# Reconnection, turbulence and intermittency in coronal-hole jets

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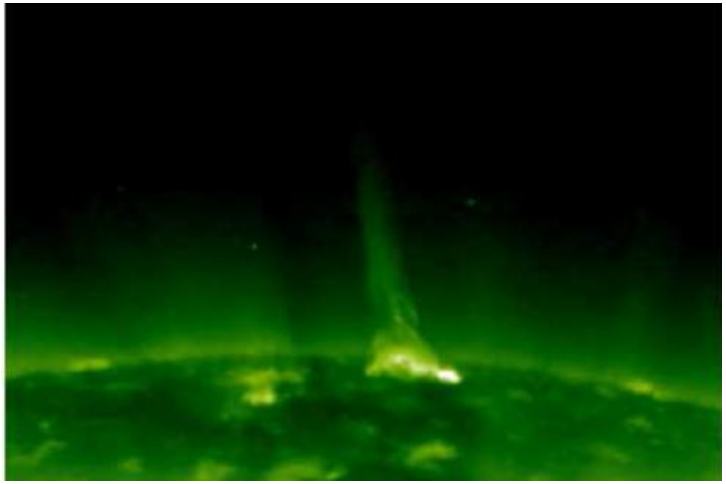
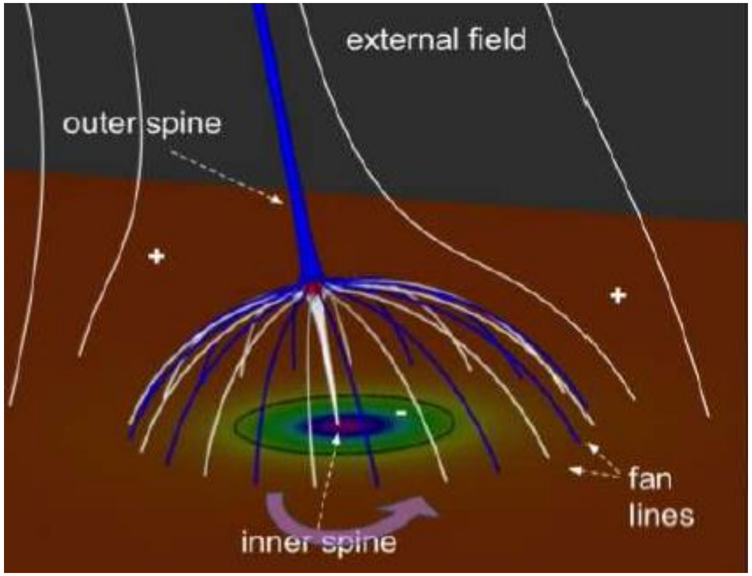
# Outline

- Extreme-ultraviolet and X-ray jets often occur in magnetically open coronal holes on the Sun.
- We performed a detailed statistical analysis of a coronal-hole jet simulated with an adaptively refined MHD model (Karpen et al., ApJ 2017).
- The results show the generation and evolution of *intermittent* 3D turbulence in the simulated jet, consistent with an ensemble of nonlinear Alfvén waves caused by untwisting reconnected magnetic field (Uritsky et al., ApJ 2017) .
- Comparison with Ulysses observations shows quantitative agreement with key signatures of turbulence in the fast solar wind.
- In situ observations by Solar Probe Plus will be instrumental for understanding the physics of the reconnection-driven turbulence in these important solar events.

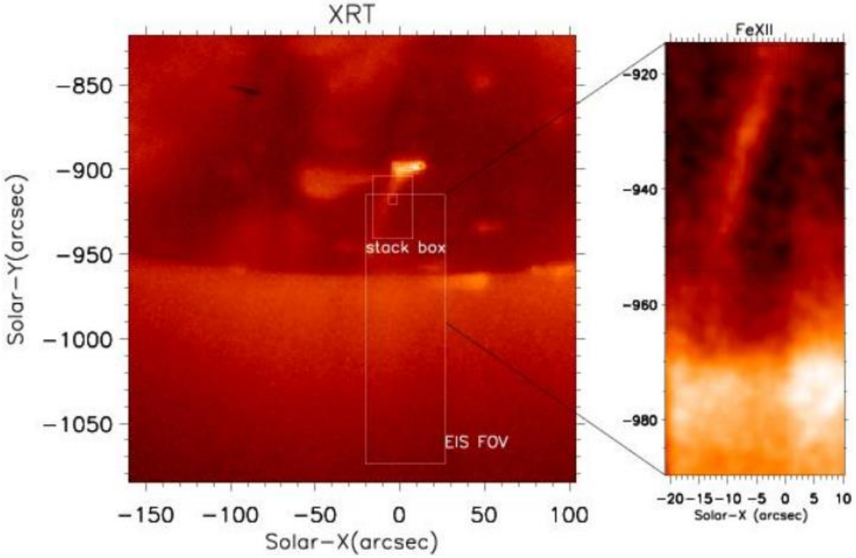
# Coronal hole jets



Coronal hole jet observed by STEREO EUVI (Patsourakos et al. 2008)




Magnetic topology of the embedded - bipole jet model (Pariat et al., ApJ 2009)



