Turbulence and ion heating downstream of the termination shock

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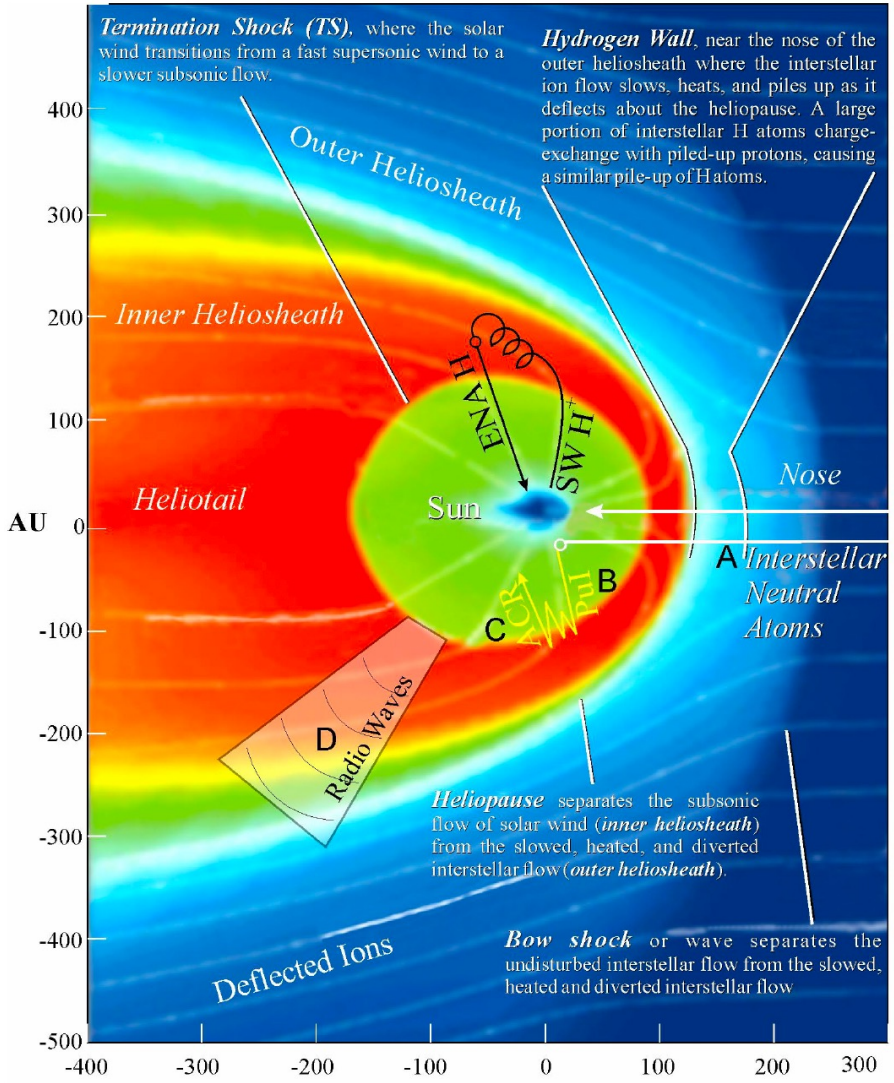
Energetic neutral atoms

ENAs are created by charge exchange between neutrals and

- Transmitted and heated solar wind ions through the termination shock (TS).
- Transmitted (including reflected and then transmitted) and heated pickup ions through TS.
- New pickup ions generated in the heliosheath.
- Sources in the interstellar medium.

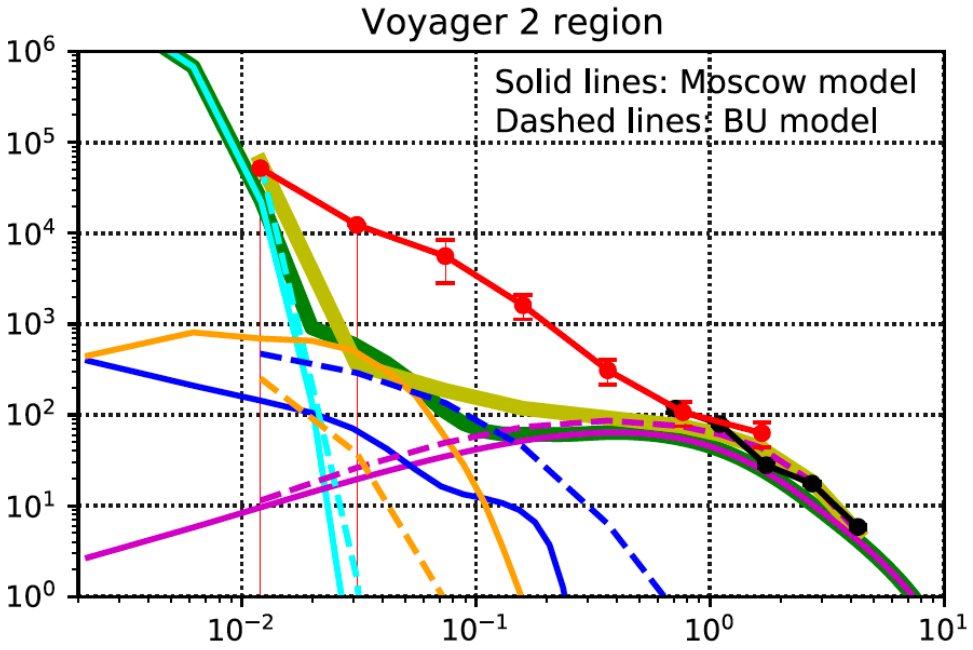
To contribute to observed ENA fluxes, the parent ion must have an inward velocity in the solar inertial frame.



