Solar wind proton and α particle velocity distributions, temperature anisotropies, and heating models guided by Parker Solar Probe perihelia data

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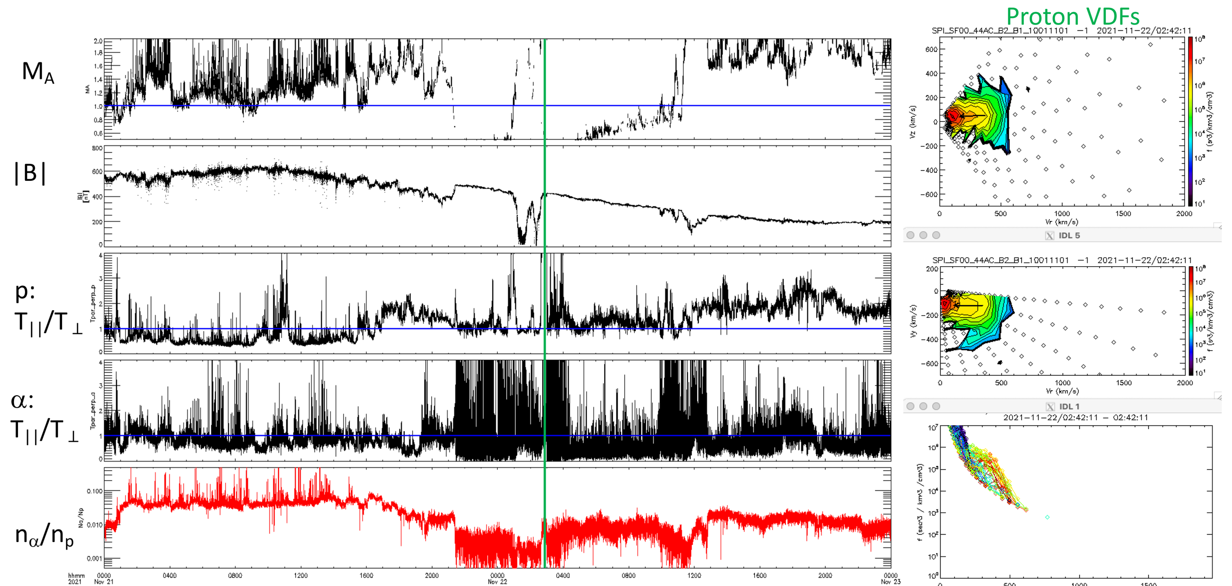
Abstract

We analyze the PSP/SPAN-I data of the proton VDFs with beams during perihelia encounters, as well as plasma moments such as density, anisotropic temperature, and alpha particle data. The FIELDS instrument provides the corresponding kinetic wave activity magnitude, spectra and polarizations that helps identify the dominant kinetic wave modes. Guided by the observations, we use 2.5D and 3D hybrid-particle-in-cell (hybrid-PIC) models of kinetic protons and alpha particles with background electron fluid in an expanding box model to study the kinetic instabilities driven by unstable VDFs such as super-Alfvénic beams and ion relative drifts in the inner solar wind. The model studies the super-Alfvénic as well as sub-Alfvénic solar wind properties. The proton and α particle populations physical properties, such as the drift speeds, anisotropic temperatures, magnetic energy and spectra are modeled and compared to observed PSP solar wind data near perihelia. We find the ion kinetic instabilities associated with the plasma properties and investigate in the conversions between the kinetic energy from ion instabilities to magnetic and thermal energies in the solar wind plasma. In particular, the quantification of the partition the couplings between α particle and proton populations through wave-particle interactions provide insights into the heating and acceleration of the solar wind plasma. We will investigate Artificial Intelligence Machine Learning (AI/ML) data analysis methods for the classification of VDFs produced by the hybrid model with the goal of applying the methods to PSP data.

