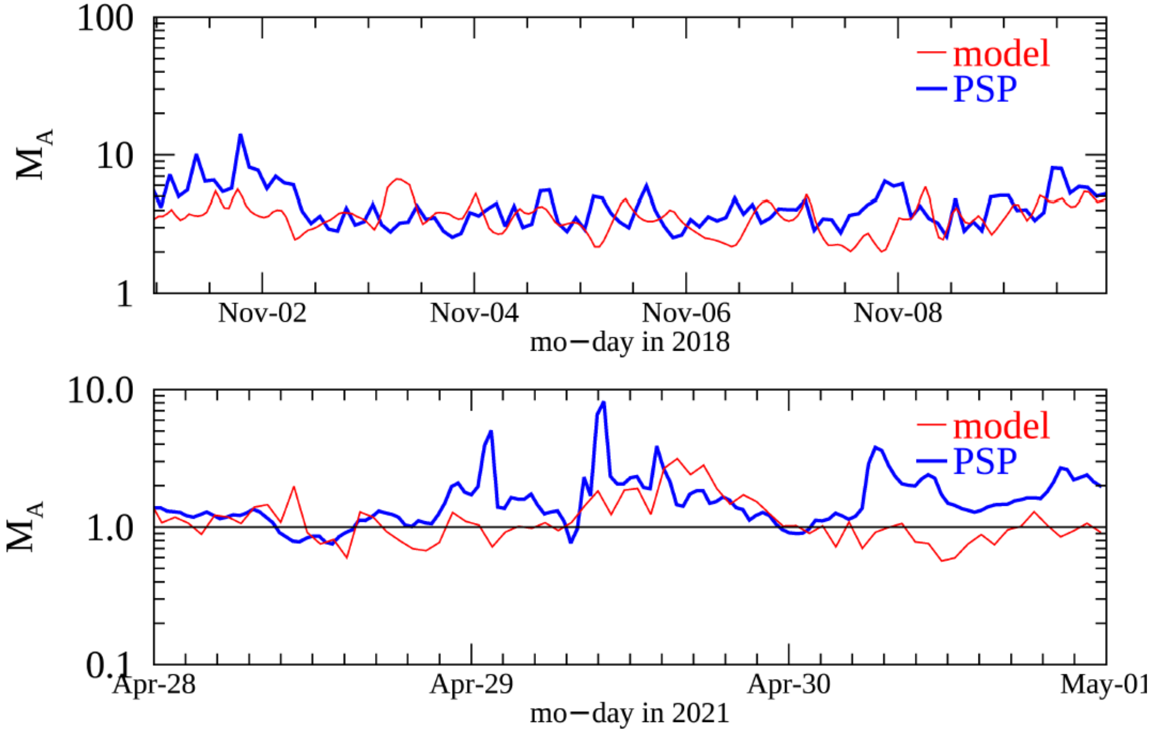
Meridional plane



Chhiber et al. 2022, *MNRAS*

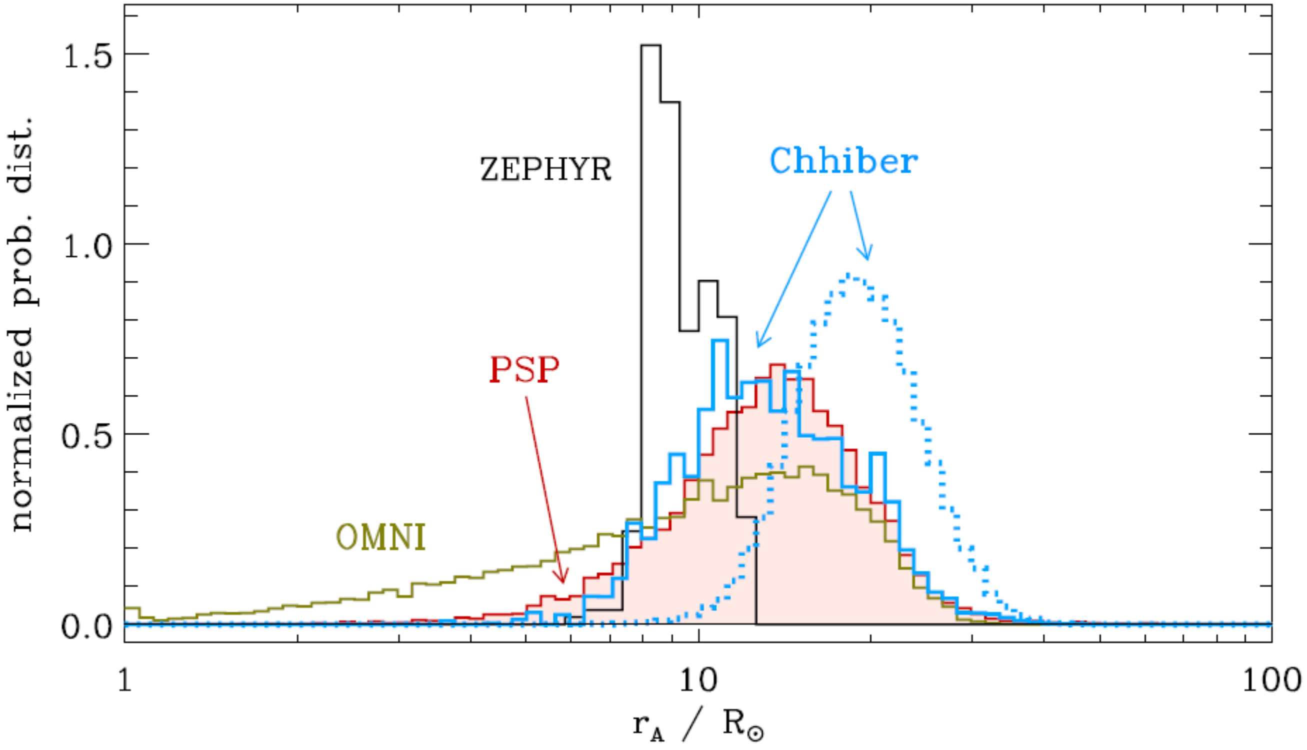
Comparison with PSP observations

Virtual PSP trajectory along sim driven by magnetograms corresponding to PSP E1 and E8



Chhiber+ 2022, *MNRAS*

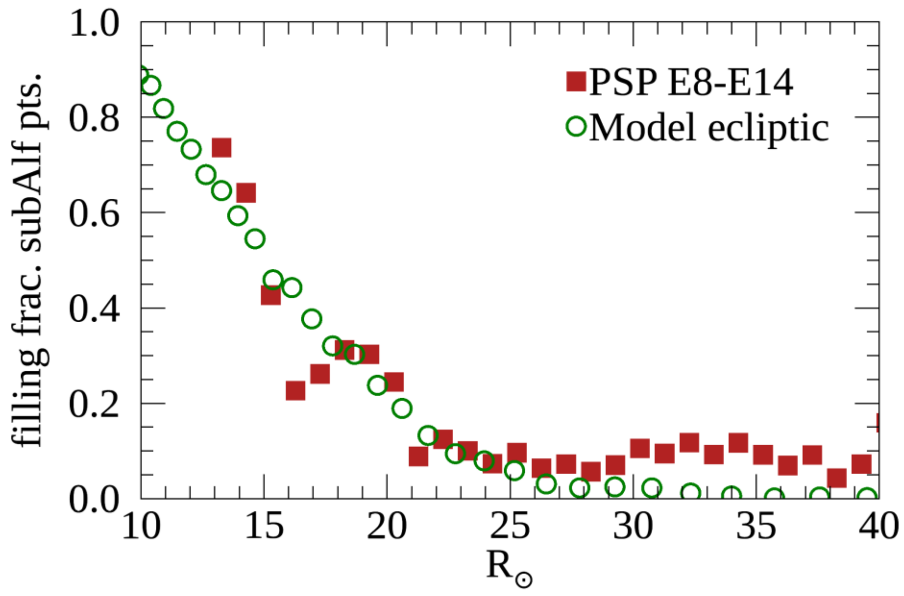
Probability of Alfvenic transition as a function of helioradius