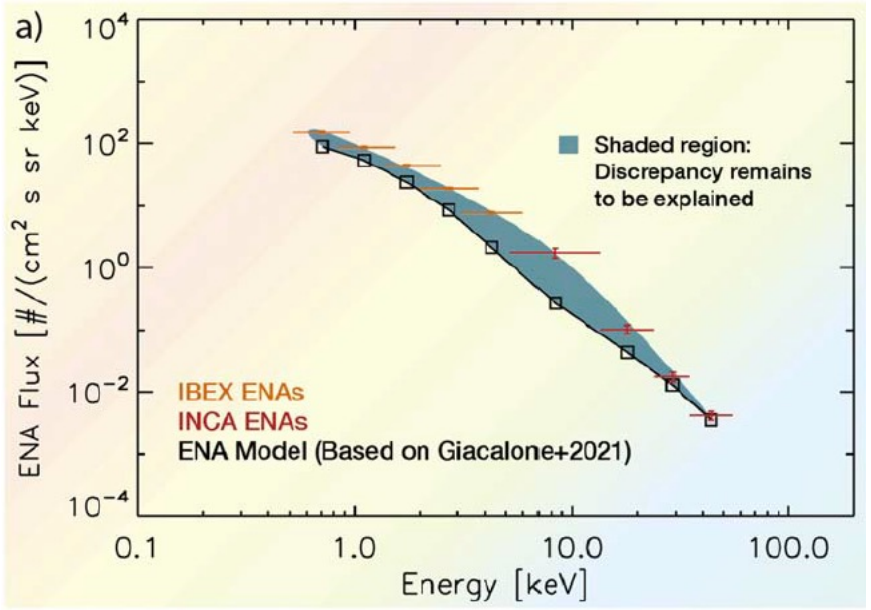
McComas et al. 2004

ENA observations and models

- Observations of energetic neutral atoms (ENAs) provide insights into the distribution of ions in the heliosheath.