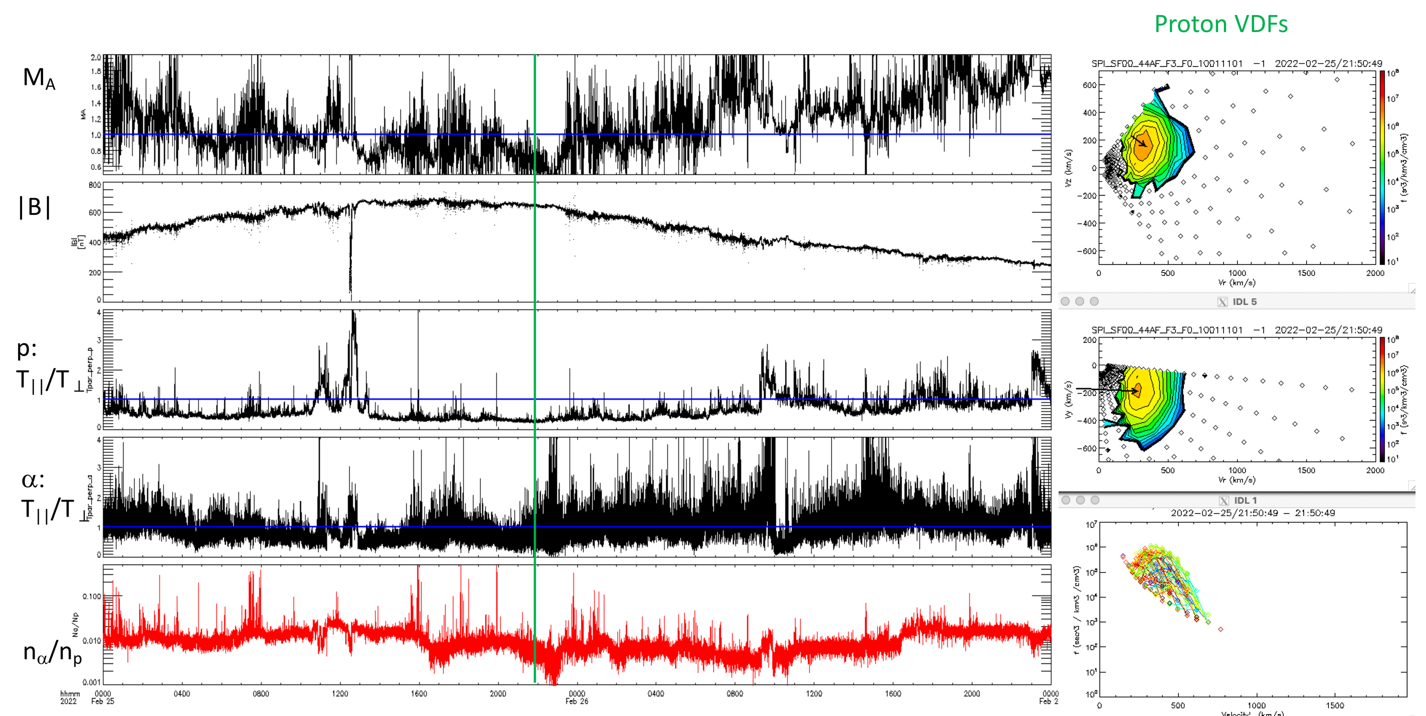
Background and Motivation

- The PSP SPAN-I and FIELDS instruments provide details of the magnetic field, kinetic waves, ion temperature anisotropies, and ion velocity distribution functions (VDFs) at perihelia.
- The sub-Alfvénic region is the acceleration region of the solar wind (SW), believed to hold the key to the physical processes that heat and accelerate the plasma.
- Recently the PSP has crossed into sub-Alfvénic SW near perihelia, with apparently different plasma properties than the previously observed SW.
- Motivated by recent PSP data at E10 and E11 we develop the first hybrid-kinetic models of the SW plasma ions in the sub-Alfvénic region.

PSP Data of sub-Alfvénic solar wind near E10



PSP Data of sub-Alfvénic solar wind near E11



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Hybrid Model

Parallel 3D hybrid model (Ofman 2019): an extension of the 2.5D parallel hybrid model (Ofman & Viñas 2007, Ofman et al. 2014, 2017, 2022).

Proton and other ion equations of motion are solved using Particle-in-Cell (PIC):

$$\frac{d\vec{x}_k}{dt} = \vec{v}_k$$

$$m_k \frac{d\vec{v}_k}{dt} = Ze\left(\vec{E} + \frac{\vec{v}_k \times \vec{B}}{c}\right)$$

- Supplemented with Maxwell's equations:

$$\nabla \times \vec{B} = \frac{4\pi}{c}\vec{J}, \quad \nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}$$

Electrons as fluid: the electron momentum equation (neglecting electron inertia) is

$$\frac{\partial}{\partial t} n_e m_e v_e = 0 = -en_e\left(\vec{E} + \frac{\vec{v}_e \times \vec{B}}{c}\right) - \nabla p_e,$$