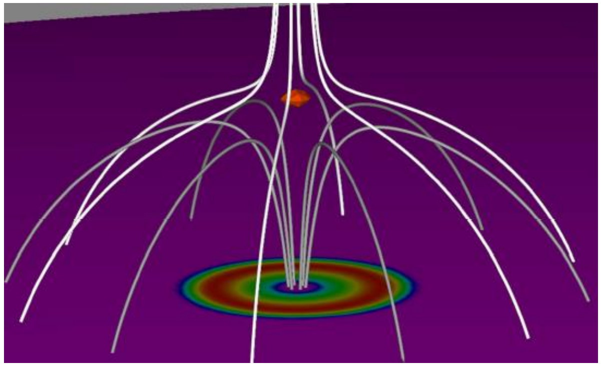

Coronal hole jet observations by Hinode XRT and EUV imaging spectrometer (Chandrashekhar et al., A&A 2014)

# The jet model (Karpen et al., ApJ 2017)

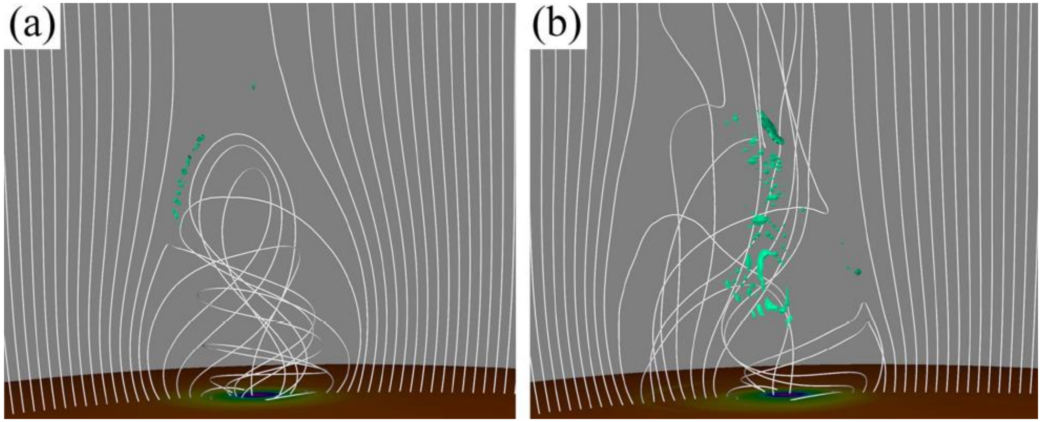
$$\frac{\partial \rho}{\partial t} + \nabla \bullet (\rho \boldsymbol{v}) = 0,$$

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \bullet (\rho \boldsymbol{v} \boldsymbol{v}) = -\nabla P + \rho \boldsymbol{g} + \frac{1}{4\pi}(\nabla \times \boldsymbol{B}) \times \boldsymbol{B},$$

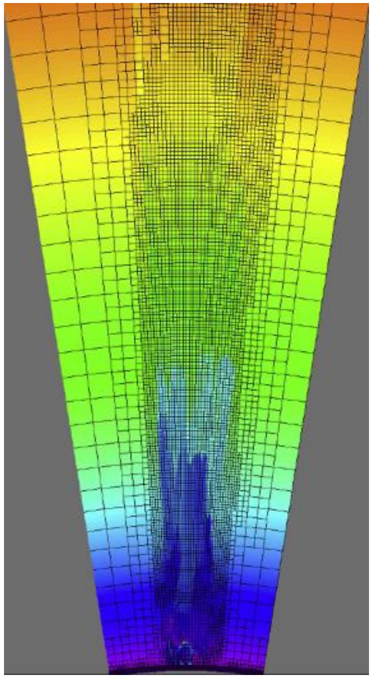
$$\frac{\partial \boldsymbol{B}}{\partial t} - \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) = 0, \qquad P = 2\frac{k_B}{m_p}\rho T.$$



The jet-producing region at t=0 s



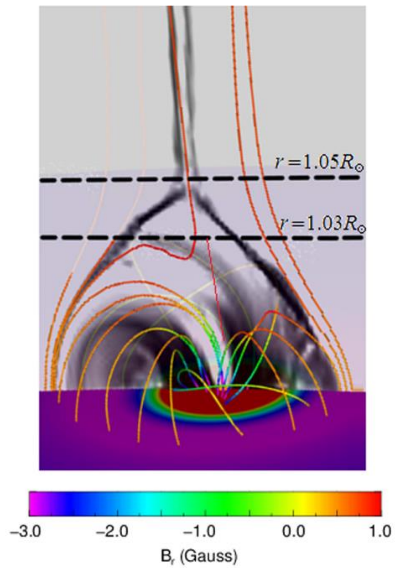

Jet source region during the energy-release phase. White curves: magnetic field lines; green blobs: isosurface of β = 2 showing null points. (a) t=2800 s; (b) t=2925 s. Color shading on the bottom surface indicates magnitude of $B_{radial}$.