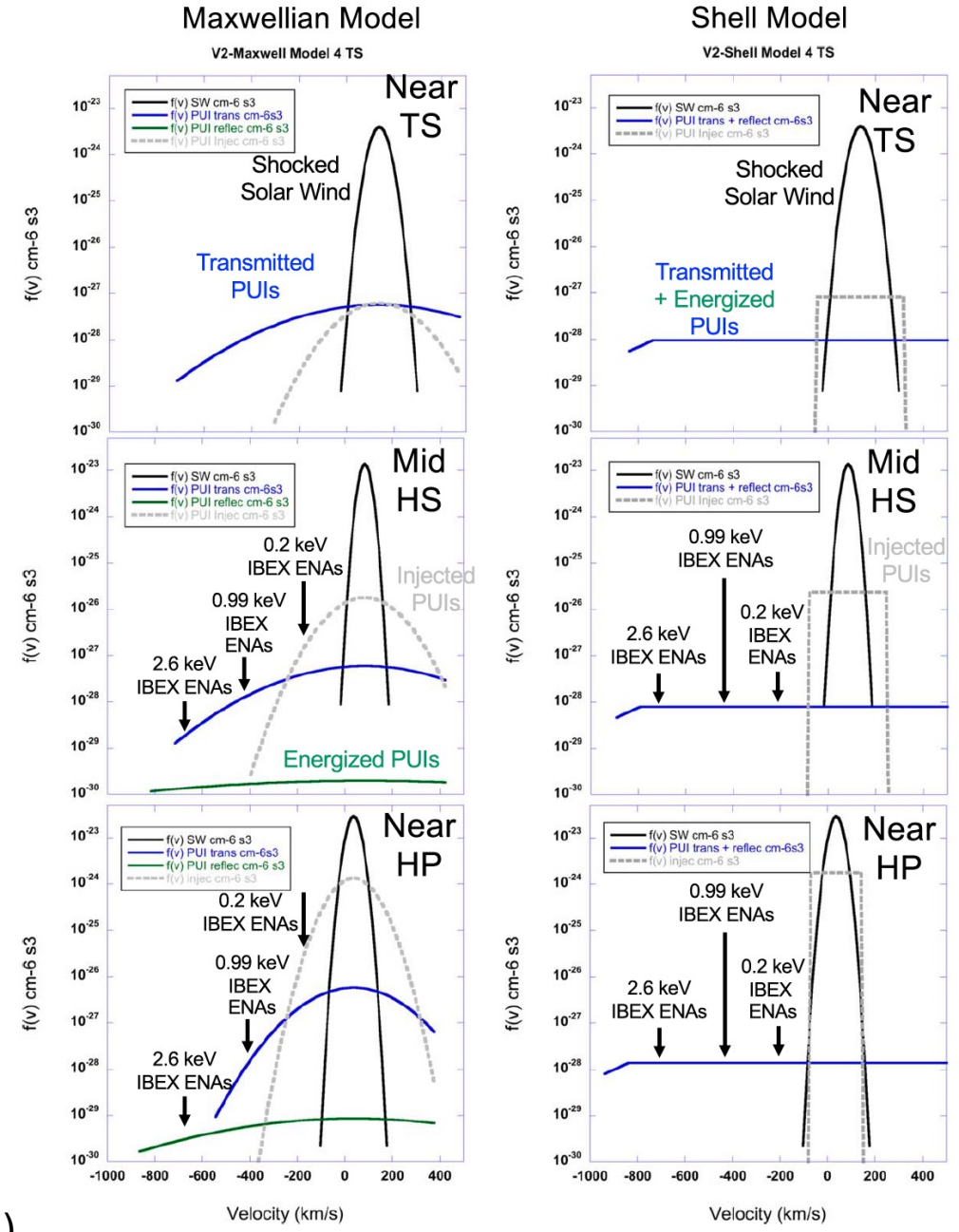
Galli et al. (2023)



Gkiolidou et al. (2022), see also Kornbleuth et al. (2023) for an updated version.

Low-energy (~100 eV) ENA

- Transmitted solar wind ions are generally too cold to contribute.
- In the Maxwellian model (strong energy diffusion), new PUIs are the main source for low-energy ENAs.
- In the shell model (weak energy diffusion), transmitted PUIs are the main source for low-energy ENAs.



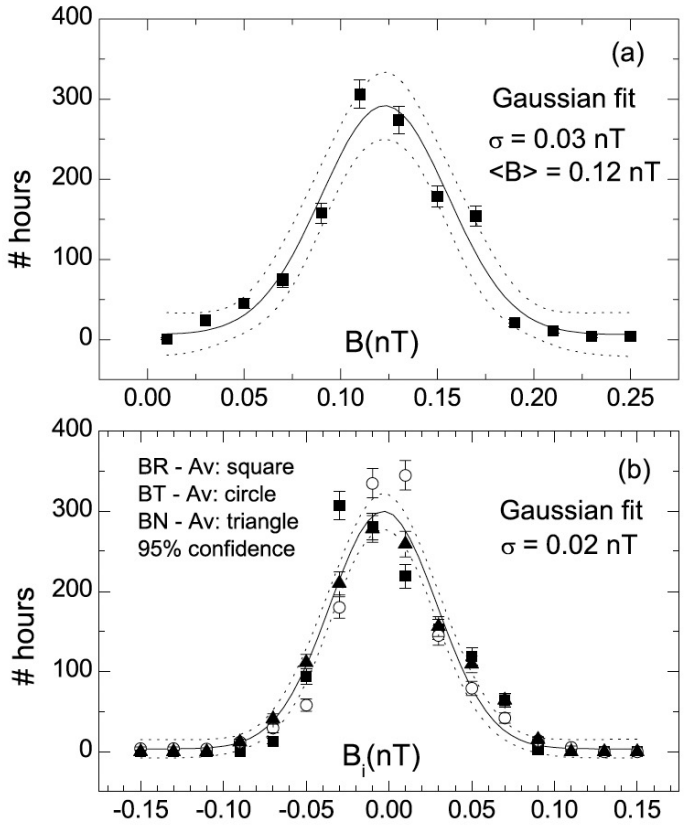
Fuselier et al. (2021)

Effects of turbulence

- Turbulence can cause heating of the ions as they are advected along streamlines across the heliosheath, which affects the sources of ENAs.
- Turbulence is also associated with velocity fluctuations that effectively broaden the ion velocity distribution function.
- Effects of turbulence is missing in most ENA models, but velocity diffusion was discussed with theoretical diffusion coefficients (Fahr et al., 2016; Zirnstein et al. 2018).