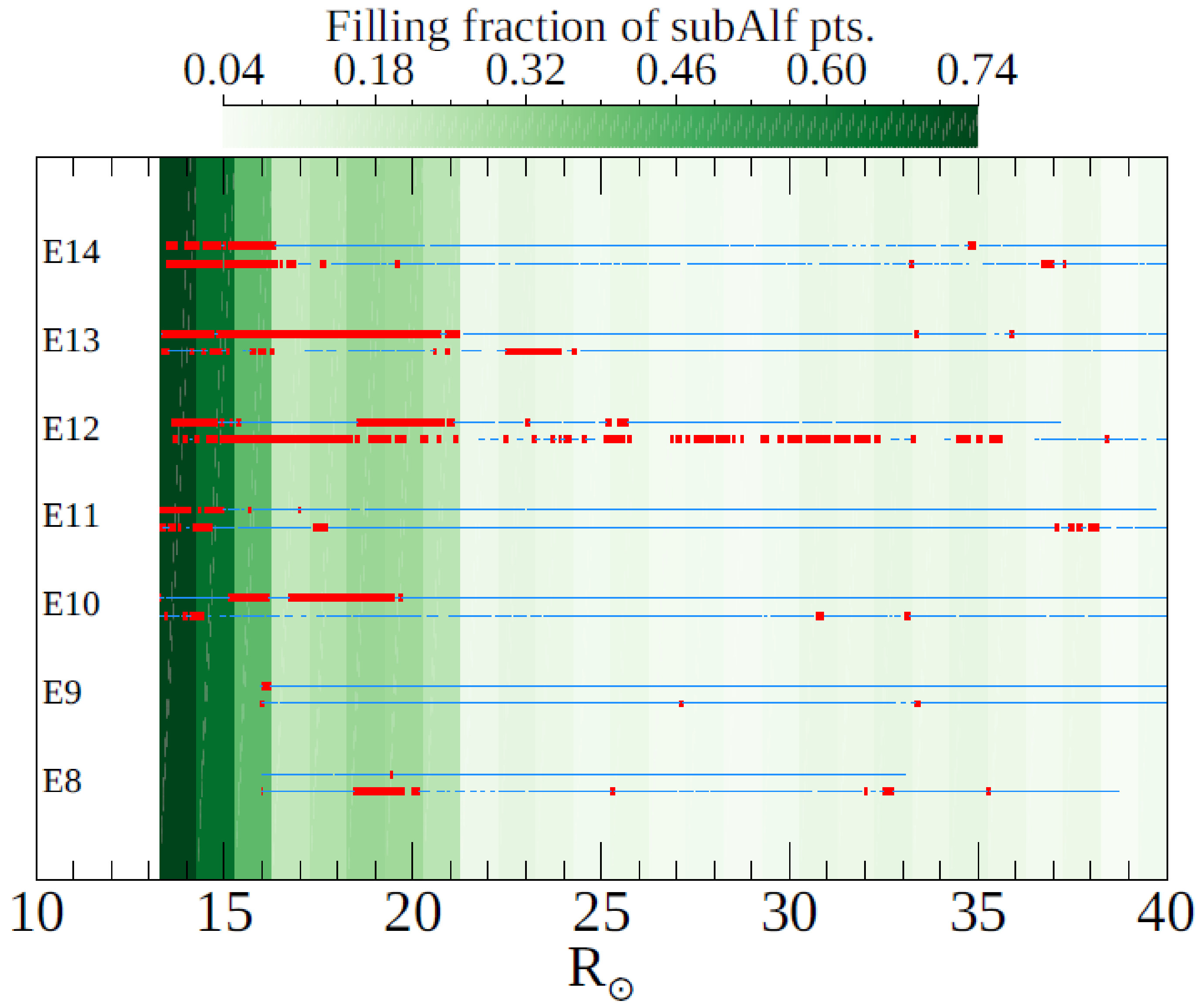


Cranmer+ 2023, *Solar Phys.*

Global properties of Alfven zone – PSP and Model

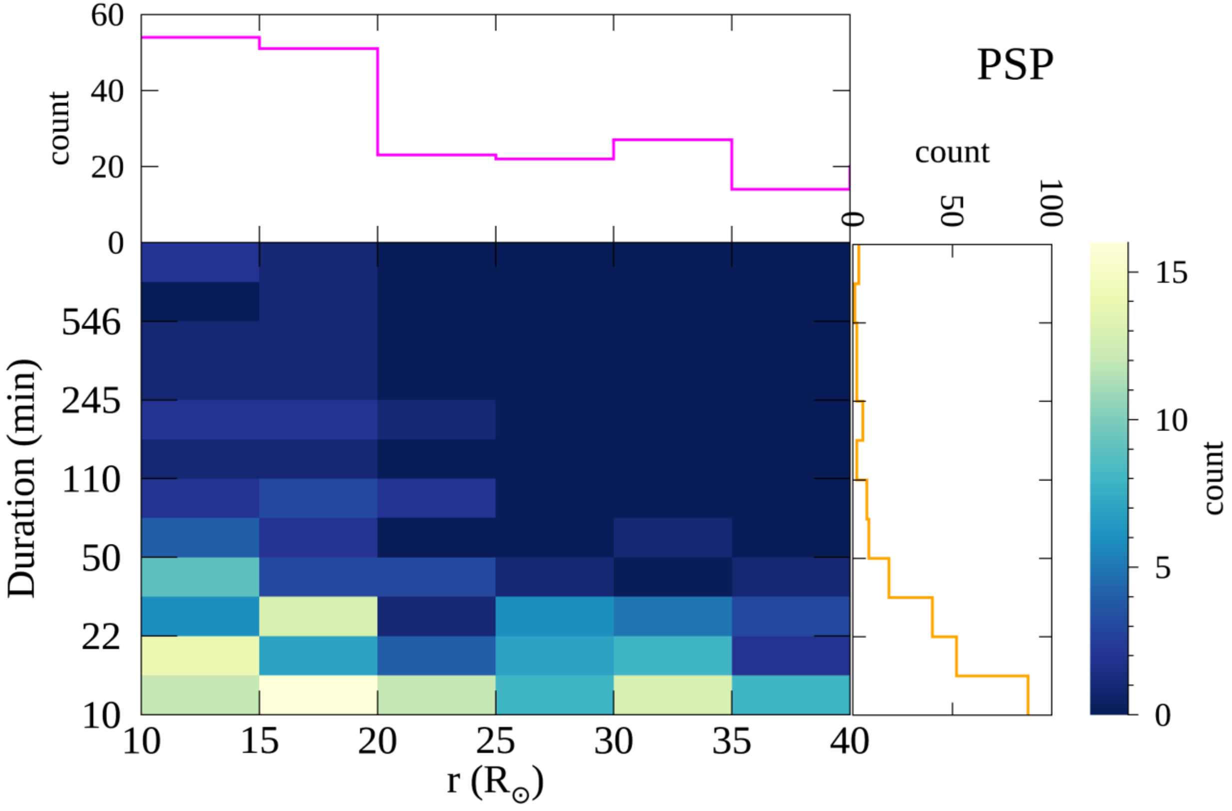
- PSP data E 8 – 14
- Data resampled to 1-min cadence
- Identified subAlfvenic periods longer than 10 min duration