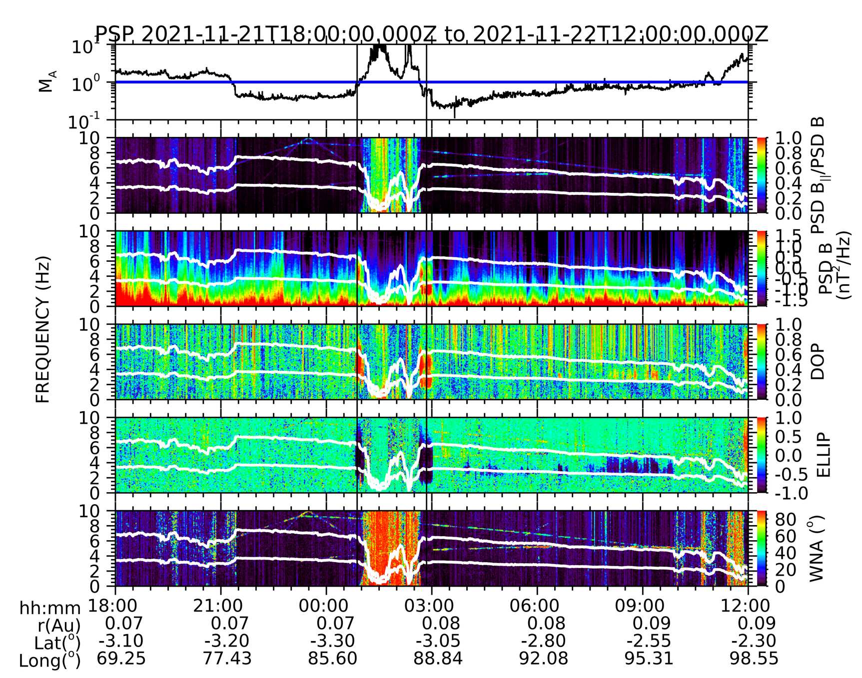
where $p_e = n_e T_e$ and quasi-neutrality: $n_e = n_p + Zn_i$.

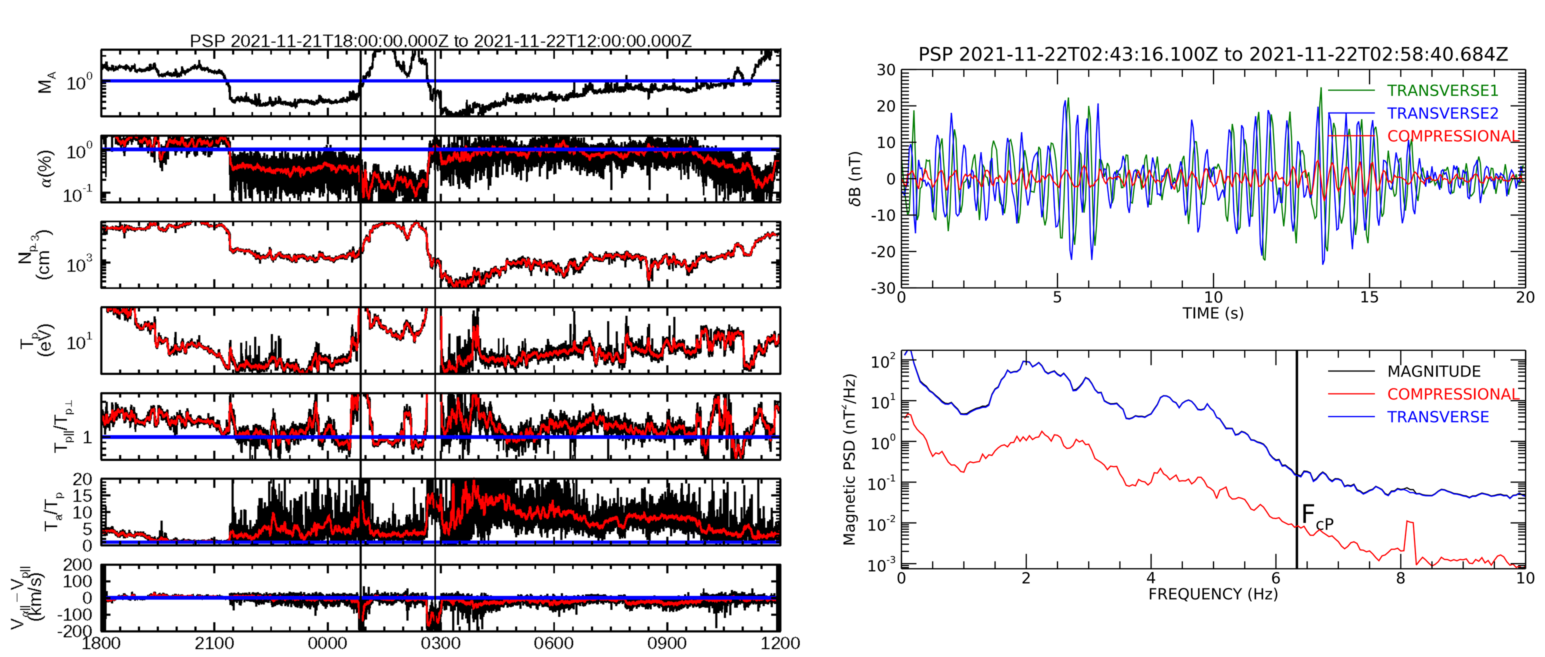
Periodic boundary conditions (reflecting for shocks).