Turbulence in the heliosheath

- Magnetic turbulence was observed by Voyagers.
- Voyager observations characterize turbulence in the heliosheath as Kolmogorov-like (power spectrum $\sim f^{-5/3}$) and compressible (strong $\delta B_{\parallel}$).
- Turbulence may cause ion heating and velocity fluctuations.
- If the distribution of ions in the heliosheath is affected by turbulence, it should be considered by ENA models.



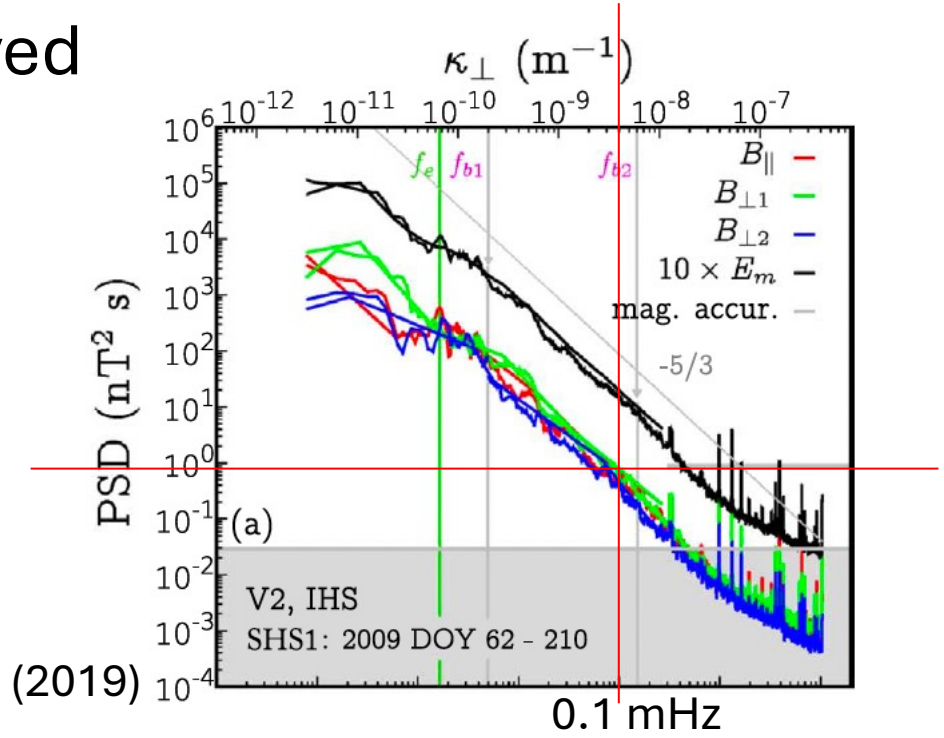
Burlaga et al. (2006)

Energy consideration

- How much energy is contained in turbulence?
- Assuming an approximate steady state, the energy dissipation rate balances the energy cascade rate and the energy injection rate.
- Estimate energy cascade rate from observed turbulence spectrum (e.g., Isenberg et al. 2023).

$$\varepsilon_K = \frac{f_{sc}^{5/2}\,[E(f_{sc})]^{3/2}\,(21.8)^3}{V_{sw}\,n_p^{3/2}}\ \mathrm{km^2\ s^{-3}}, \qquad (5)$$

- $\sim 10^{-7}(\mathrm{km/s})^2\ \mathrm{cm^{-3}s^{-1}}$ @0.1mHz



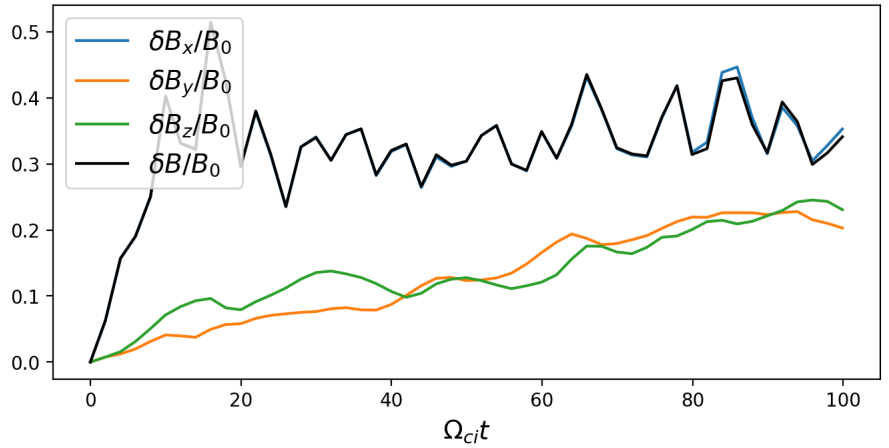
Fraternale+ (2019)

