Synergies between astrophysical, space, laboratory, and fusion plasma physics: Turbulence and Kinetic Processes

1) What are your research interests in the area of turbulence and kinetic processes?
2) Where do you see synergies between your research and the other plasma-physics communities?

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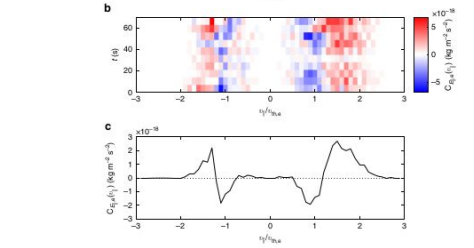
Field Particle Correlations (FPC)

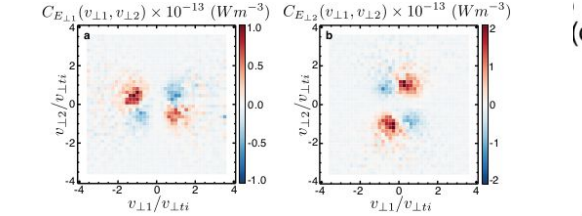
What "Heats" Plasmas?

We manipulate the Vlasov Equation to extract the term responsible for energy transfer between fields & the VDF:

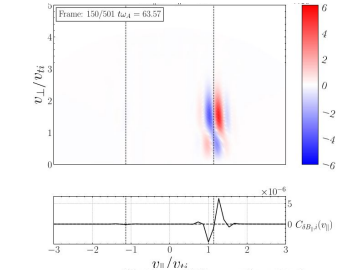
$$\frac{\partial f_s}{\partial t} + \mathbf{v}\cdot\nabla f_s + \frac{q_s}{m_s}\left[\mathbf{E} + \frac{\mathbf{v}\times\mathbf{B}}{c}\right]\cdot\frac{\partial f_s}{\partial \mathbf{v}} = \left(\frac{\partial f_s}{\partial t}\right)_{\text{coll}} \longrightarrow C_{E_j}(\mathbf{v}) = \int_{t-\tau/2}^{t+\tau/2} dt' \frac{q_s v_j^2}{2} E_j \frac{\partial f_s(\mathbf{v})}{\partial v_j}$$



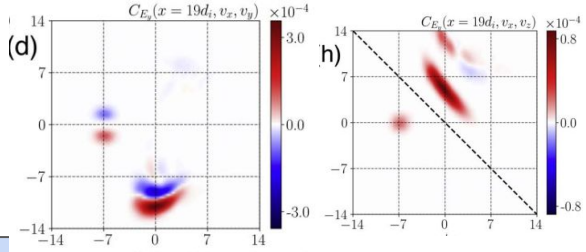
Chen et al 2019 NatCom (LD, MMS)



Afshari et al 2024 NatCom (CD, MMS)



Huang et al 2024 JPP (TTD)



Juno et al 2024 (Shocks)

The velocity space structure of the FPC is a signature of the kind of energy transfer. This enables the identification of specific *dissipation* mechanisms, even in strongly turbulent systems.

The eventual goal is to build a 'Rosetta Stone' of known signatures, enabling identification in complex systems, and potentially parameterization of when specific mechanisms dominate.

FPC Applications

To avoid the cost of nonlinear simulations, we have implemented in PLUME a calculation of δf and **E** for a linear eigenmode, enabling the *quasilinear* calculation of C_E (Brown et al PoP, in revisions)

Synergies: If you have a model or measurement of E and f(v), we can diagnose what mechanism transfers energy between fields and charged particles.

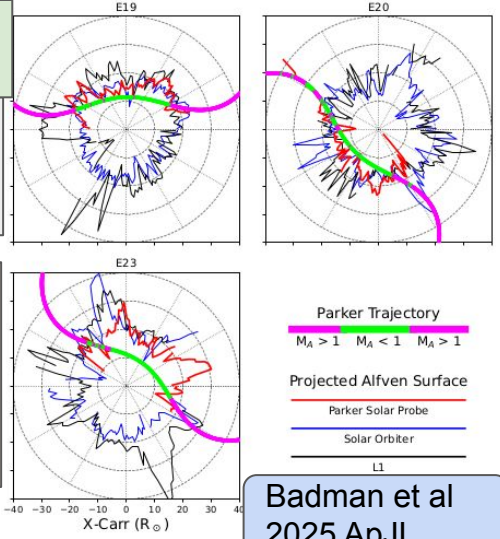
Parker Solar Probe (PSP)

How is the Solar Wind Accelerated and Heated?