Typical 3D hybrid numerical parameters:
128^3 up to 256^3 cells
64 ppc => ~1.3×10^8 – 10^9 particles
1024 Processors (MPI parallel)

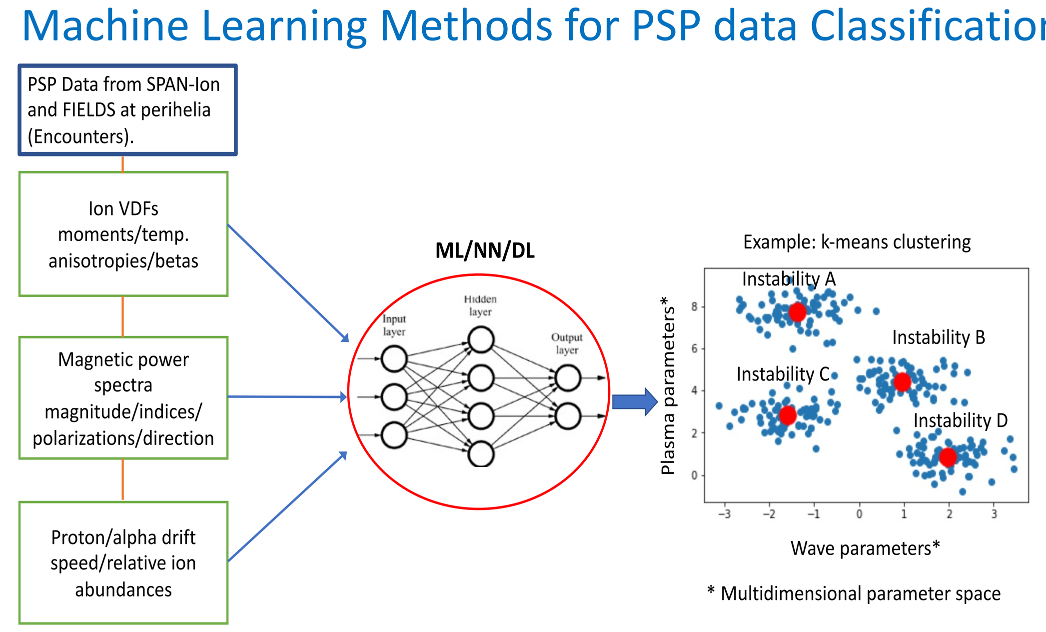
Expanding Box Model (EBM)

Analysis of kinetic wave activity (E10)