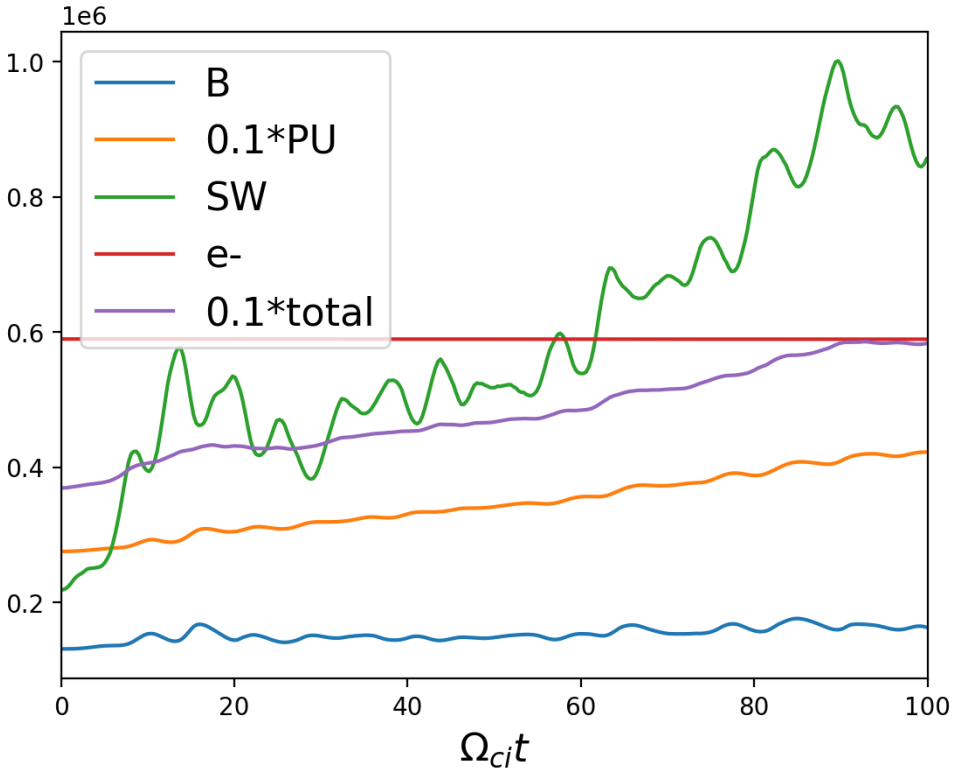
Turbulence energy

- Multiplying by the heliosheath crossing time ~ 30 AU/150 km/s ~ 8400 hours, the total energy dissipation is ~ $3(\mathrm{km/s})^2\ \mathrm{cm}^{-3}$, comparable with the measured solar wind thermal energy density ($0.002\ \mathrm{cm}^{-3}$ and 150,000 K).
- Turbulent dissipation should be important for heating the thermal ions, and probably less important for the transmitted pickup ions since they are already much more energetic.
- Some caveats: the cascade rate formula only works for incompressible, Kolmogorov turbulence, while the heliosheath turbulence may be neither (e.g., Zieger et al. 2020); crossing time may be longer as radial velocity decreases with distance.

Hybrid simulation

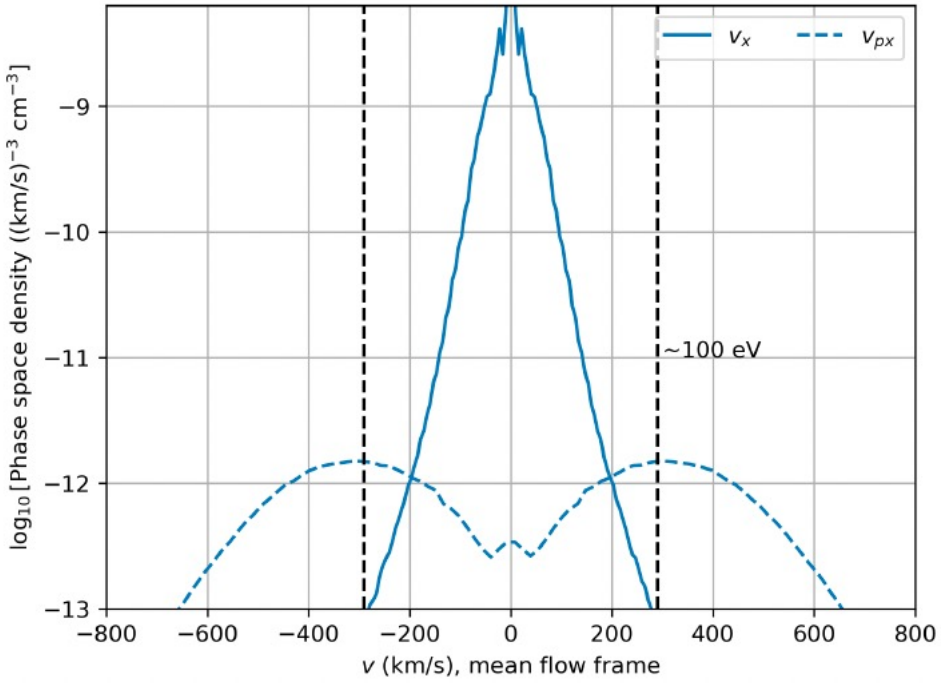
- We use 3D hybrid simulations to investigate ion heating by turbulence.
- Turbulence is injected continuously in the form of compressible magnetic field fluctuations.
- Initial ion distribution taken from Giacalone et al. (2021) downstream of the termination shock.
- We find that solar wind ions are heated significantly (factor of ~ 4).