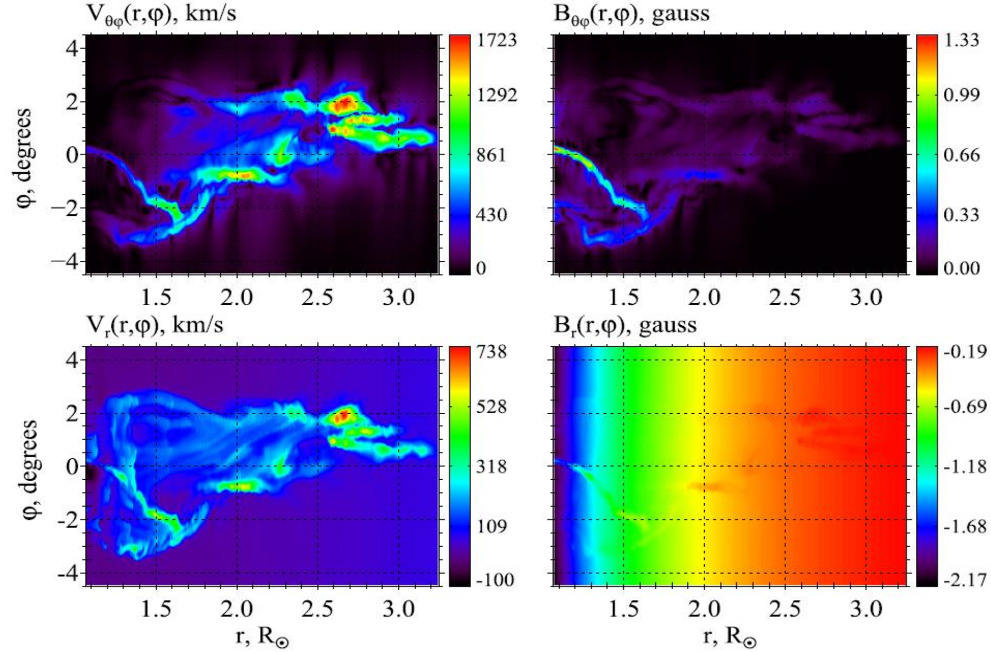


Plasma density at t=4000 s in our jet simulation using the ARMS code. Black lines are boundaries of grid blocks composed of 8x8x8 cells, showing the effects of mesh adaptivity.

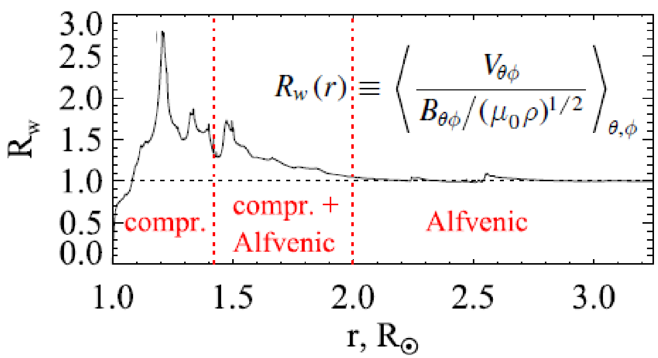
# Reconnection-driven turbulent outflow (t=3650 s)

Magnetic field lines in the low corona

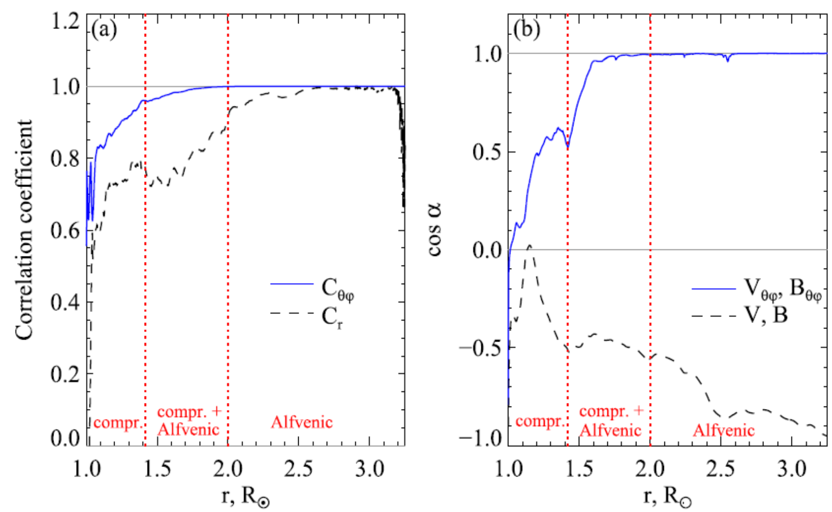



Constant-latitude cross-sections of transverse and radial V and B fields



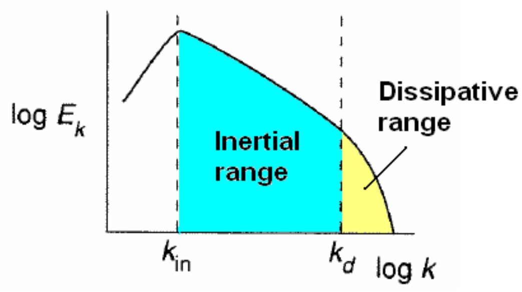

The Walén (1944) number: a test for shear Alfven waves




Radial dependence of linear correlation and directional alignment between V and B field fluctuations

# Phenomenology of the turbulent spectrum

## HOMOGENEOUS FLUID CASCADE (Kolmogorov, 1941)




$$k_{in} \ll k \ll k_d$$

$$E_k = \int d\Omega_k \hat{E}_k, \quad E = \int_{\infty}^{0} dk E_k$$
$$\epsilon_{in} = \epsilon_t = \epsilon_d := \epsilon$$

$$l_0 > l_1 > \cdots > l_N, \quad k_0 < k_1 < \cdots < k_N$$
$$l_n = k_n^{-1} = 2^{-n} l_0, \quad l_0 \sim L$$