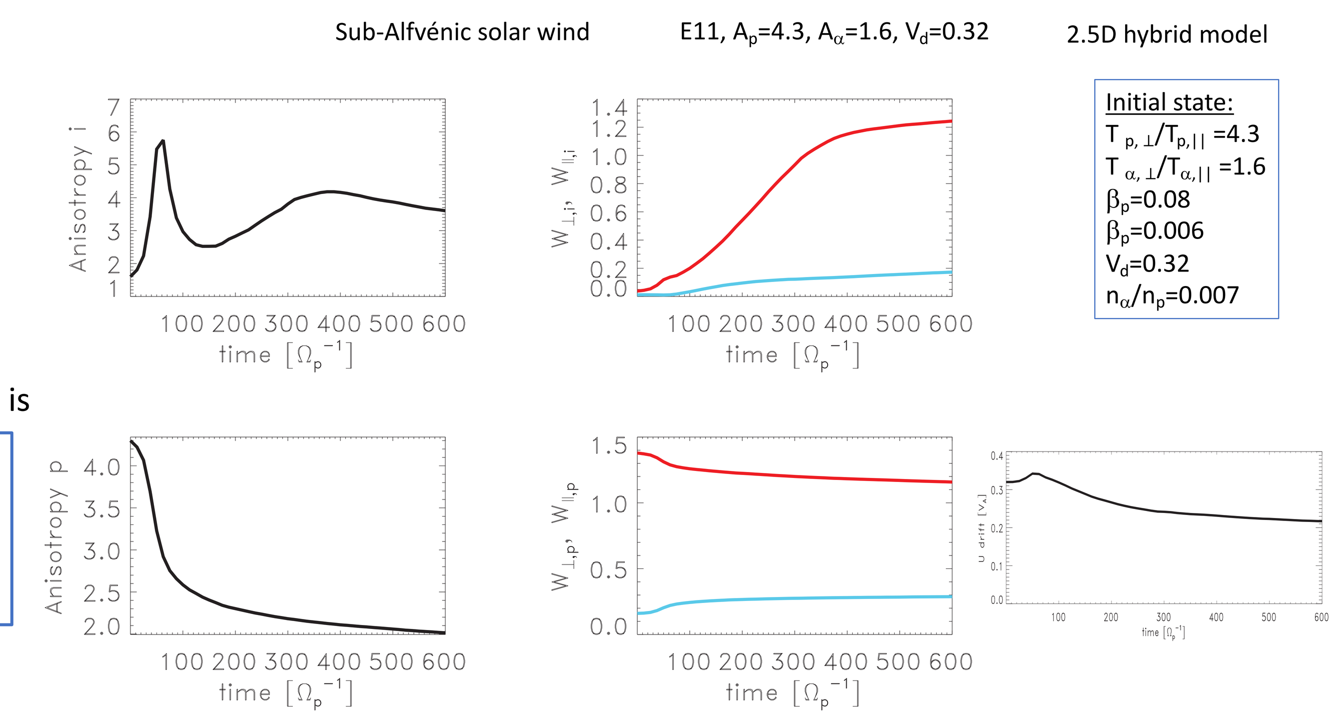


Machine Learning Methods for PSP data Classification

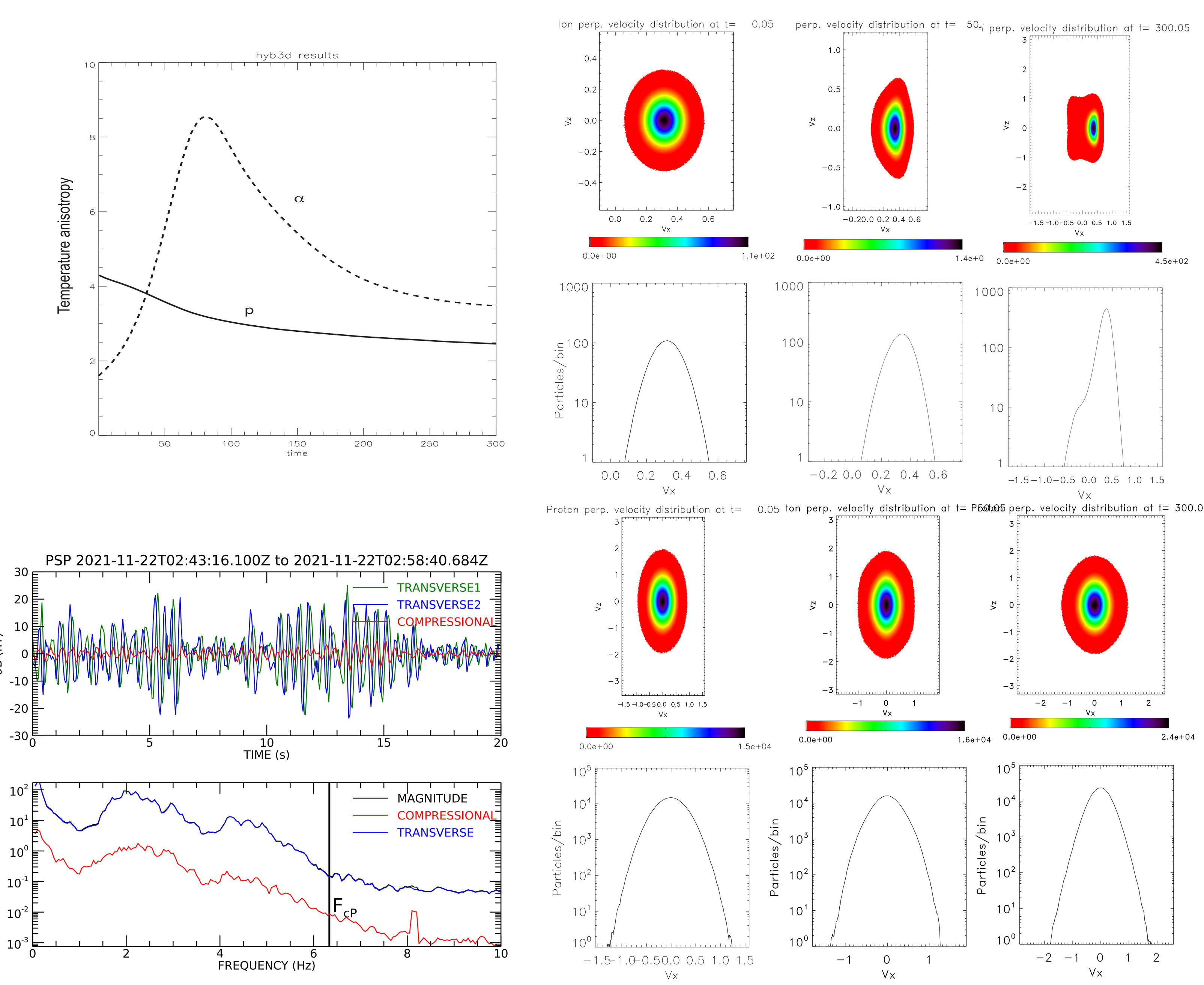


The conceptual flow-chart of the application of Machine Learning methods using Neural Networks (NN) and Deep Learning (DL) of the classification of instability conditions associated with the proton and α particle populations VDFs obtained from PSP SPAN-I during the perihelia (encounters), together with the kinetic wave activity from FIELDS instrument, relative ion drifts, and α to proton relative abundances. The output is the k-means clustering classifications of the various instabilities such as ion-cyclotron, mirror, firehose, magnetosonic ion drift, represented by letters A-D.