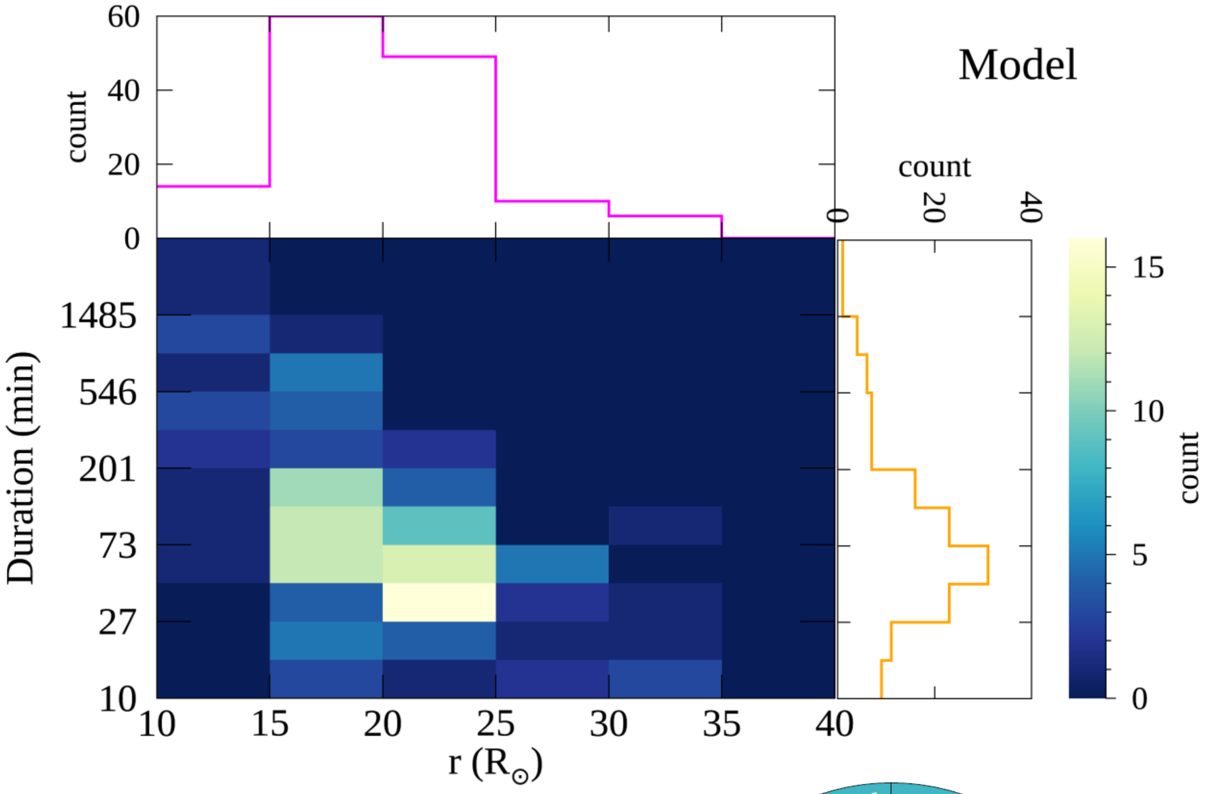




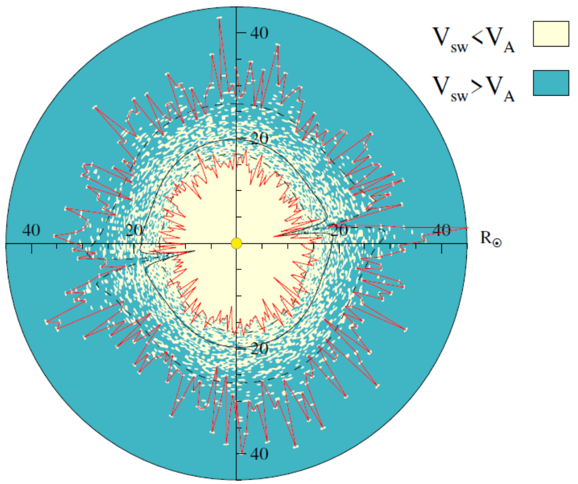
Chhiber+ 2024, *MNRAS-L*

Joint distributions of subAlfvenic-interval duration and heliodistance



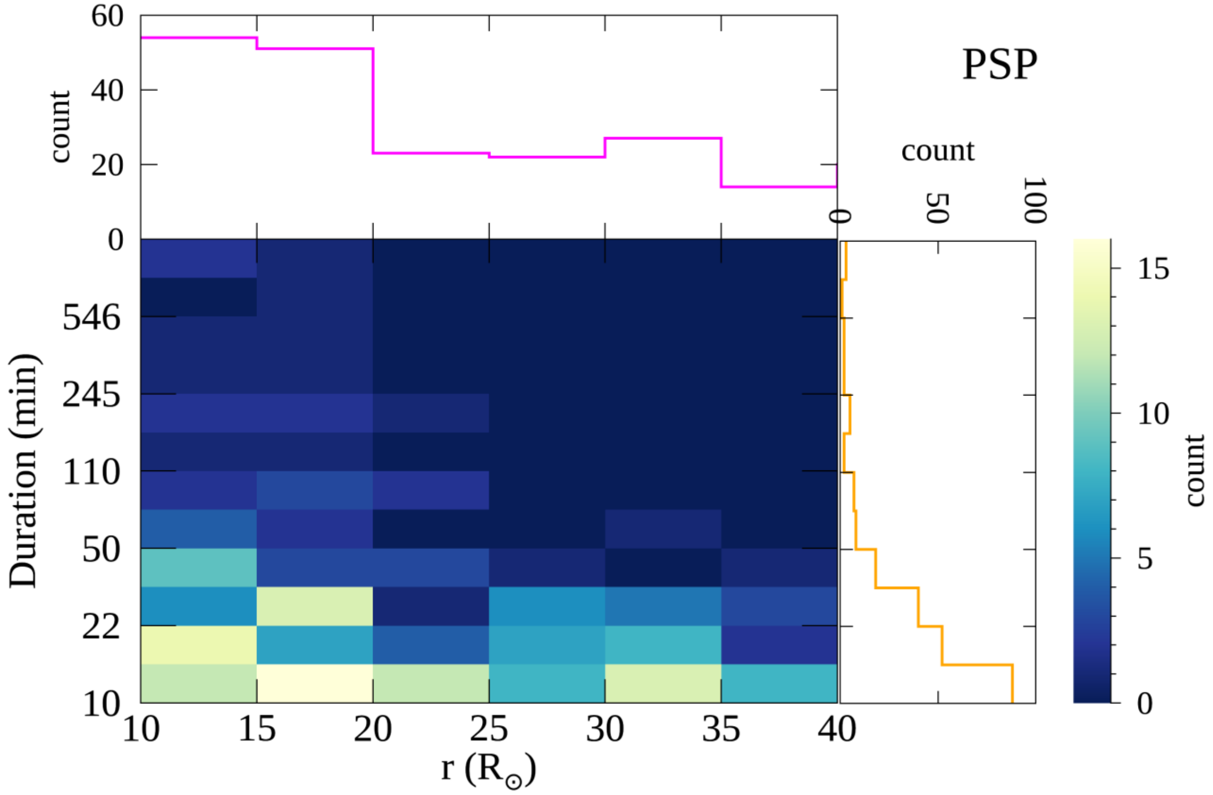


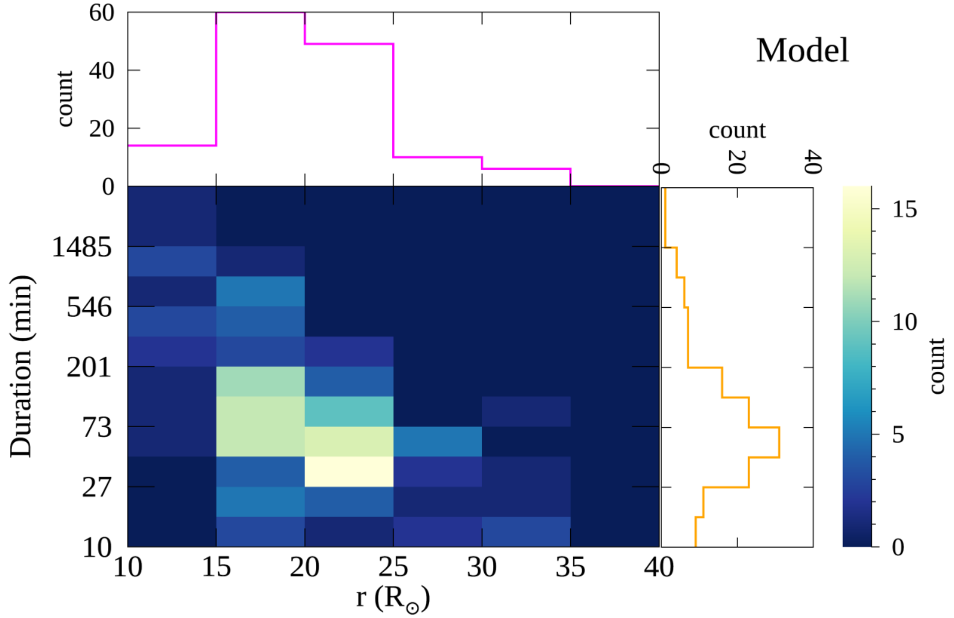
Chhiber+ 2022 prediction on Alfven zone – both frequency and duration/size of subAlfvenic intervals will increase approaching Sun