Launched in 2018, PSP has measured the near-Sun solar wind, reaching 9.86 R_S, sampling below the Alfven surface (V_A=V_{SW}) and observing the in situ acceleration of the solar wind. (Rivera et al 2024, Halekas et al 2024, review in Raoufi et al 2023),

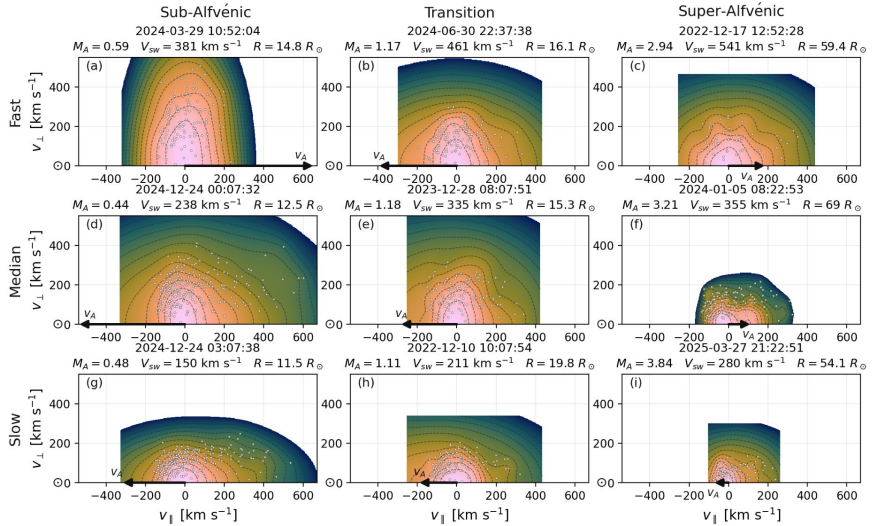
The ion and electron VDFs are far from local thermodynamic equilibrium. They exhibit anisotropies, secondary populations, and non-maxwellian features, varying with Vsw, radial distance, and plasma conditions. What drives these features and what role they play in solar wind's evolution are open questions.

The transition from low to high β, high to low cross helicity, and sub to super Alfvenic; these transitions impact the system's turbulence and heating.

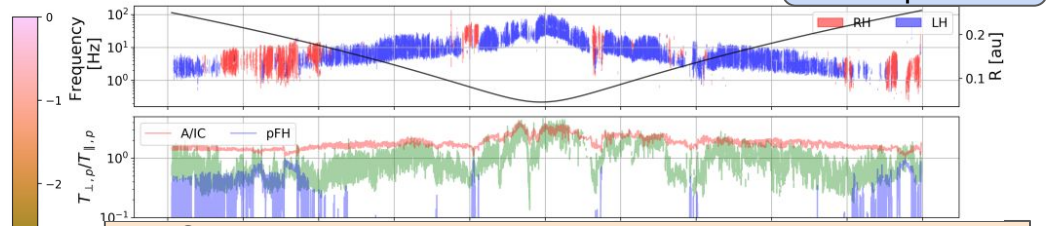


Badman et al 2025 ApJL

Klein 2027 ARAA (in prep)



Niranjana et al 2026 ApJS



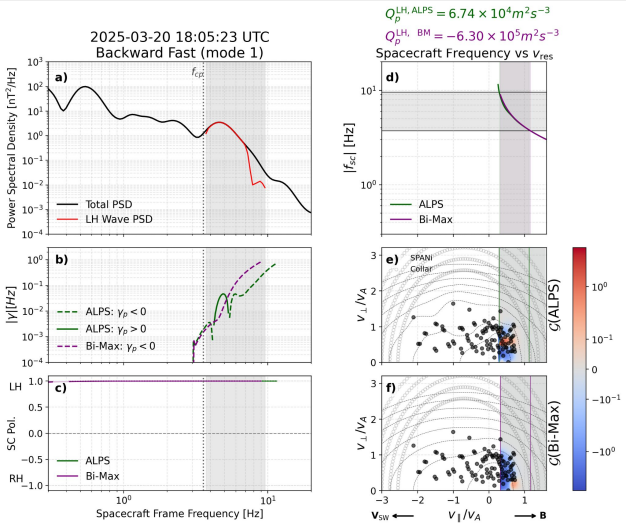
Ion-Scale Waves are abundant, (https://zenodo.org/records/17539353) and play a role in the system's thermodynamics (e.g. helicity barrier, cyclotron breaking)