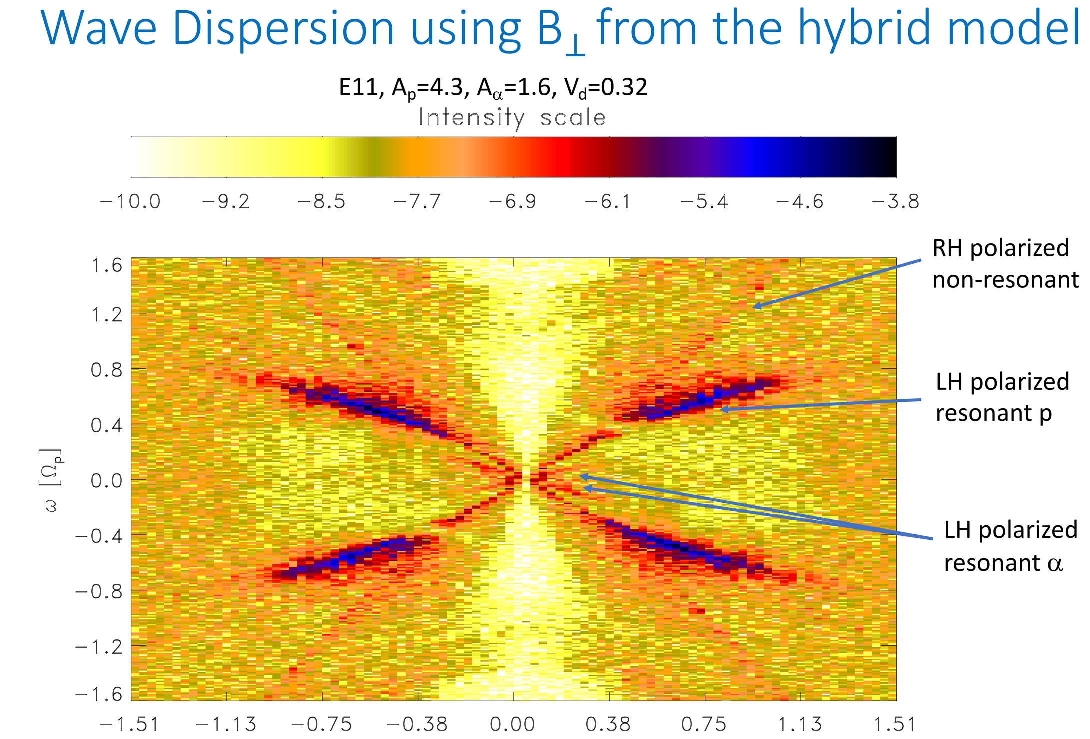
Temporal Evolution of T anisotropies, energies, and p-α drift



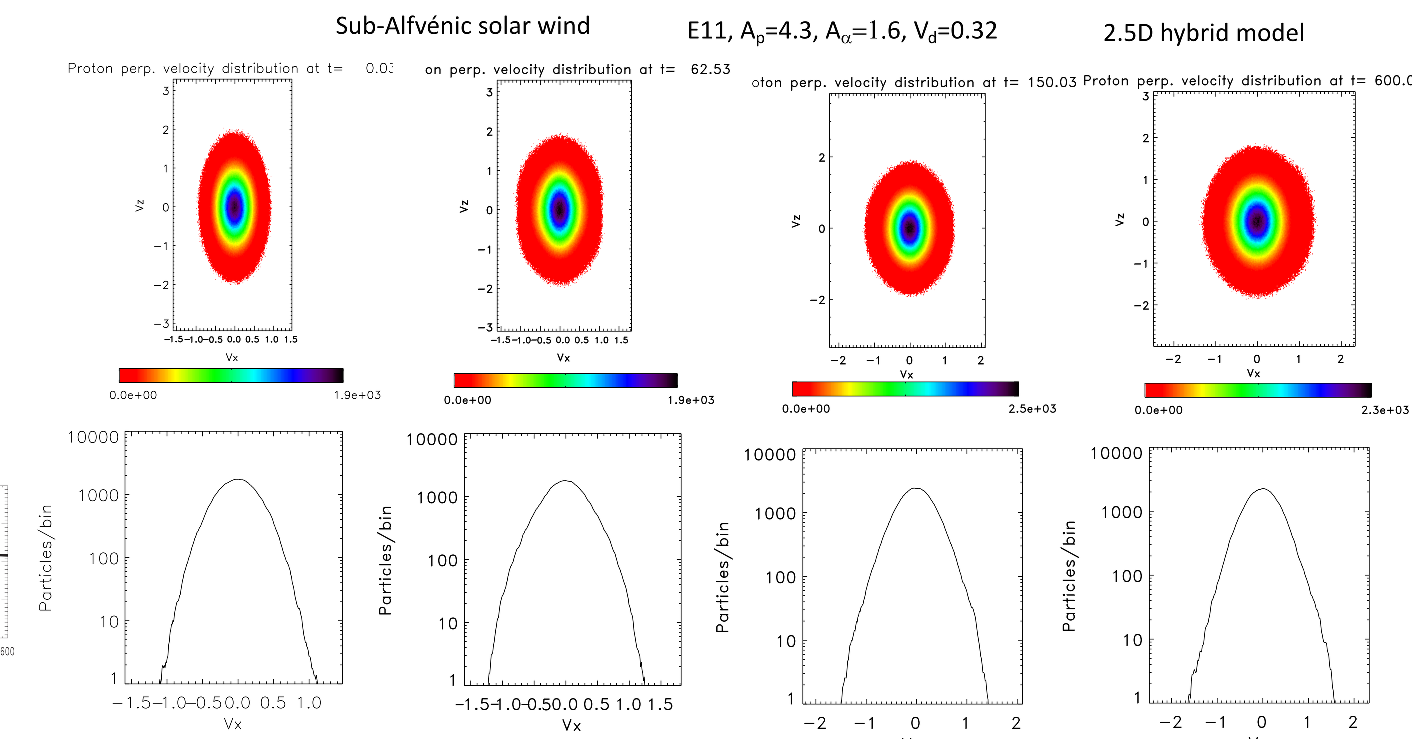
3D Hybrid Modeling Results: T anisotropies α and p VDFs