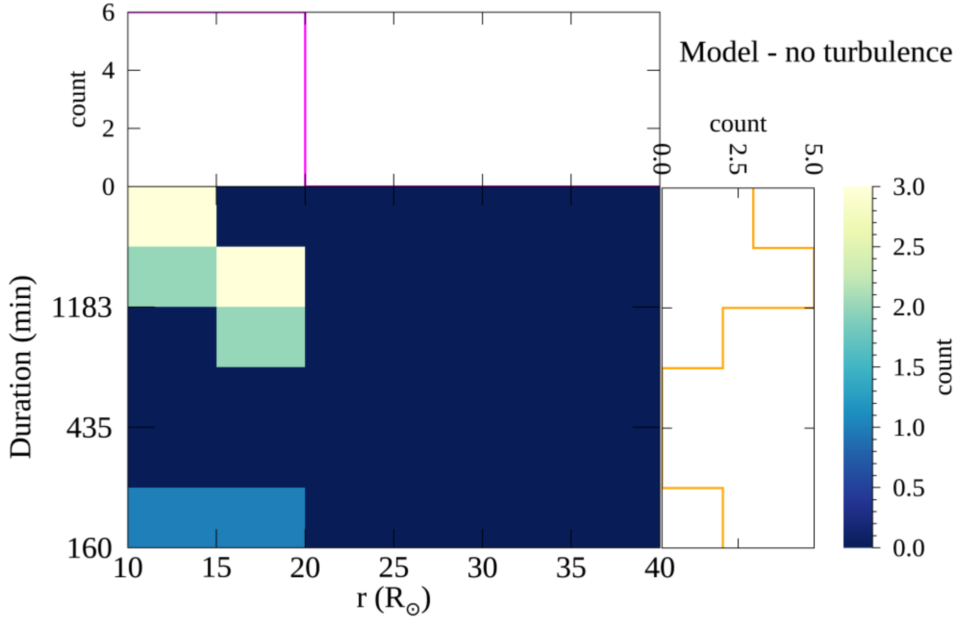


Chhiber+ 2024, *MNRAS-L*

Joint distributions of subAlfvenic-interval duration and heliodistance

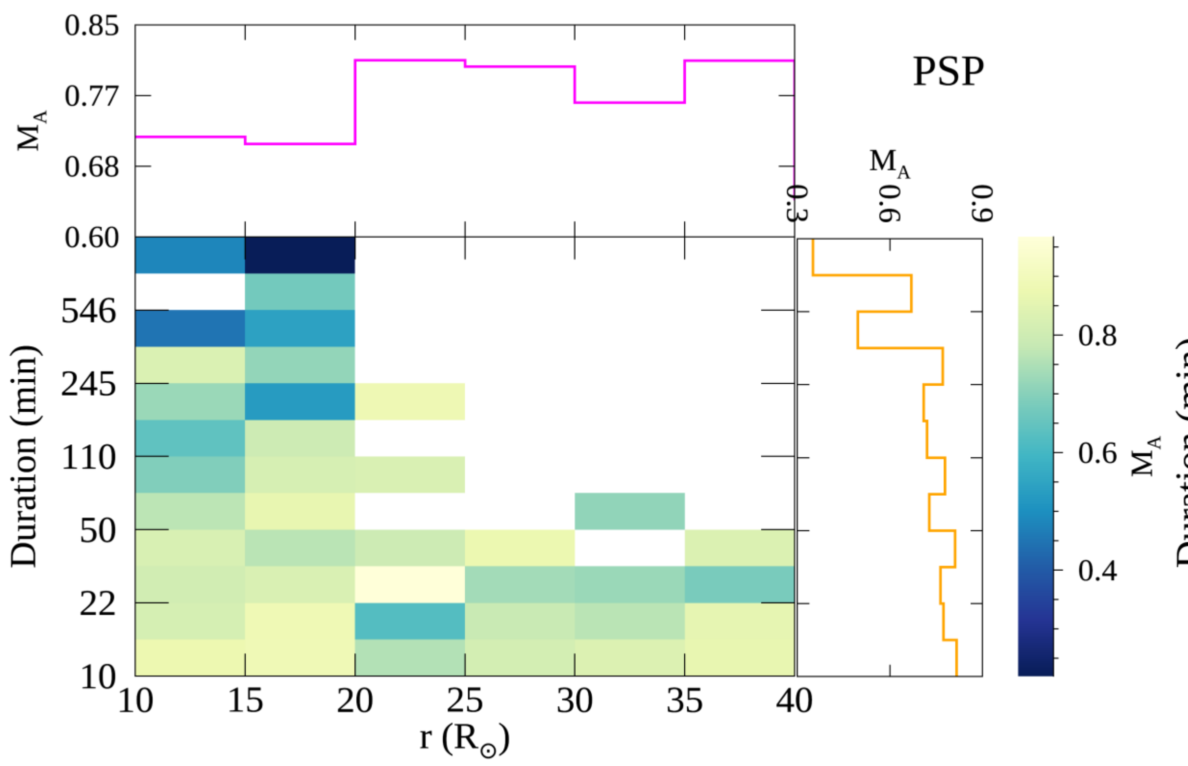




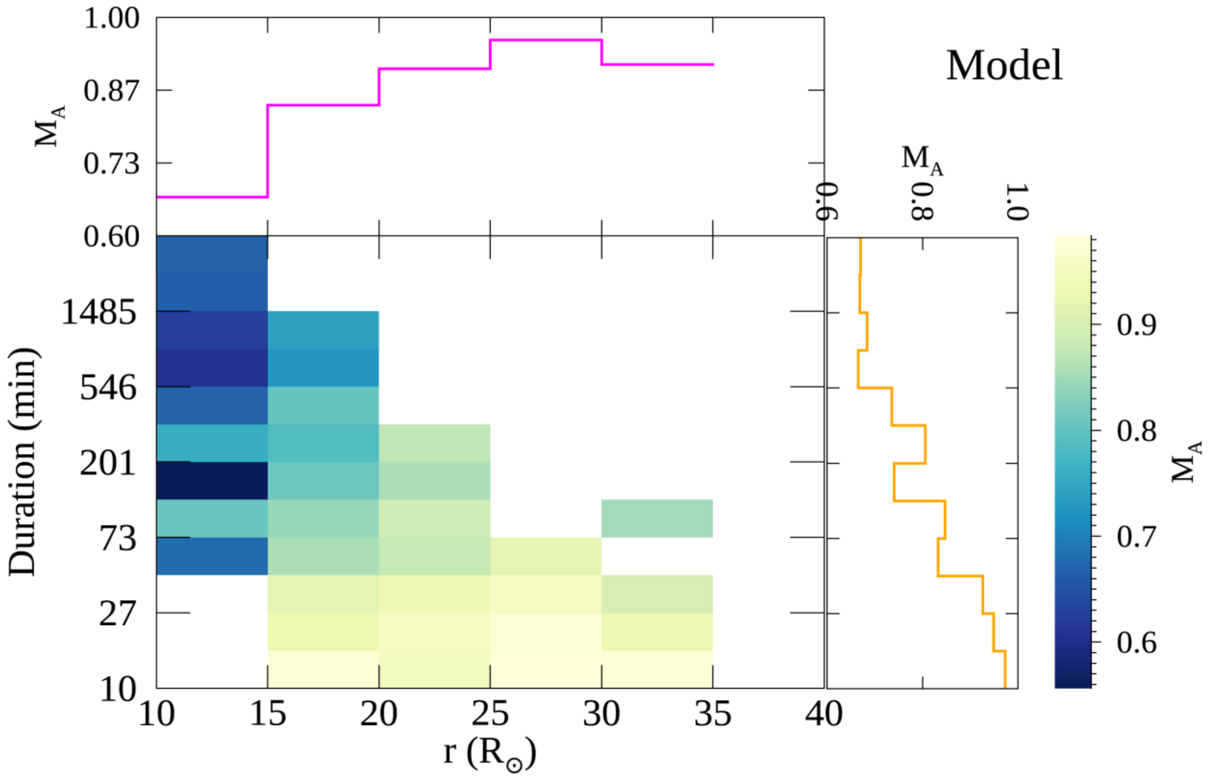


Chhiber+ 2024, *MNRAS-L*

M_A of subAlfvenic intervals



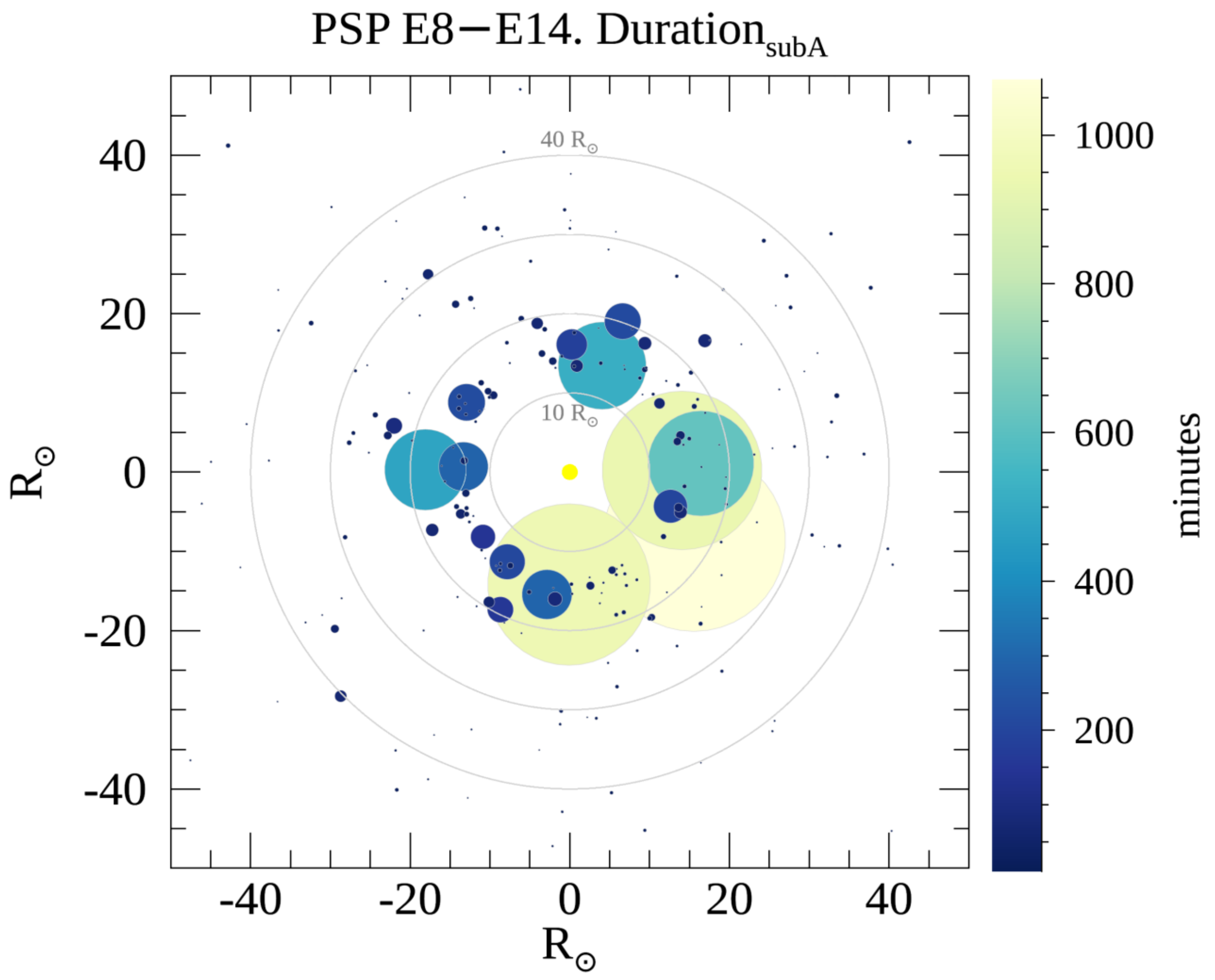
PSP

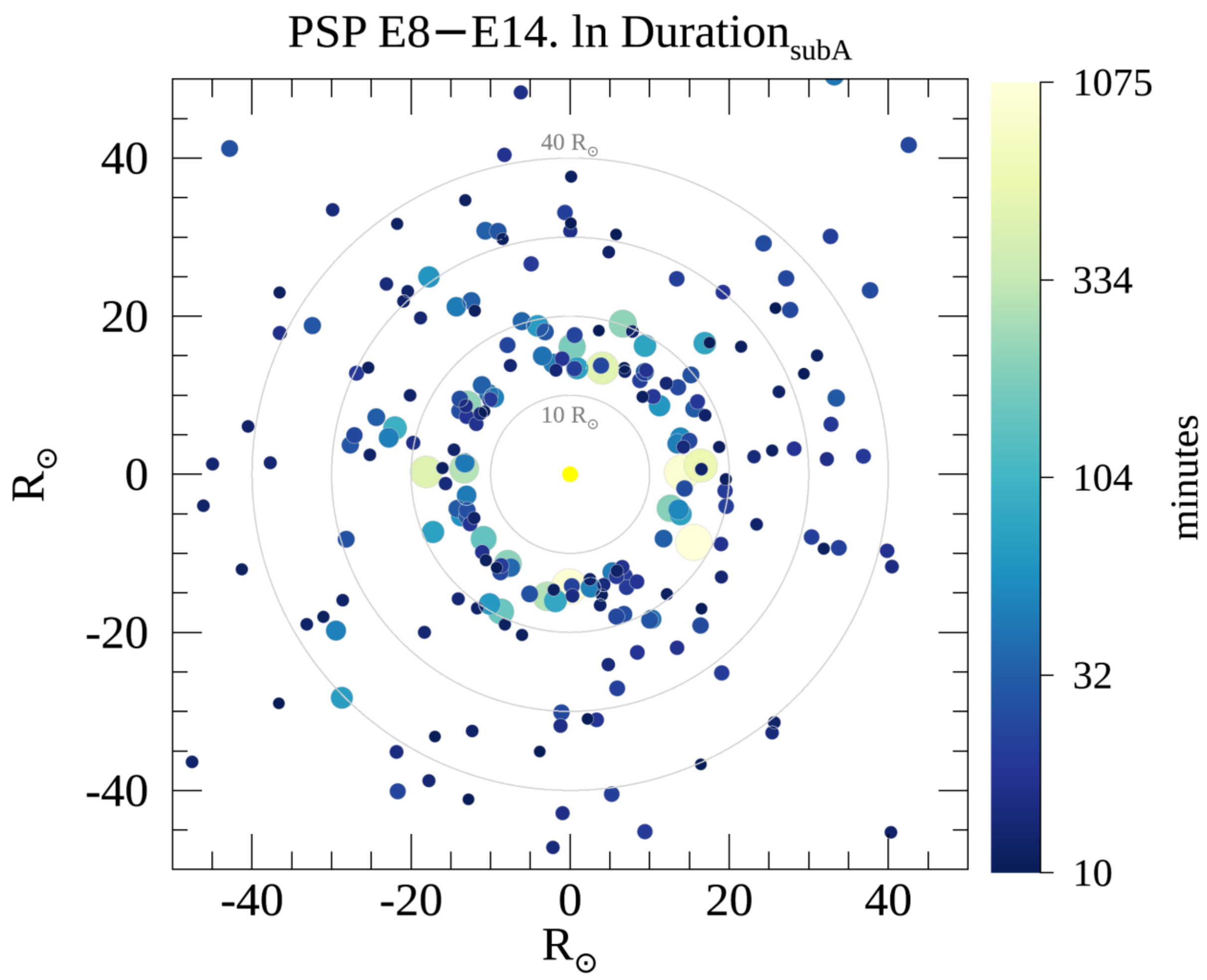


Model

Chhiber+ 2024, *MNRAS-L*

“Bubble plots” of subAlfvenic interval duration





- Heliolongitude of intervals randomized
- Circle Diameter represents [*left*:] interval duration [*right*:] log (duration)
- Colorbar shows interval duration

Chhiber+ 2024, *MNRAS-L*

Sunward-propagating Alfvenic signals

- Sunward propagation of Alfvenic signals indicates subAlfvenic solar wind flow

- Feature tracking has been used with STEREO data to infer a location for the Alfven surface (DeForest+ 2014)

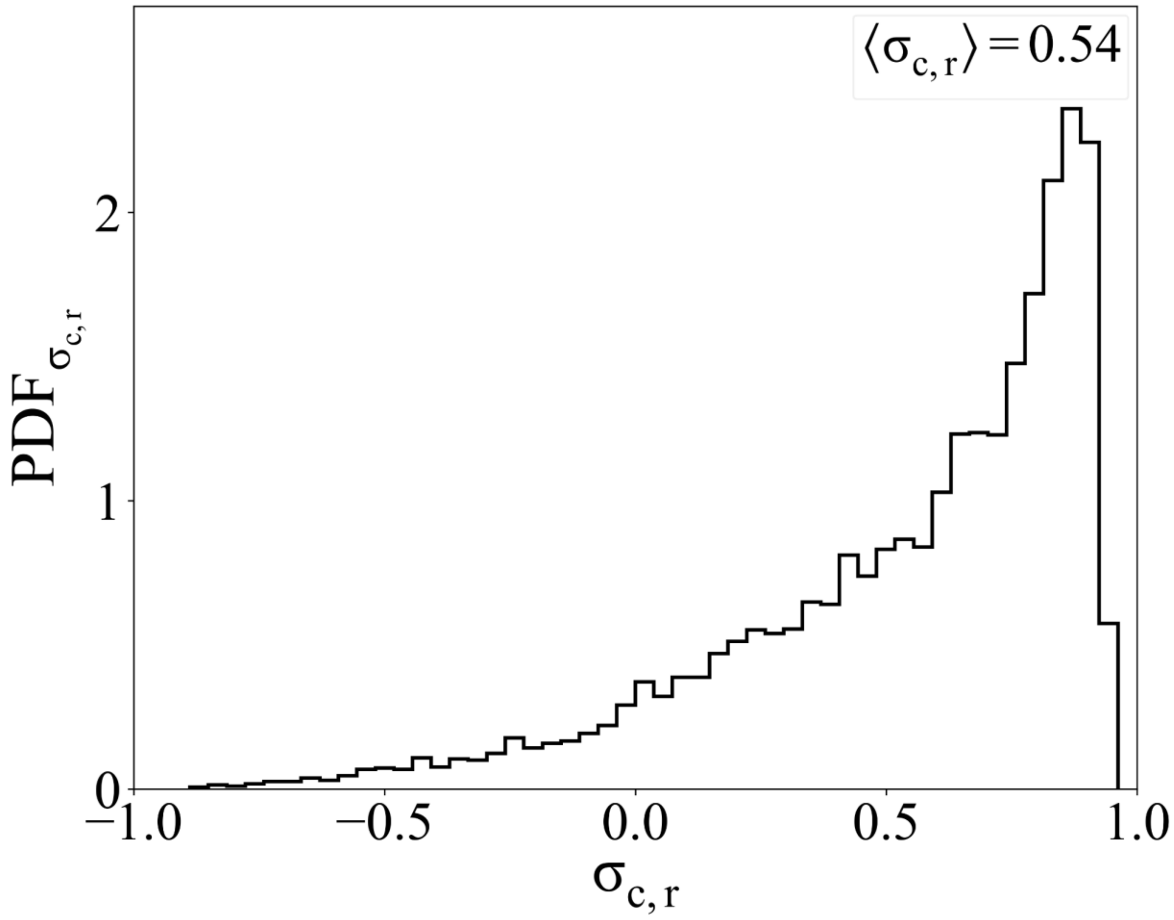
- Normalized cross helicity: $\sigma_c \equiv 2\langle \boldsymbol{v} \cdot \boldsymbol{b} \rangle / Z^2$, where $Z^2 \equiv \langle v^2 + b^2 \rangle$. Indicates correlation of velocity and magnetic fluctuations