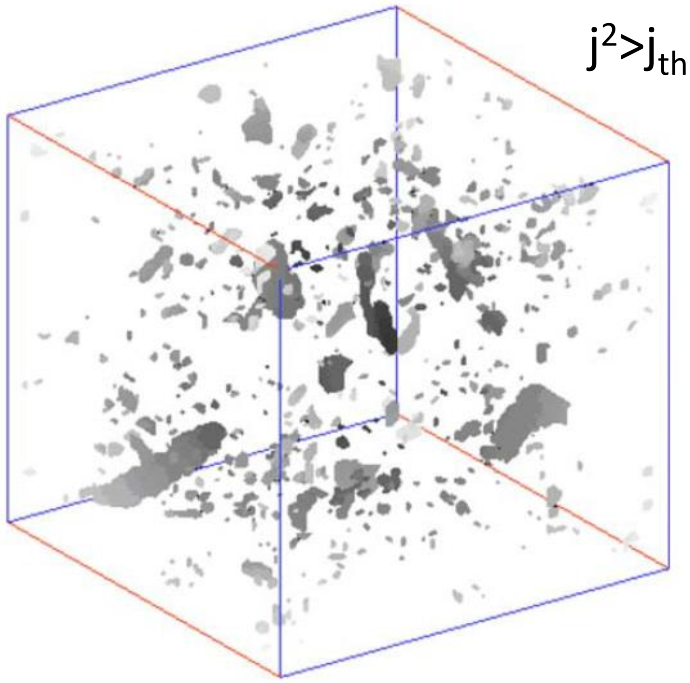
$$\tau_n \sim l_n / \delta v_n, \quad \delta v_n \equiv \delta v_{l_n}$$
$$E_n / \tau_n \sim \delta v_n^3 / l_n \sim \epsilon \ \Rightarrow \ \delta v_n \sim \epsilon^{1/3} l_n^{1/3}$$
$$\delta v_n^2 \simeq E_n \simeq \int_{k_n}^{k_{n+1}} E_k dk \simeq E_{k_n} k_n$$

$$\boxed{E_k \sim \epsilon^{2/3} k^{-5/3}}$$

## INTERMITTENCY

$$\partial_t \mathbf{v} + \mathbf{v} \cdot \nabla \mathbf{v} = -\rho_0^{-1} \nabla \mathcal{P} + \mathbf{j} \times \mathbf{b} + \nu \nabla^2 \mathbf{v},$$

$$\partial_t \mathbf{b} = \nabla \times (\mathbf{v} \times \mathbf{b}) + \eta \nabla^2 \mathbf{b}$$



$j^2 > j_{th}^2$

Current sheets in 3D incompressible MHD (Uritsky et al., *PRE*, 2010)

# Hierarchical models of intermittent turbulence
## (Muller & Biskamp, PRL 2000)

$$\delta B_l = (\boldsymbol{B}(\boldsymbol{r}+\boldsymbol{l}) - \boldsymbol{B}(\boldsymbol{r}))\cdot \boldsymbol{l}/l\,, \quad S_q(l) = \langle|\delta B_l|^q\rangle$$

$$\boxed{S_q(l) \sim l^{\zeta(q)}}$$

$\zeta(q)$– defined by the turbulent regime:

$$\boxed{\zeta(q) = (1-\gamma)q/g + C(1-[1-\gamma/C]^{q/g}]}$$

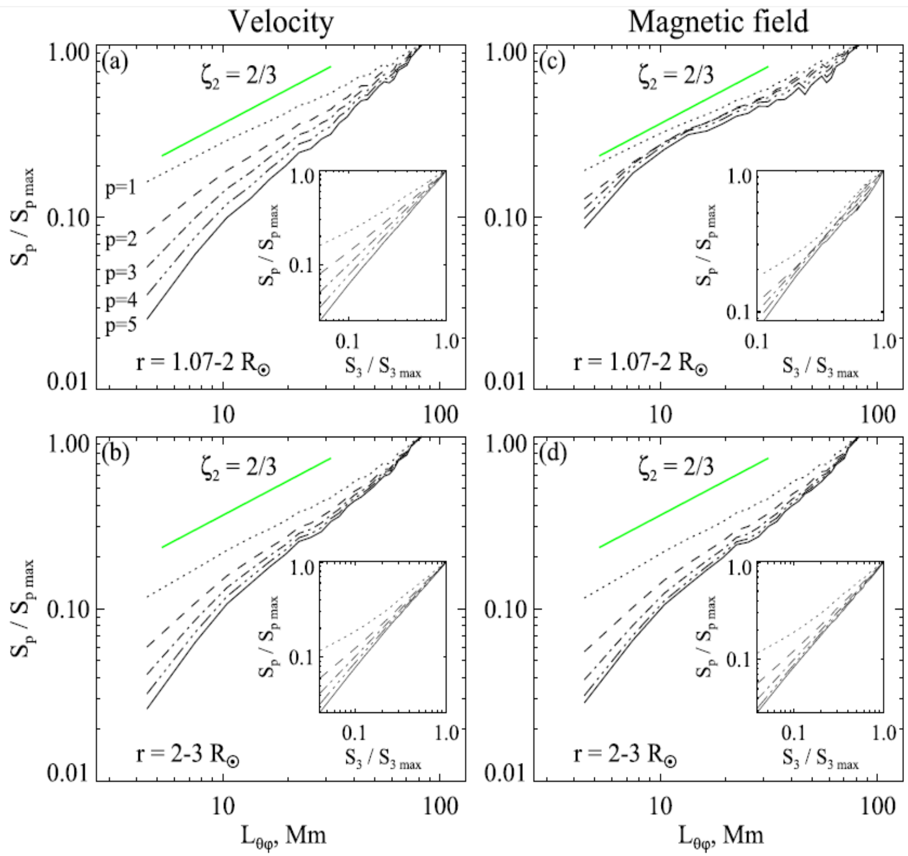
$\delta v \sim \ell^{1/g} \qquad t_e \sim \ell^{\gamma}$