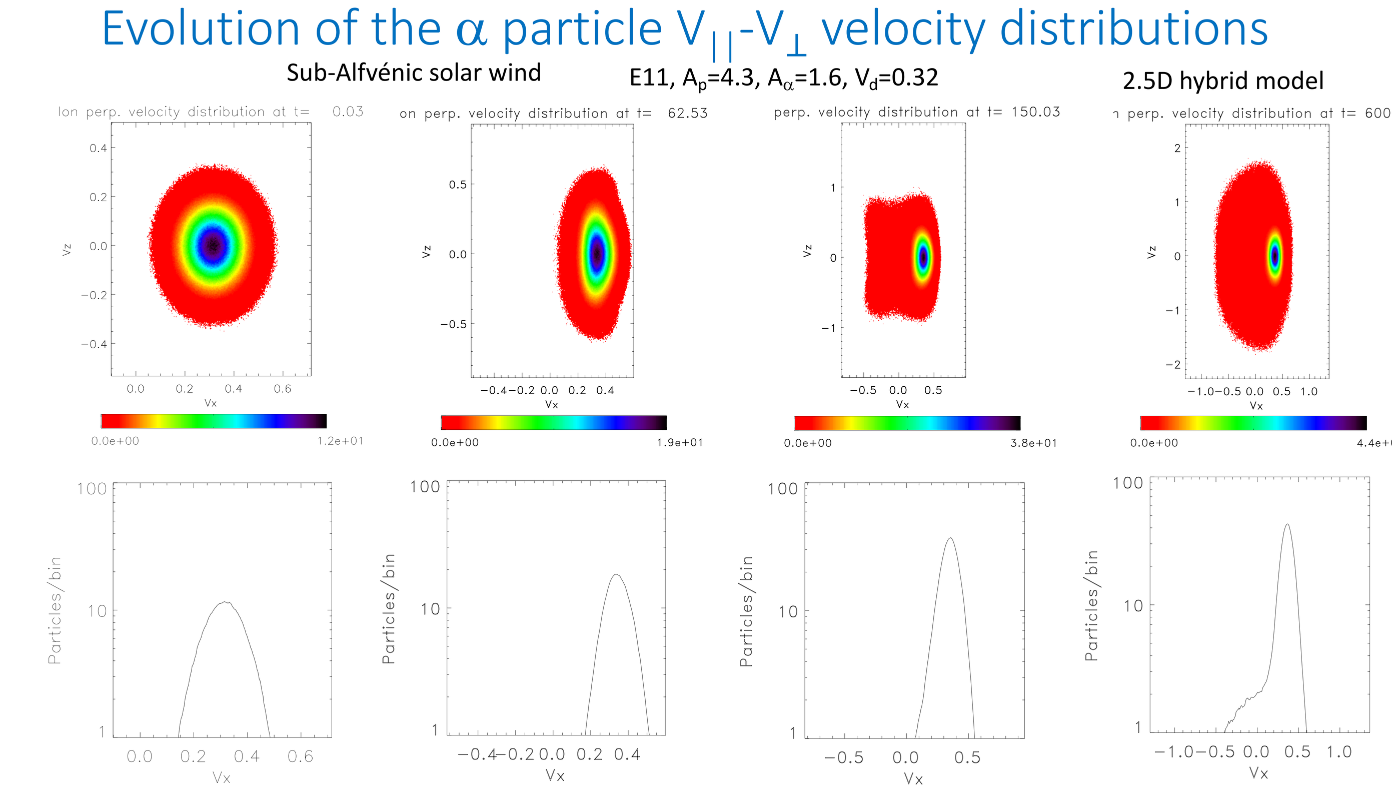
Wave Dispersion using $B_\perp$ from the hybrid model