- When $B_r > 0$ then $\sigma_c < 0$ indicates "outward" propagation of Alfven wave; when $B_r < 0$ then $\sigma_c > 0$ is outward

- Sector rectification: when $B_r > 0$ then $\sigma_c \rightarrow -\sigma_c$. Then positive σ_c always indicates outward propagation

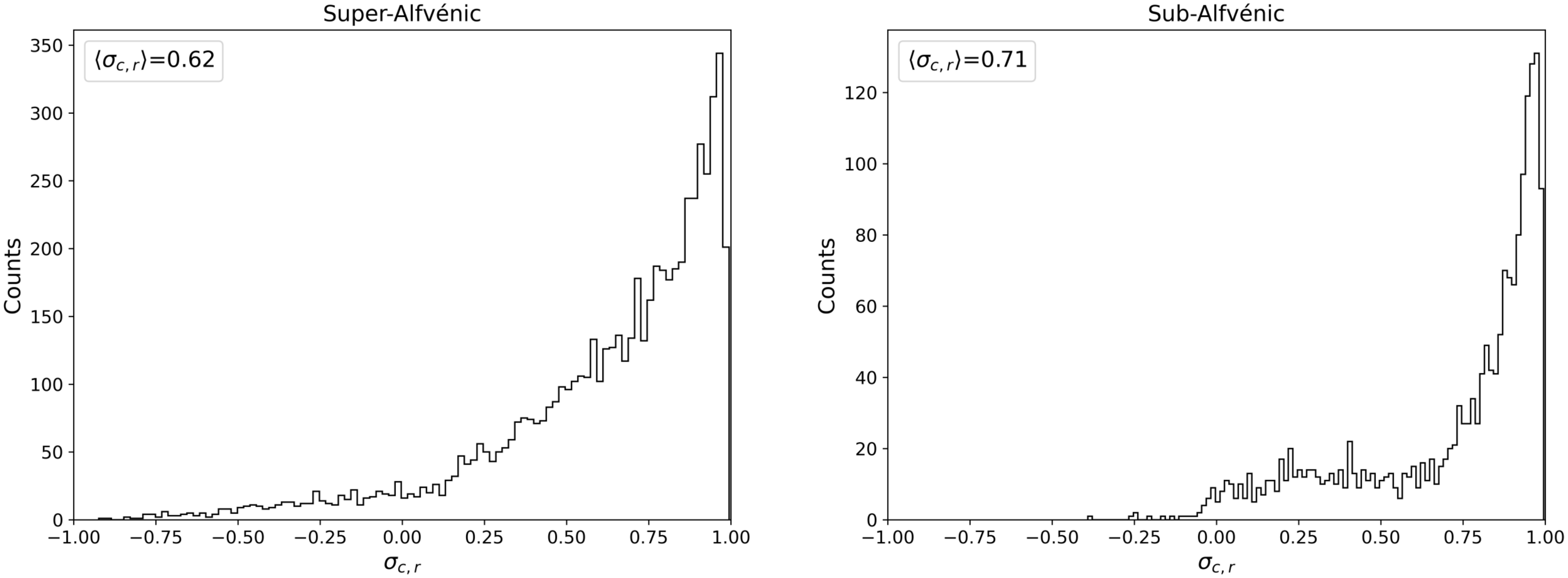
Sector rectified cross helicity from ten years of ACE data (1 AU)

- $\sigma_c = \frac{Z_+^2 - Z_-^2}{Z_+^2 + Z_-^2}$, where $Z_\pm$ are strengths of outward/inward Aflven modes
- Figure shows PDF based on several thousand 12-hr intervals



Credit: Victoria Wang

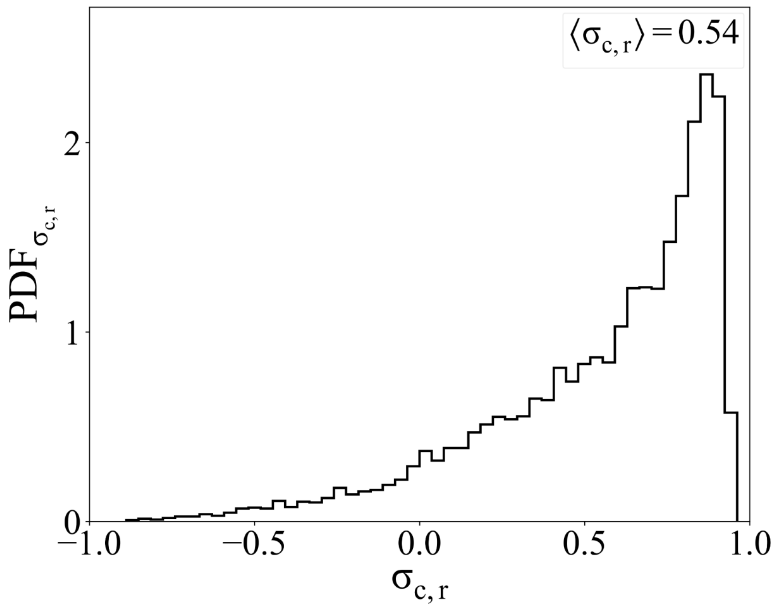
Sector rectified cross helicity from PSP encounters (13-30 $R_\odot$) (Preliminary)



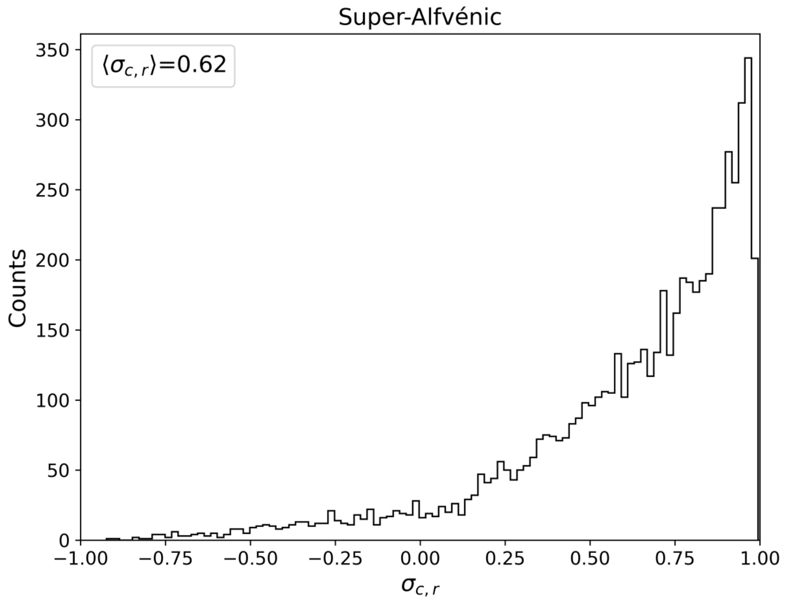
Credit: Sohom Roy

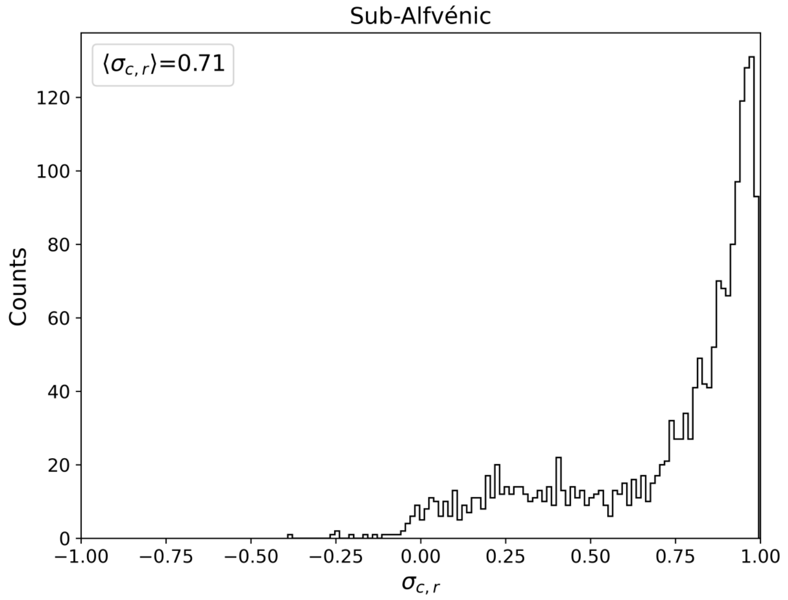
- 10-min intervals
- Almost no subAlfvenic intervals with dominant Sunward propagation

Sector rectified cross helicity in the inner heliosphere (Preliminary)