$t_e$ – energy transfer time at smallest inertial scale $\ell$

$C$ – codimension of dissipative structures

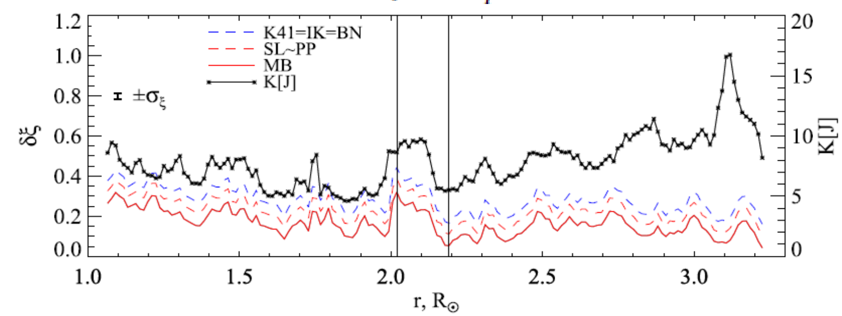
| Model | $q$ | $\gamma$ | $C$ | Cascading Structures | Dissipative Structures |
|---|---|---|---|---|---|
| *Non-intermittent* | | | | | |
| Kolmogorov (1941) (K41) | 3 | 0 | ⋯ | Fluid vortices | ⋯ |
| Iroshnikov & Kraichnan (IK) | 4 | 0 | ⋯ | Alfvén wave packets | ⋯ |
| Brownian noise (BN) | 2 | 0 | ⋯ | ⋯ | ⋯ |
| *Intermittent* | | | | | |
| She & Leveque (SL) | 3 | 2/3 | 2 | Fluid vortices | Vortex filaments |
| Politano & Pouquet (PP) | 4 | 1/2 | 1 | Alfvén wave packets | Current sheets |
| Müller & Biskamp (MB) | 3 | 2/3 | 1 | Fluid vortices | Current sheets |

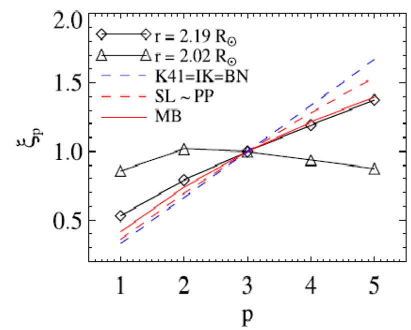
# Structure function analysis of reconnection-driven turbulence in the simulated coronal hole jet

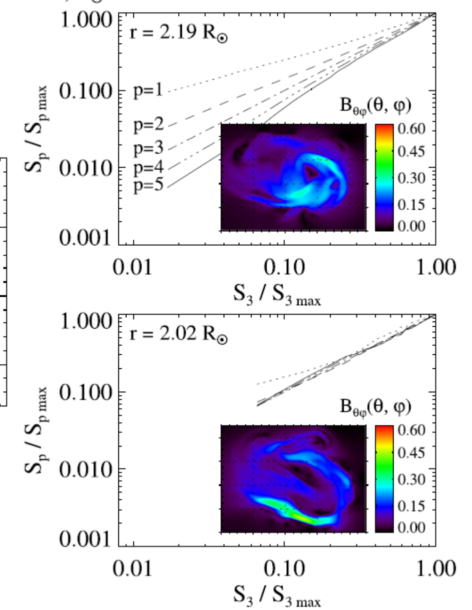



Structure functions (SFs) of transverse V and B field fluctuations at t=3650 s, below (top) and above (bottom) the altitude $r = 2R_S$. The insets show SFs compensated using extended self-similarity (ESS).