Synergies: PSP Observations serve as a well diagnosed model for magnetic dominated plasmas, as well as systems transitioning regimes.

ALPS

How Do Non-Maxwellian VDF Impact Plasma Response?

The Arbitrary Linear Plasma Solver is a parallelised numerical code that solves the Vlasov-Maxwell dispersion relation in hot (even relativistic) magnetised plasma. ALPS allows for any number of particle species with arbitrary gyrotropic velocity distribution functions (VDF) supporting waves with any direction of propagation with respect to the background magnetic field.



ALPS can be applied to observations or simulations of collision poor plasmas, determining the change in growth or damping rates of normal modes, as well as the specific velocity structure responsible for the change.

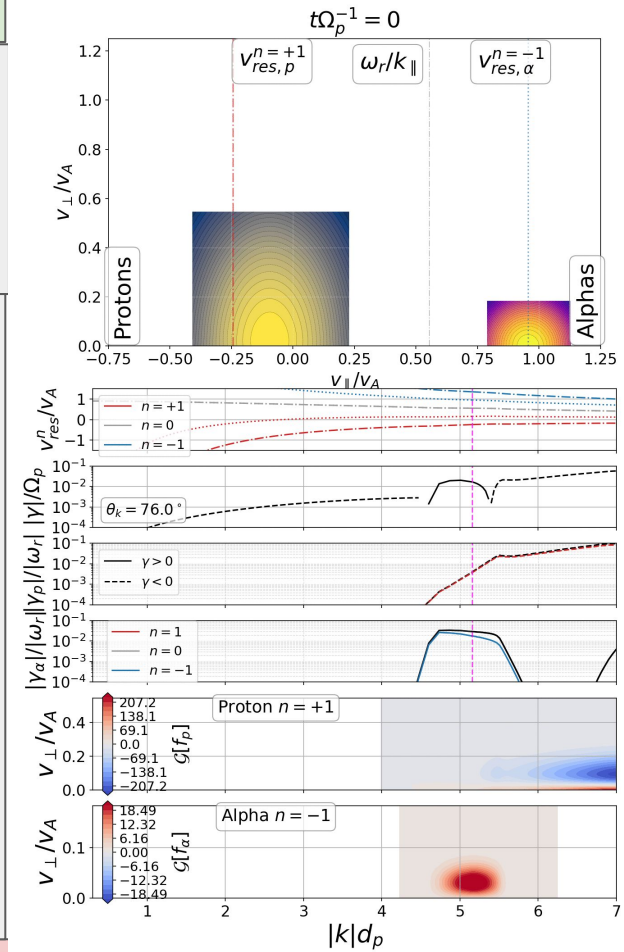
The wave equation is solved by numerically integrating the velocity gradients of f(v), and then identifying the frequencies ω(k) that satisfy the dispersion relation. ALPS also determines the power absorbed or emitted by each component and the eigenfluctuations of density, velocity, and E and B.

ALPS github

Klein et al 2026 in prep (PSP)

Code details in Verscharen et al 2018, JPP, Klein and Verscharen 2024 PoP

Martinovic et al 2026 PRL (accepted)