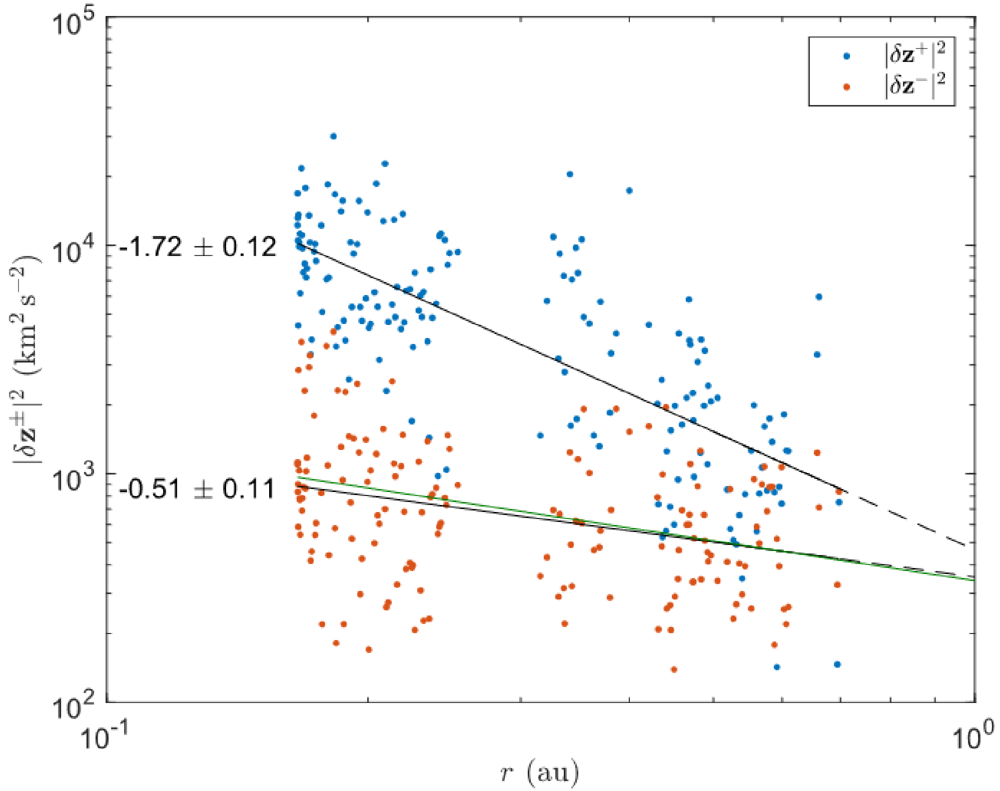
1 AU



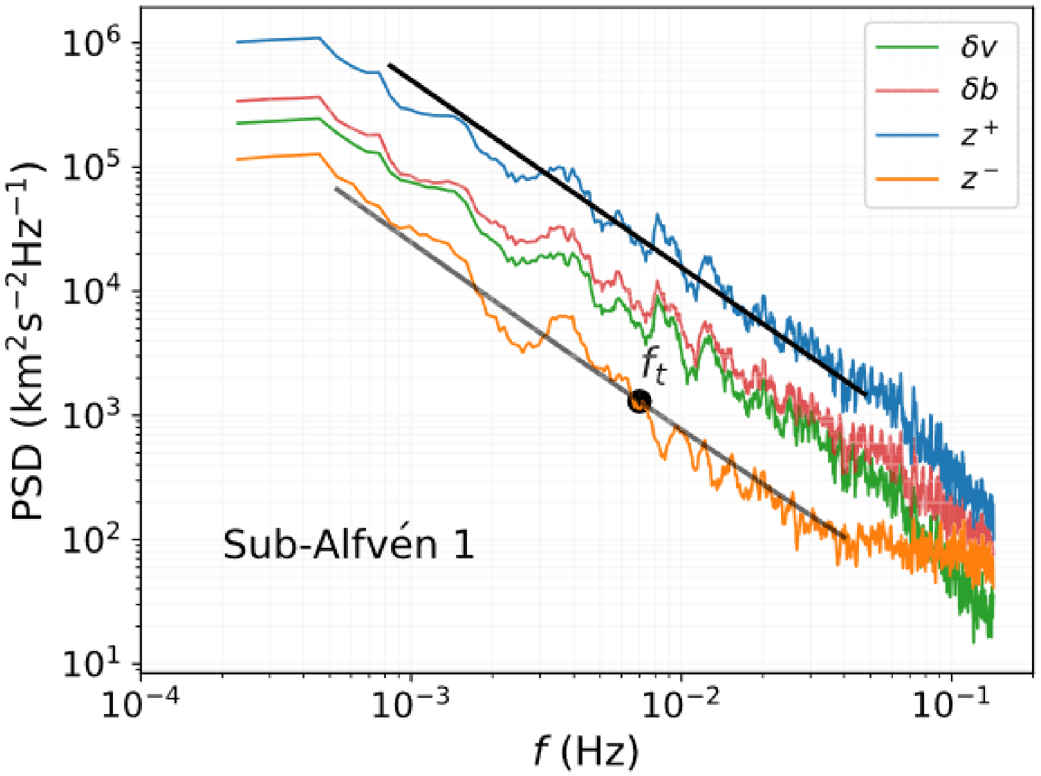


~ 0.1 AU

The Sunward mode exists, just weak compared to outward (weaker nonlinearities)



Chen+ 2020



Zhao+ 2022

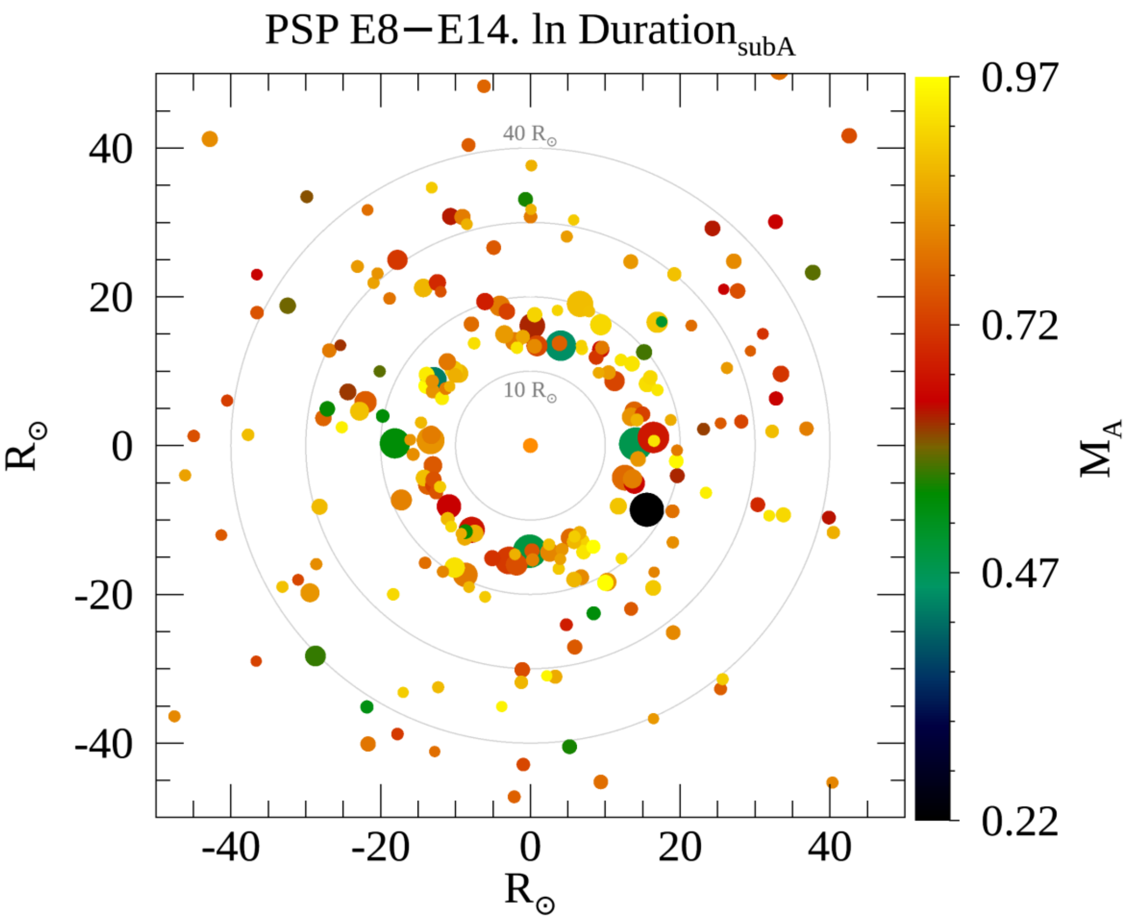
Conclusions

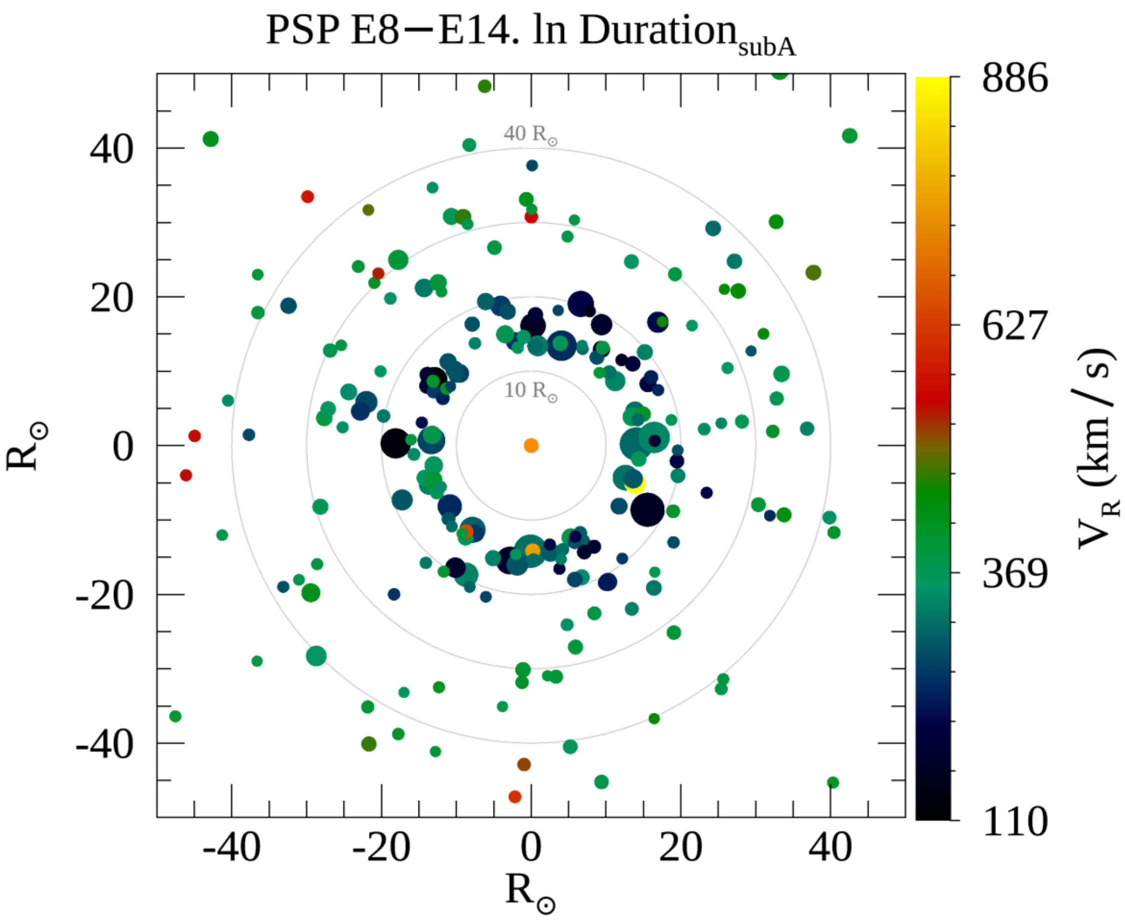
- Turbulence implies an extended spatial region of transition from subAlfvenic to superAlfvenic flow

- PSP observations consistent with patchy and fragmented morphology of Alfven zone, extending over a range of helioradii