$$\delta\xi \equiv \langle (\xi_p - \xi_p^{\rm th})^2 \rangle_p^{1/2}$$

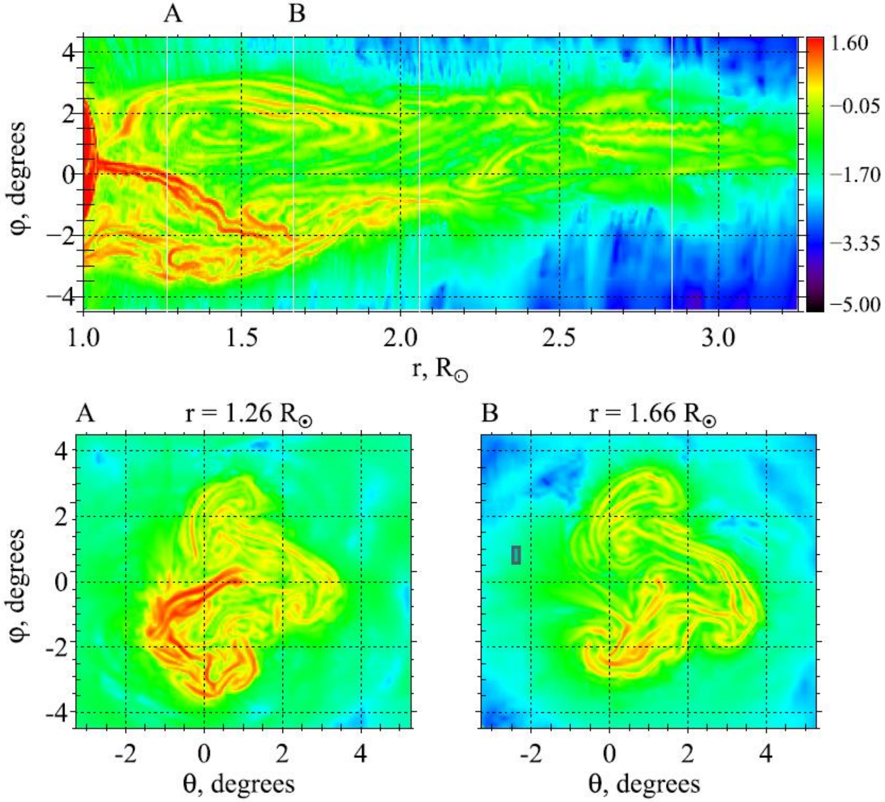


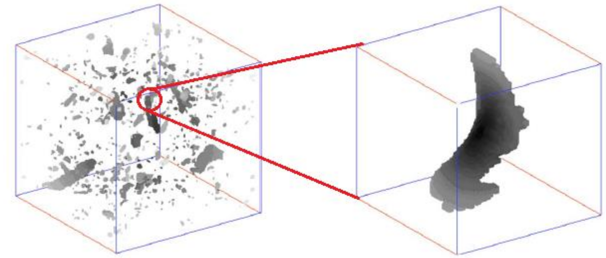



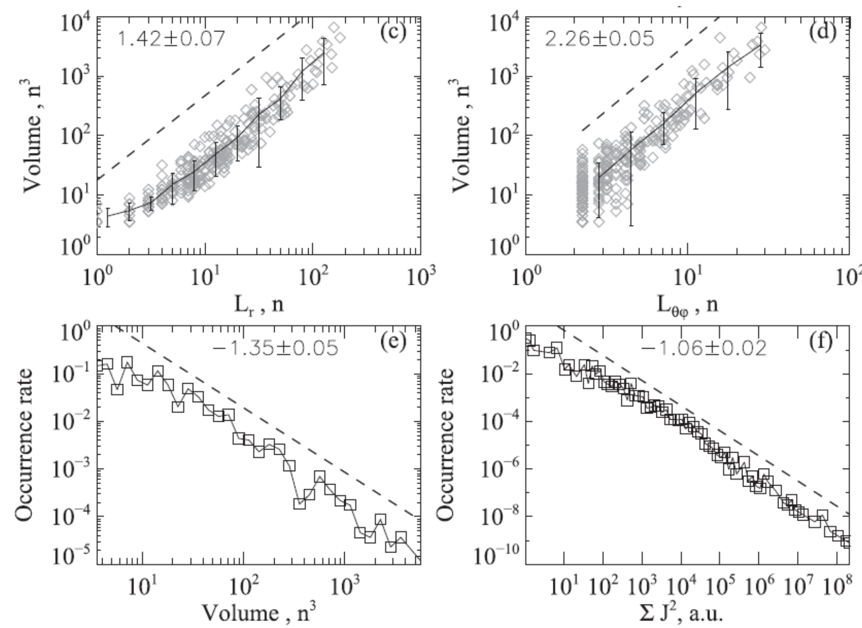

Radial dependence of ESS SF exponents of transverse B-field fluctuations, showing that the discrepancies with theoretical models are caused by intermittent current structures

# Turbulence-driven intermittent current sheets



Detection of intermittent structures in turbulent flows (Uritsky et al., PRE 2010)



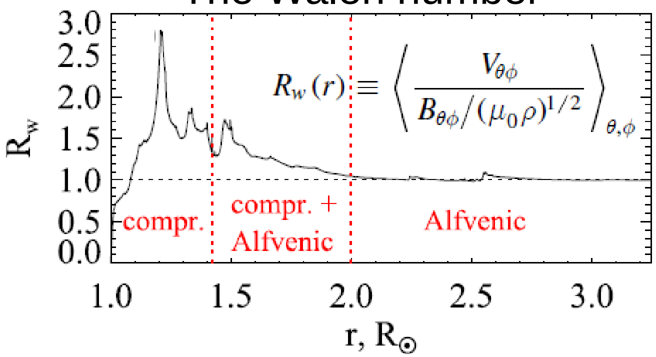

Constant-latitude (top) and constant-radius (A and B, bottom) cross-sections of the logarithmic current density magnitude, revealing multiple current sheets of various sizes and complex shapes

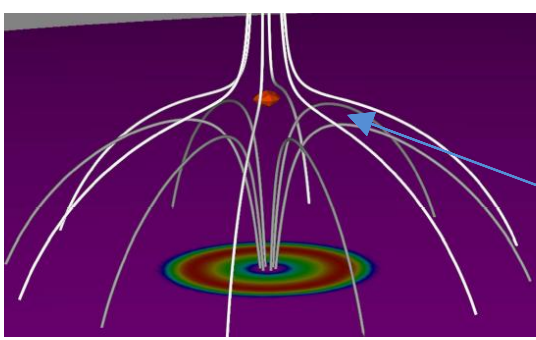
Statistics of turbulent current sheets inside the simulated jet, revealing their multiscale anisotropic morphology