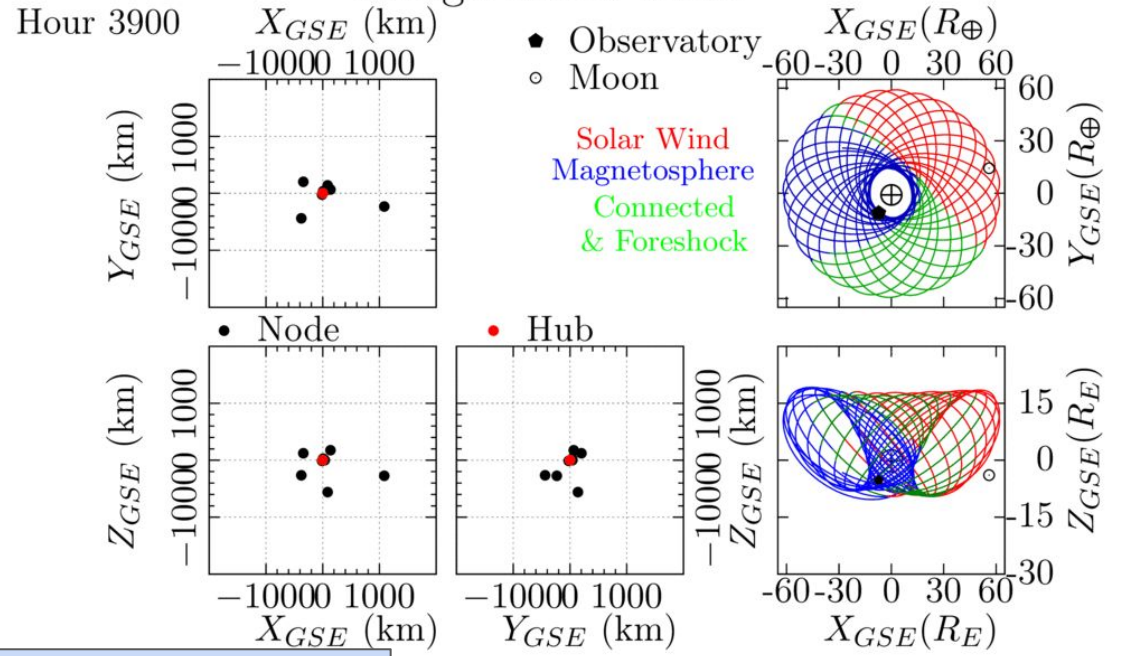


Synergies: With measurements or models of f(v), ALPS characterizes the system's stability, and changes to the supported eigenmodes.

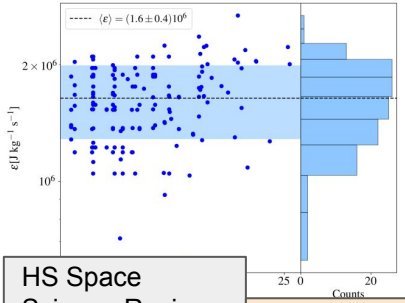
HelioSwarm

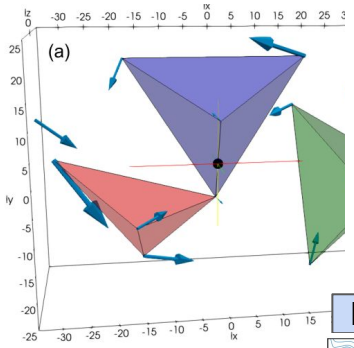
What is the Multi Scale Nature of Turbulence?

HS is a 9-S/C **Multi Scale Observatory** set to launch in 2030. Trajectories are designed to simulataneously sample MHD and ion scales in the pristine solar wind, foreshock, and magnetosphere, with geometries shaped to enable accurate application of multipoint analysis techniques.



Pecora al 2023 PRL

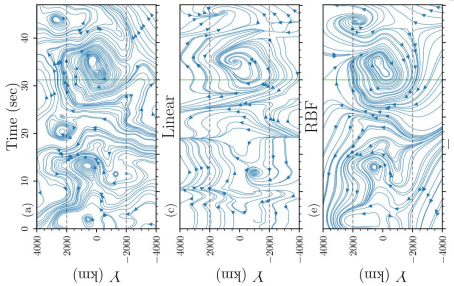


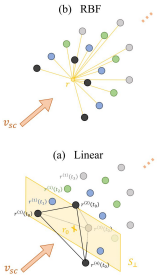


HS Space Science Review (Klein et al 2023)

In preparation for this mission, we are extending methods developed for 4 S/C (e.g. Cluster and MMS) to 9.

Broeren et al 2024 EASS





Synergies: Looking to develop or improve methods for reconstructing spatial and spectral distributions of power given sparse spatial measurement resolution.