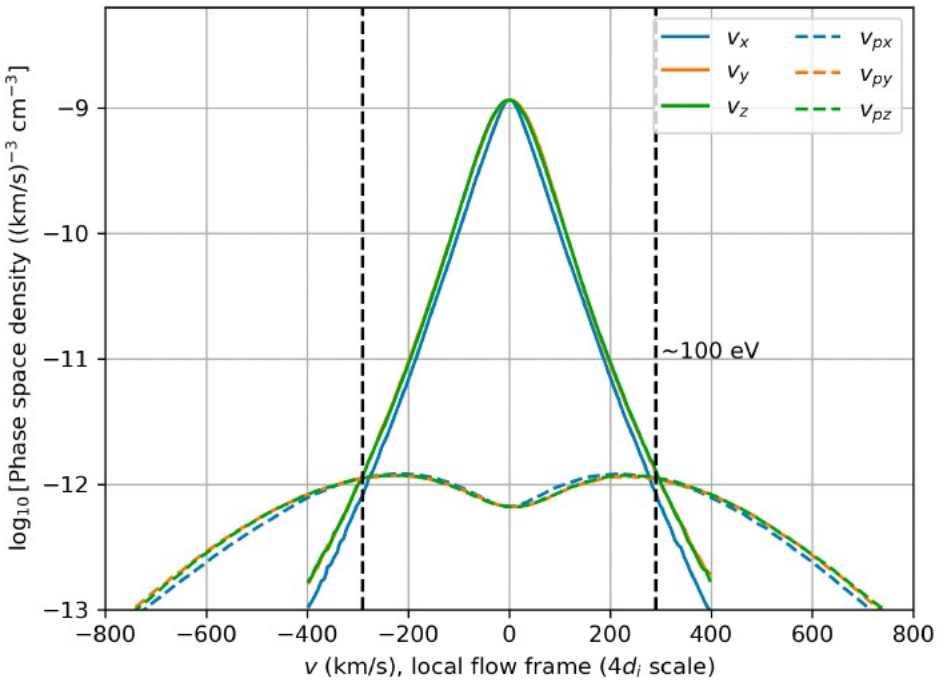


Velocity distribution function

- Simulation is in the flow frame. If flow velocity ~150 km/s, 100 eV ENA -> ion velocity ~290 km/s in the flow frame.



Initial



End

Velocity fluctuation and MHD fast mode

- Perpendicular wavevector, $\theta = 90°, \delta B_\perp = 0, \frac{\delta u_\perp / V_f}{\delta B_\parallel / B_0} \sim 1.$

$$\delta\hat{u}_x = \frac{\pm V_{f,s}^3}{V_{f,s}^2 - V_{A0}^2 \cos^2\theta} \cos\phi \sin\theta \frac{\delta\hat{P}}{\gamma P_0};$$

$$\delta\hat{u}_y = \frac{\pm V_{f,s}^3}{V_{f,s}^2 - V_{A0}^2 \cos^2\theta} \sin\phi \sin\theta \frac{\delta\hat{P}}{\gamma P_0};$$