# Complex morphology of turbulent structures in the reconnection-driven coronal-hole jet

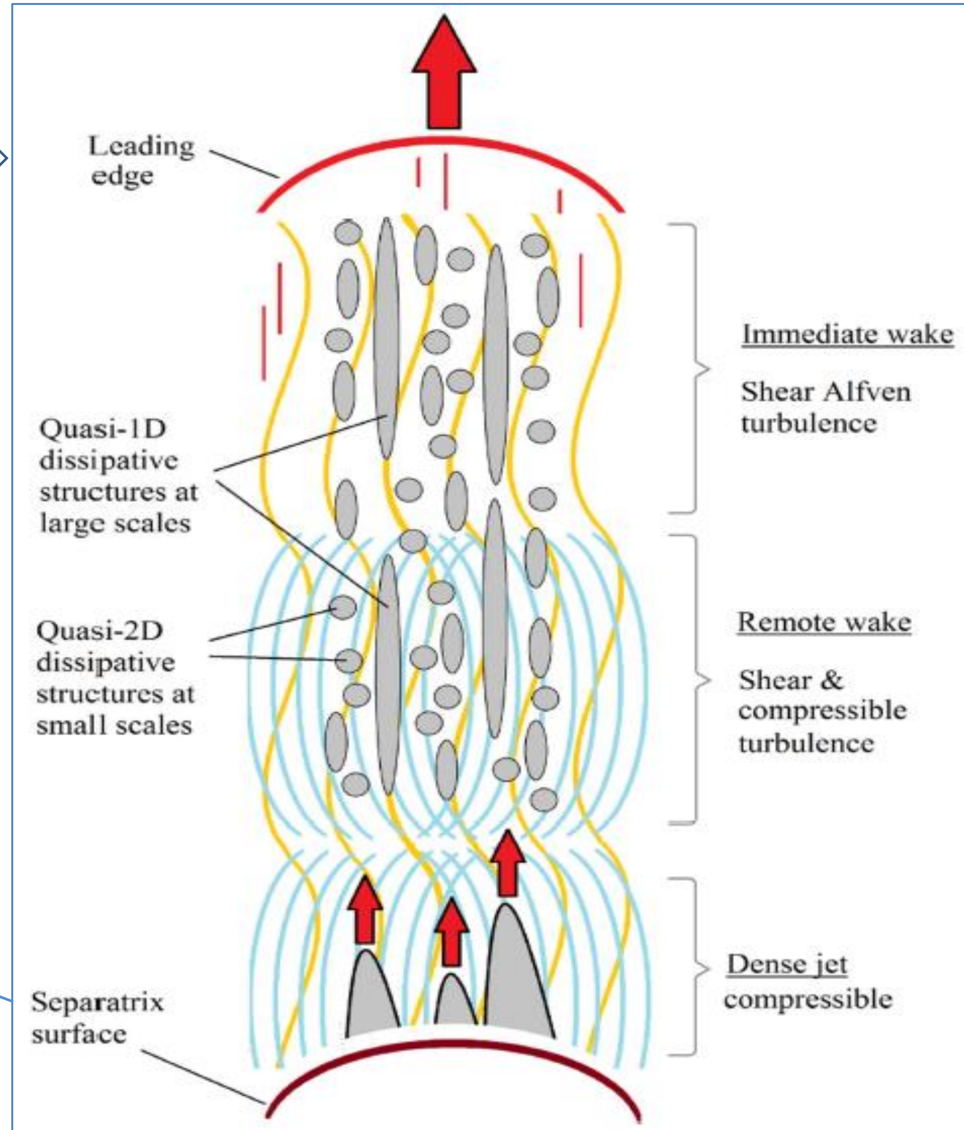
Internal structure of the jet according to our analysis. Alfvénic and compressible regions are marked with yellow and blue curves

The Walén number



The jet-producing region at t=0 s



# Comparison with Ulysses observations

- Ulysses measurements above 30 degrees latitude: strong statistical correlations between the transverse components of B and V fields characteristic of Alfvénic turbulence (Goldstein et al. 1995; Smith et al. 1995).

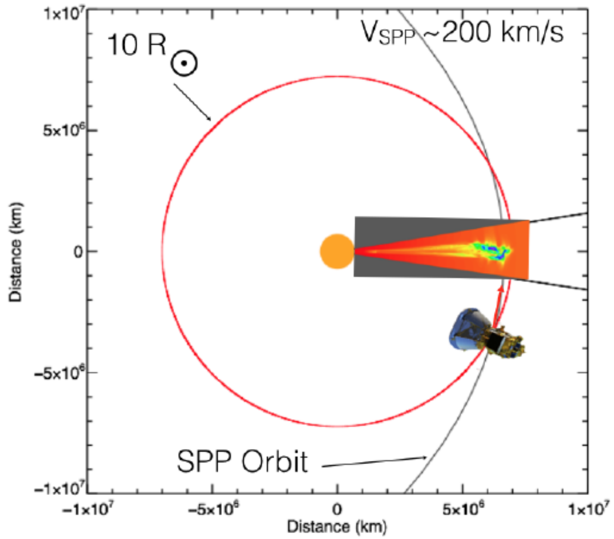
- The spectral index of B-field variations in the fast wind is close to 5/3 at frequencies above ~$10^{-3}$ Hz (Horbury et al. 1995, 1996). Within statistical uncertainty, this estimate is indistinguishable from the spectral index predicted by the MB model and the index of magnetic fluctuations in the flows in the immediate wake of our jet.