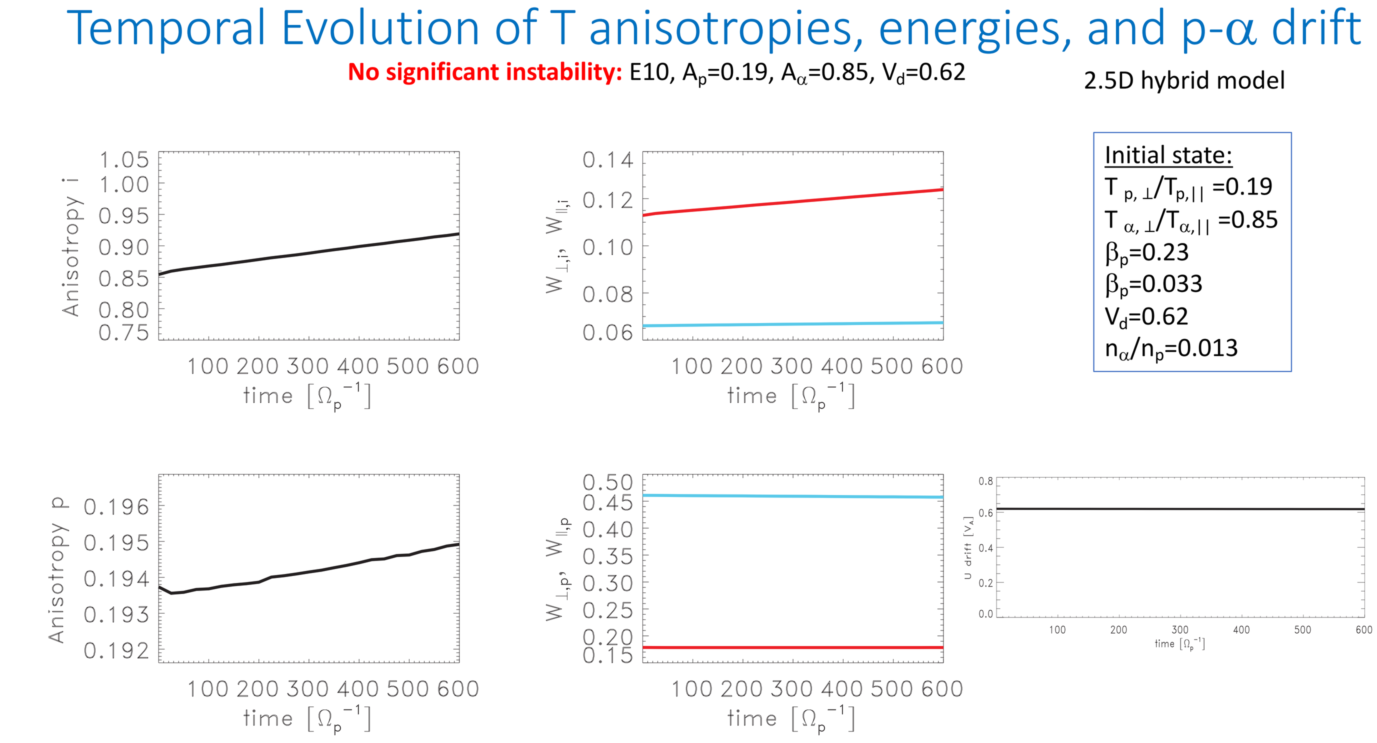
Evolution of the proton $V_{||}$-$V_\perp$ velocity distributions



Evolution of the α particle $V_{||}$-$V_\perp$ velocity distributions



Temporal Evolution of T anisotropies, energies, and p-α drift



Summary and Conclusions

- We show several examples of sub-Alfvenic solar wind PSP data SPAN-I and FIELDS at E10 with moments, proton VDFs and wave analysis.
- Motivated by the PSP observations at E10 and E11 of ion VDFs and kinetic waves we model proton and α particle populations and study kinetic instabilities with the associated ion-scale wave spectra using 2.5D and 3D hybrid models.
- When protons and α particles are anisotropic in low-β plasma the ion-cyclotron instability is produced resulting in perpendicular α particle heating with subsequent relaxation of the temperature anisotropy.
- The models show the evolution of the ion temperature anisotropies, kinetic and magnetic energies, and the various forms of VDFs of protons and α particles.
- We demonstrate the wave dispersion spectra modeled in the SW plasma produced by the ion-cyclotron instability in qualitative agreement with linear dispersion branches.
- We extend 2.5D hybrid modeling studies of proton and α beam instabilities and temperature anisotropies to more realistic full 3D hybrid model and find similar results.
- We plan to implement ML/AI methods for automated classification VDFs, and instabilities in PSP data.

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