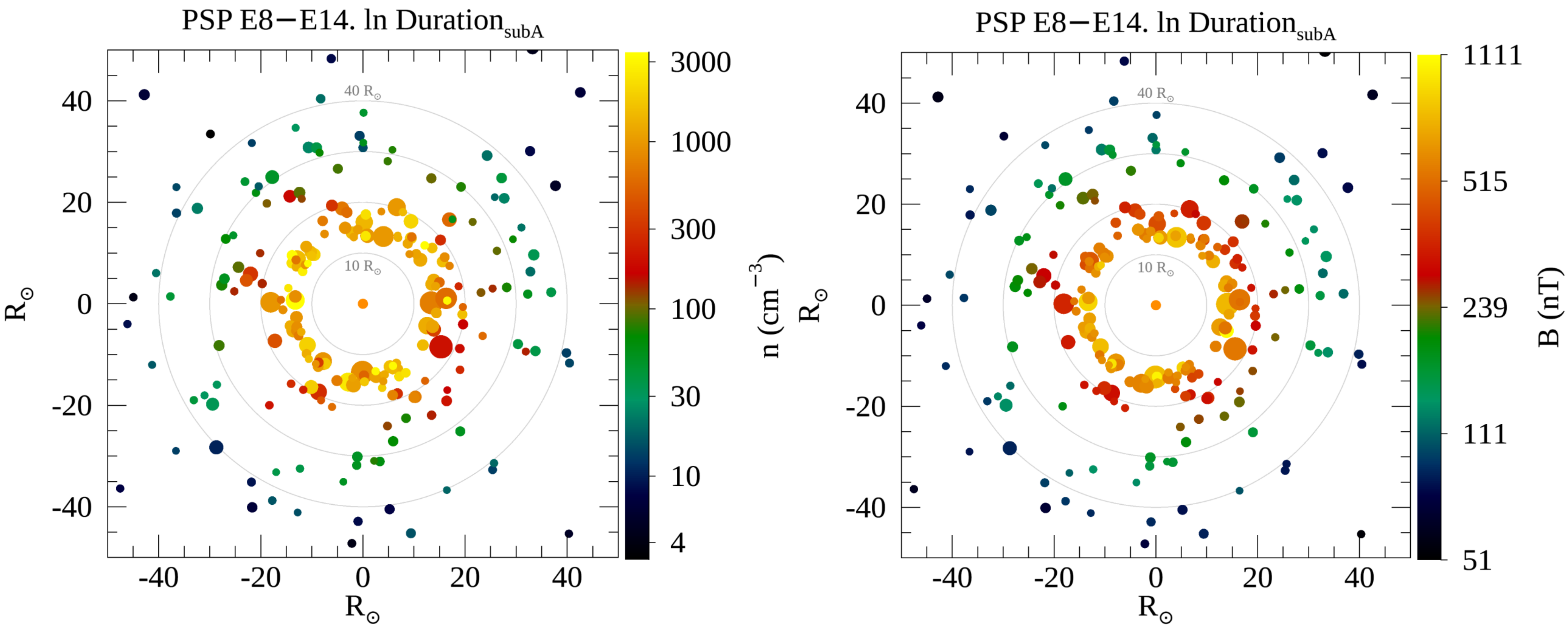
- (Preliminary) Intervals with dominant Sunward propagation of Alfven waves are rare near Alfven surface; strength of Sunward mode continues to decrease crossing below Alfven surface: weaker NL interactions

Global properties of Alfven zone

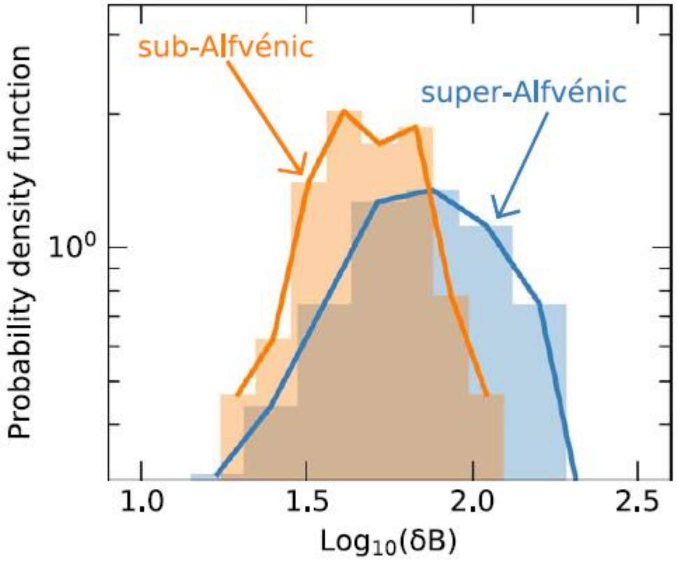


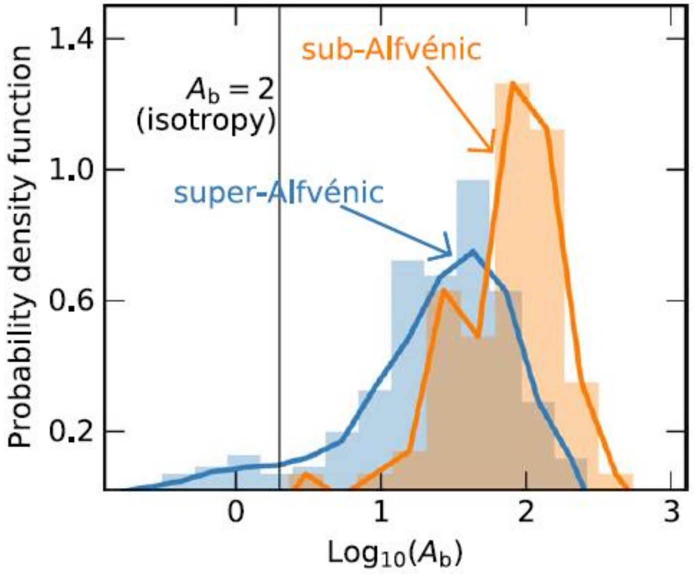


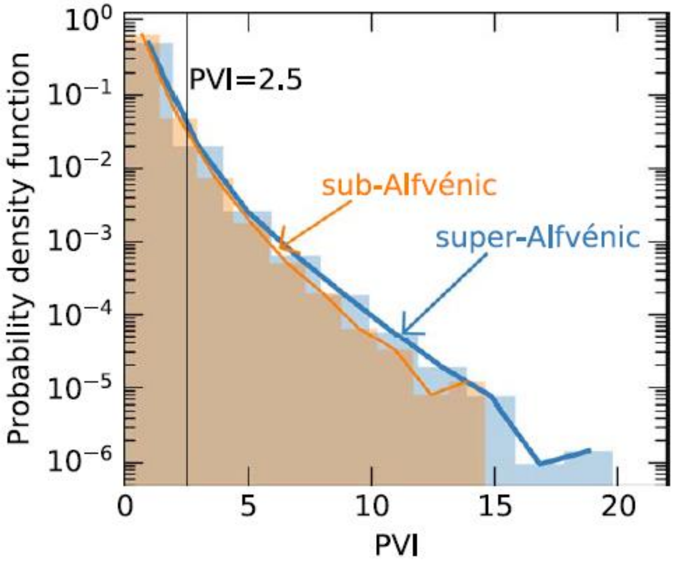
Global properties of Alfven zone



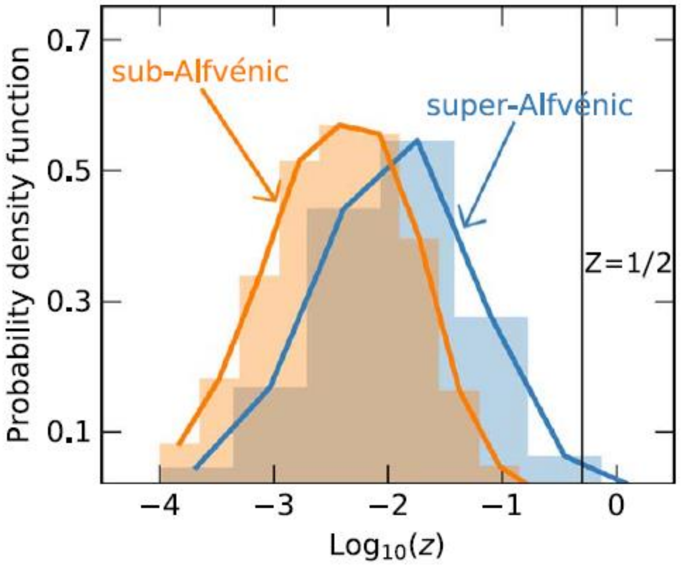
Turbulence compared between subAlfvenic and superAlfvenic intervals (PSP)







Clockwise from top left – fluctuation amplitude, variance anisotropy, intermittency (PVI), number of switchbacks



Bandyopadhyay+ 2022

Global simulation with turbulence modeling – Schematic of Reynolds-Averaging Approach

- Global simulation of corona/solar wind cannot explicitly resolve turbulence
- Reynolds decomposition splits fields (ã) into mean (a) and fluctuation (a'; arbitrary amplitude)

Resolve large-scale/mean flow explicitly

Describe “subgrid” fluctuations statistically

Large-scale (mean field) model equations (MHD):
- Density
- Momentum
- Magnetic field
- internal energies (Te & Tp)

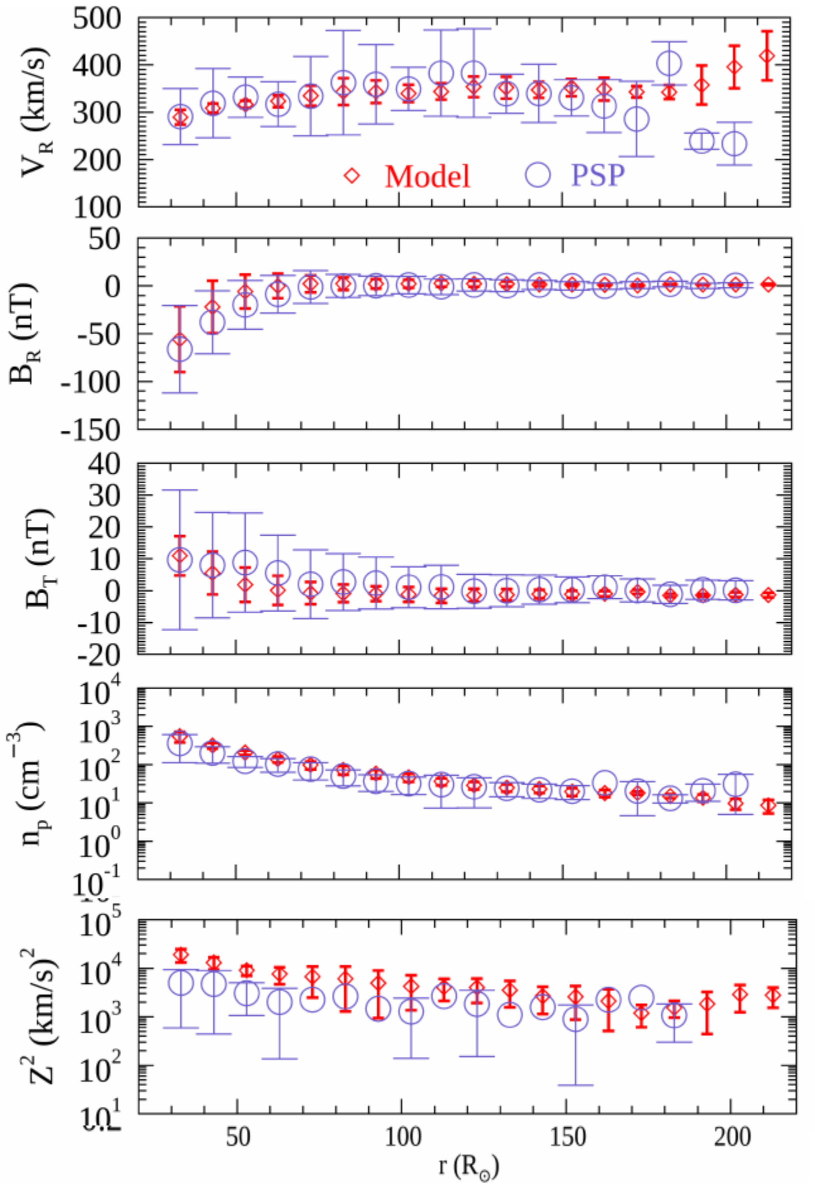
$$\tilde{\mathbf{a}} = \mathbf{a} + \mathbf{a}'$$