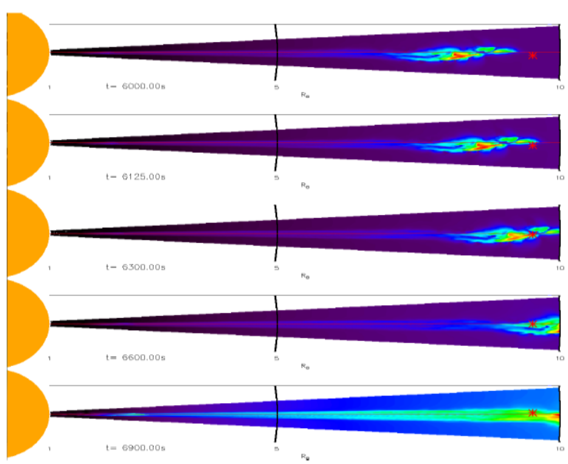
- For a nominal flow speed on the order of 700 km/s and the lowest frequency ~$10^{-3}$ Hz, the radial scales of the MHD turbulence in the polar wind are typically below $7 \times 10^5$ km. The largest radial scale of jet fluctuations is on the order of $10^5$ km, which agrees with polar wind measurements.

- Higher-order structure-function analysis of magnetic field fluctuations above the Sun's polar coronal holes (Nicol et al. 2008) supports the MB scenario in the fast wind, consistent with our results.

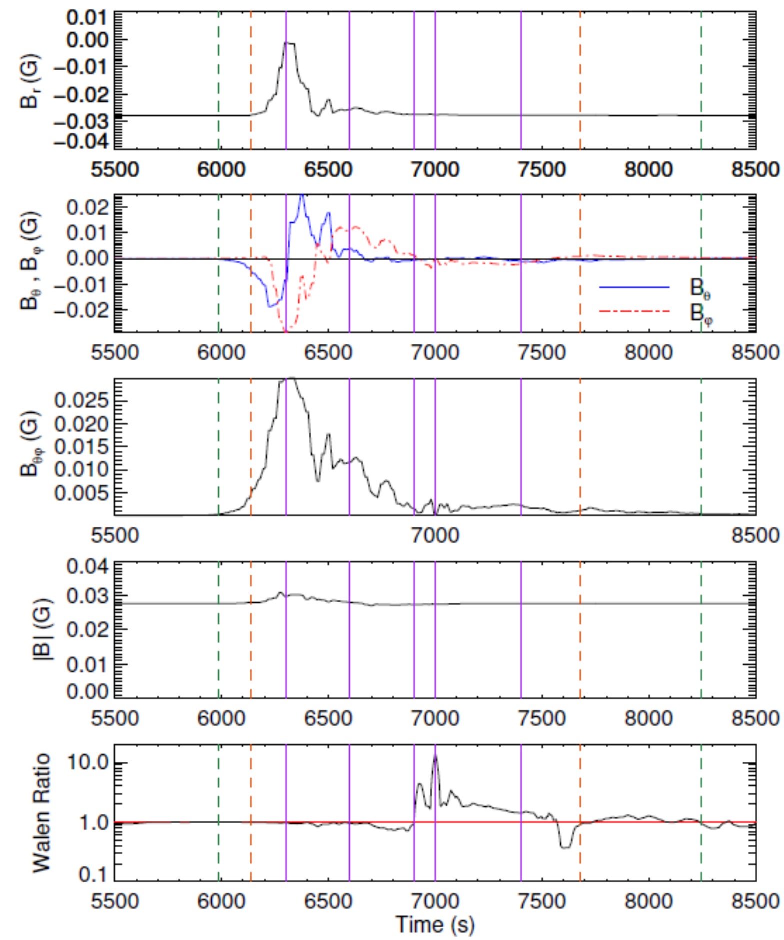
Solar Probe Plus will be instrumental in further understanding the coronal hole jet structure & dynamics

# **Simulated SPP fly-throughs** (M. Roberts et al., in prep.)



Velocity field of the progressing jet to be observed by the SPP (red asterisk)




Magnetic field fluctuations recorded by a virtual SPP flying through the immediate wake region of the simulated coronal-hole jet

# Conclusions

- We found 3D, reconnection-driven, Alfvenic turbulence in the Karpen et al. (2017) coronal-hole jet simulation. Spatial correlations of magnetic fluctuations agree with the Muller-Biskamp scaling model (intermittent current sheets coupled via hydrodynamic turbulent cascade).

- Observations suggest that the fast wind turbulence is dominated by the same type of energy cascade as that found in our coronal-hole jet simulation.

- The cumulative effect of many such events may generate long-lived formations at the Sun such as coronal plumes, and could strongly influence magnetic and velocity fluctuations further out in the heliosphere.

- The upcoming Solar Probe Plus (and Solar Orbiter) missions are expected to yield critical insights into the physics of the jet turbulence and its relevance to the solar wind.

- Indicative single-spacecraft turbulence tests that could be conducted by these missions include: (1) time-domain structure functions, (2) Walén ratio test, (3) velocity - magnetic field orientation analysis, (4) compressibility analysis.