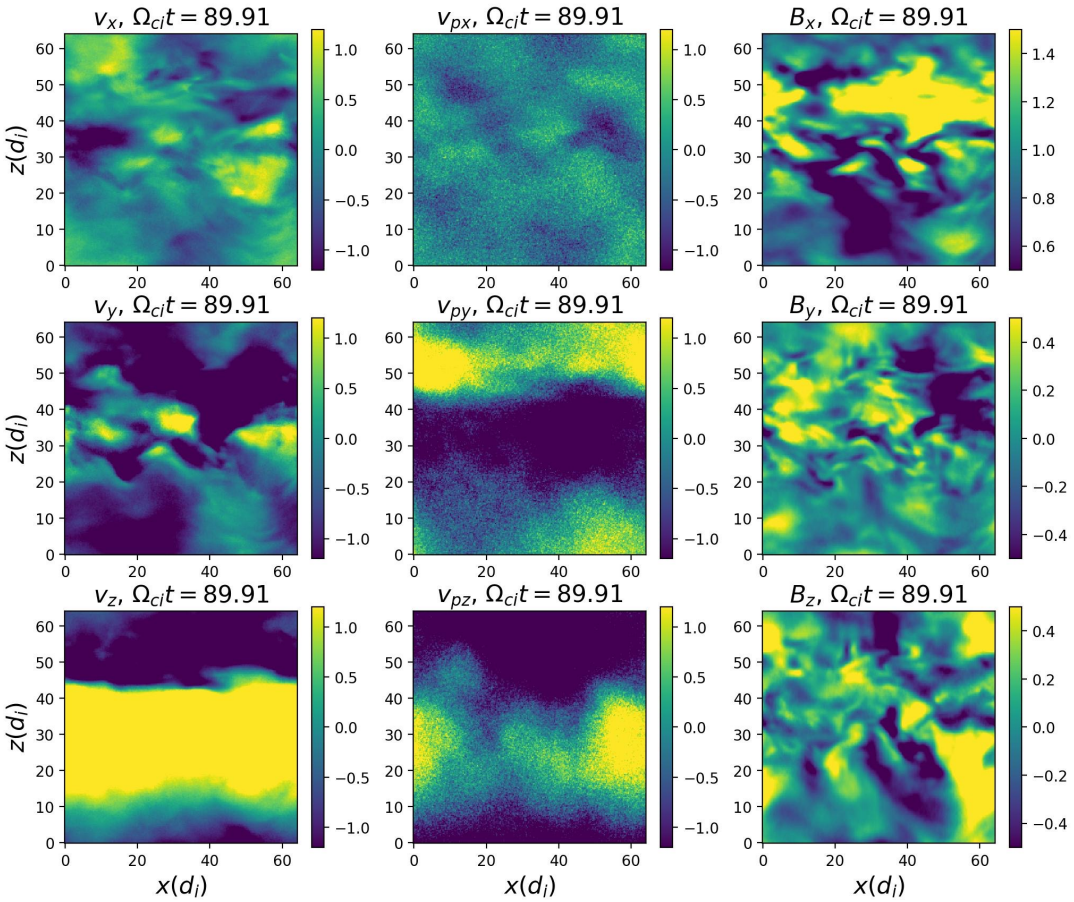
$$\delta\hat{u}_z = \frac{\pm a_0^2}{V_{f,s}} \cos\theta \frac{\delta\hat{P}}{\gamma P_0};$$

$$\frac{\delta\hat{B}_x}{B_0} = \frac{-V_{f,s}^2 \cos\theta}{V_{f,s}^2 - V_{A0}^2 \cos^2\theta} \cos\phi \sin\theta \frac{\delta\hat{P}}{\gamma P_0};$$

$$\frac{\delta\hat{B}_y}{B_0} = \frac{-V_{f,s}^2 \cos\theta}{V_{f,s}^2 - V_{A0}^2 \cos^2\theta} \sin\phi \sin\theta \frac{\delta\hat{P}}{\gamma P_0};$$

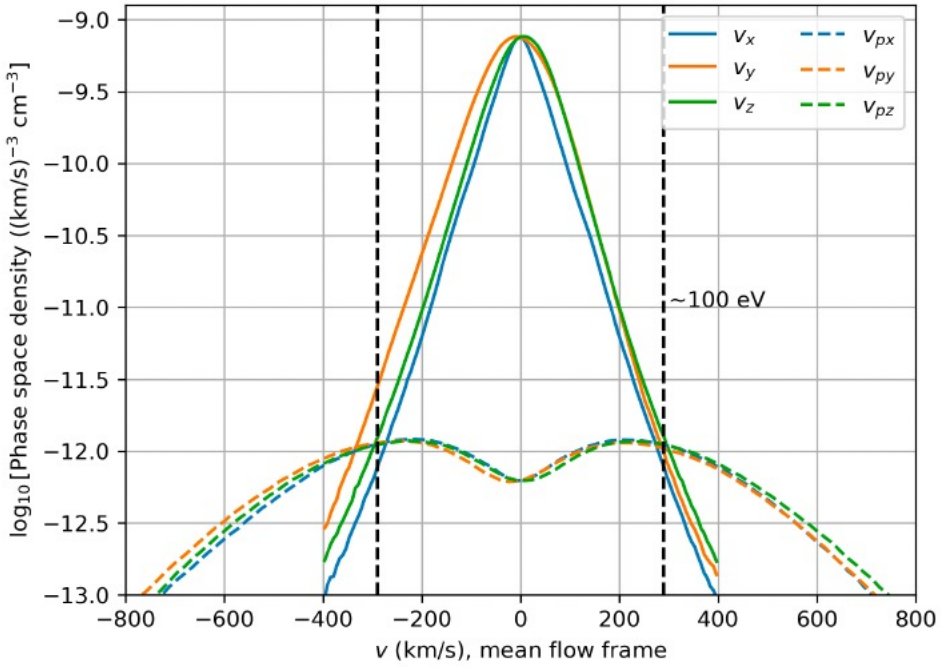
$$\frac{\delta\hat{B}_z}{B_0} = \frac{V_{f,s}^2 - a_0^2 \cos^2\theta}{V_{f,s}^2} \frac{\delta\hat{P}}{\gamma P_0};$$