Equations for energy, cross helicity, correlation scale

- Two-way coupling – turbulence accelerates and heats wind, and gradients in large-scale fields drive turbulence
- Well-tested, good agreement with observations (Usmanov+ 2018, Chhiber+ 2021)

Global sim w' turbulence modeling – Comparison with five PSP orbits

$$Z^2 = \langle v'^2 + b'^2 \rangle$$



Chhiber+ 2021, ApJ

Two-Fluid Reynolds Averaged MHD Equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot \left[\rho \mathbf{v}\mathbf{u} - \frac{1}{4\pi}\mathbf{B}\mathbf{B} + \left(P_S + P_E + \frac{B^2}{8\pi} + \frac{\langle B'^2 \rangle}{8\pi} \right)\mathbf{I} + \boldsymbol{\mathcal{R}} \right] = -\rho \left(\frac{GM_\odot}{r^2} + \boldsymbol{\Omega} \times \mathbf{u} \right)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B} + \boldsymbol{\varepsilon}_m \sqrt{4\pi\rho})$$

$$\frac{\partial P_S}{\partial t} + (\mathbf{v} \cdot \nabla) P_S + \gamma P_S \nabla \cdot \mathbf{u} + (\gamma - 1) \frac{P_S - P_E}{\tau_{SE}} = f_p Q_T$$

$$\frac{\partial P_E}{\partial t} + (\mathbf{v} \cdot \nabla) P_E + \gamma P_E \nabla \cdot \mathbf{u} + (\gamma - 1) \left[\frac{P_E - P_S}{\tau_{SE}} + \nabla \cdot \mathbf{q}_H \right] = (1 - f_p) Q_T$$

- P_S and P_E are the proton and electron pressure
- $\mathbf{u}$ is the velocity in the inertial frame
- $\mathbf{v}$ is the velocity in the rotating frame
- τ_{SE} is the electron-proton Coulomb collision rate
- $\boldsymbol{\mathcal{R}} = \langle \rho \mathbf{v}'\mathbf{v}' - \frac{\mathbf{B}'\mathbf{B}'}{4\pi} \rangle$ is the Reynolds stress tensor
- $\boldsymbol{\varepsilon}_m = \frac{\langle \mathbf{v}' \times \mathbf{B}' \rangle}{(4\pi\rho)^{1/2}}$ is the mean turbulent electric field
- Q_T is the turbulent heating rate
- $\mathbf{q}_H$ is the electron heat flux

Two-Fluid Reynolds-averaged MHD with Turbulence Transport

- Turbulence transport equations obtained by subtracting mean-flow eqns. from full eqns., and averaging.

mean flow

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial(\rho \mathbf{u})}{\partial t} + \nabla \cdot \left[\rho \mathbf{v}\mathbf{u} - \frac{1}{4\pi}\mathbf{B}\mathbf{B} + \left(P_S + P_E + \frac{B^2}{8\pi} + \frac{\langle B'^2 \rangle}{8\pi}\right)\mathbf{I} + \boldsymbol{\mathcal{R}}\right] = -\rho\left(\frac{GM_\odot}{r^2} + \boldsymbol{\Omega} \times \mathbf{u}\right)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B} + \boldsymbol{\varepsilon}_m \sqrt{4\pi\rho})$$

$$\frac{\partial P_S}{\partial t} + (\mathbf{v} \cdot \nabla)P_S + \gamma P_S \nabla \cdot \mathbf{u} + (\gamma - 1)\frac{P_S - P_E}{\tau_{SE}} = f_p Q_T$$

$$\frac{\partial P_E}{\partial t} + (\mathbf{v} \cdot \nabla)P_E + \gamma P_E \nabla \cdot \mathbf{u} + (\gamma - 1)\left[\frac{P_E - P_S}{\tau_{SE}} + \nabla \cdot \mathbf{q}_H\right] = (1 - f_p)Q_T$$

turbulence

$$\frac{\partial Z^2}{\partial t} + (\mathbf{v} \cdot \nabla)Z^2 + \frac{(1-\sigma_D)Z^2}{2}\nabla \cdot \mathbf{u} + \frac{2}{\rho}\boldsymbol{\mathcal{R}} : \nabla \mathbf{u} + 2\boldsymbol{\varepsilon}_m \cdot (\nabla \times \mathbf{u}) - (\mathbf{V}_A \cdot \nabla)(Z^2\sigma_c) + Z^2\sigma_c \nabla \cdot \mathbf{V}_A = -\frac{\alpha f^+(\sigma_c)Z^3}{\lambda}$$

$$\frac{\partial (Z^2\sigma_c)}{\partial t} + (\mathbf{v} \cdot \nabla)(Z^2\sigma_c) + \frac{Z^2\sigma_c}{2}\nabla \cdot \mathbf{u} + \frac{2}{\rho}\boldsymbol{\mathcal{R}} : \nabla \mathbf{V}_A + 2\boldsymbol{\varepsilon}_m \cdot (\nabla \times \mathbf{u}) - (\mathbf{V}_A \cdot \nabla)Z^2 + (1-\sigma_D)Z^2 \nabla \cdot \mathbf{V}_A = -\frac{\alpha f^-(\sigma_c)Z^3}{\lambda}$$

$$\frac{\partial \lambda}{\partial t} + (\mathbf{v} \cdot \nabla)\lambda = \beta f^+(\sigma_c) Z$$

- $Z^2 = \langle v'^2 + b'^2 \rangle$ is (twice the incompressible yurbulent energy per unit mass
- $\sigma_c = \dfrac{2\langle \mathbf{v}' \cdot \mathbf{b}' \rangle}{\langle v'^2 + b'^2 \rangle}$ is the normalized cross helicity
- λ is the similarity (correlation) length scale

Turbulence modeling assumptions –

- Incompressible and transverse fluctuations
- Turbulent stresses modeled in terms of large-scale gradients (shear)
- NL terms modeled dimensionally (von Karman similarity)

- Physically and empirically motivated ICs and BCs
- Magnetogram-based or dipolar source magnetic field
- Numerical domain from coronal base to few AU

See Usmanov et al., 2018 for more details

Closures and other terms (extra slide)

- Electron-proton collision frequency:

$$\nu_E = \frac{8(2\pi m_e)^{1/2} e^4 N_E \ln\Lambda}{3m_p (k_B T_E)^{3/2}} \qquad \ln\Lambda = \ln\left[\frac{3(k_B T_E)^{3/2}}{2\pi^{1/2} e^3 N_E^{1/2}}\right]$$

- Classical (Spitzer) electron heat conduction (below 5 $R_\odot$):

$$\mathbf{q}_\mathrm{S} = -\kappa \hat{\mathbf{B}}(\hat{\mathbf{B}}\cdot\nabla) T_E \qquad \kappa = 8.4\times 10^{-7}\, T_E^{5/2}$$

- Collisionless (Hollweg) heat conduction: $\mathbf{q}_\mathrm{H} = (3/2)\alpha_\mathrm{H} P_E \mathbf{v}$

- Turbulent heating: $Q_T = \dfrac{\alpha f^+(\sigma_c)\rho Z^3}{2\lambda}$
- TSDIA closure for turbulent stresses:

$$\boldsymbol{\varepsilon}_m = \bar{\alpha}\mathbf{B} - \bar{\beta}\nabla\times\mathbf{V}_A + \bar{\gamma}\nabla\times\mathbf{v}$$

$$\nu_M = (7/5)\bar{\gamma}$$

$$\nu_K = (7/5)\bar{\beta}$$

$$\frac{1}{\rho}\boldsymbol{\mathcal{R}} = \frac{2}{3}K_R\,\mathbf{I} - \nu_K\boldsymbol{\mathcal{S}} + \nu_M\boldsymbol{\mathcal{M}}$$

$$K_R = \sigma_D Z^2/2$$

$$\boldsymbol{\mathcal{S}} = \nabla\mathbf{u} + \nabla\mathbf{u}^T - \frac{2}{3}(\nabla\cdot\mathbf{u})\mathbf{I}$$

$$\boldsymbol{\mathcal{M}} = \nabla\mathbf{V}_A + \nabla\mathbf{V}_A^T - \frac{2}{3}(\nabla\cdot\mathbf{V}_A)\mathbf{I}$$

$$\nu_K \approx 0.27 Z\lambda \qquad \nu_M \approx 0.22\sigma_c Z\lambda$$

Modeling NL terms

$$\frac{\partial \mathbf{z}_\pm}{\partial t} = -\mathbf{z}_\mp\cdot\nabla\mathbf{z}_\pm$$

$$\frac{\partial}{\partial t}\langle z_+^2\rangle = -2\langle \mathbf{z}_+\cdot(\mathbf{z}_-\cdot\nabla\mathbf{z}_+)\rangle$$

$$\sim -\langle z_+^2\rangle\frac{\langle z_-^2\rangle^{-1/2}}{\lambda_+},$$

$$\frac{\partial Z^2}{\partial t} \sim -\frac{Z^3}{\lambda}$$

Usmanov et al., 2018

Boundary/Initial conditions and parameters (extra slide)

Symbol	Description	Value
N_0	proton number density in the initial state at 1 $R_\odot$	$8 \times 10^7\,\mathrm{cm}^{-3}$
T_0	electron and proton temperature in the initial state at 1 $R_\odot$	$1.8 \times 10^6\,\mathrm{K}$
B_0	magnetic field strength of dipole at 1 $R_\odot$	12 G
δv_0	driving amplitude of fluctuations in the initial state at 1 $R_\odot$	$35\,\mathrm{km\,s}^{-1}$
σ_{c0}	normalized cross helicity in the initial state	0.8
λ_0	correlation scale of turbulence in the initial state at at 1 $R_\odot$	0.015 $R_\odot$

Symbol	Description	Value
σ_D	normalized energy difference (residual energy)	$-1/3$
γ	adiabatic index	$5/3$
α_{H}	constant in Hollweg's collisionless heat flux	1.05
α, β	Kármán–Taylor constants	2, 0.128
f_p	fraction of turbulent heating for protons	0.6
r_{H}	collisional/collisionless electron heat flux transition region	5 $R_\odot$

Usmanov et al., 2018

Spatial Scales Resolved in Simulations

- Resolution $\sim 700 \times 120 \times 240$ in r, θ, ϕ ($r = 1\ R_\odot$ - 5 AU)
- Grid scale Δ is generally within a factor of few correlation scales