Zank et al. (2017)



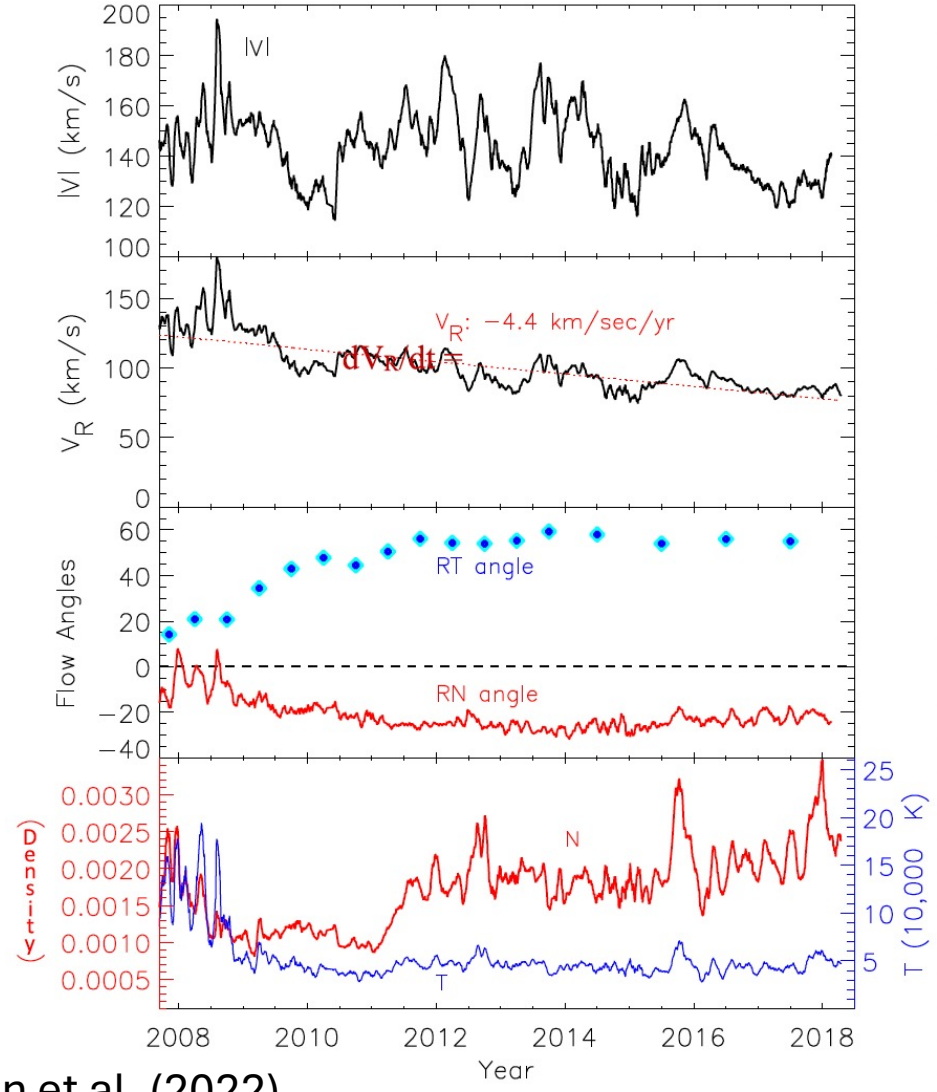
Including velocity fluctuations

- The velocity distribution is further broadened by turbulent velocity fluctuations.
- The effect of velocity fluctuations can be included if the distribution is plotted in the mean flow frame.
- Overall, thermal ions could have a comparable contribution to ~100 eV ENAs as pickup ions.



Voyager plasma observation

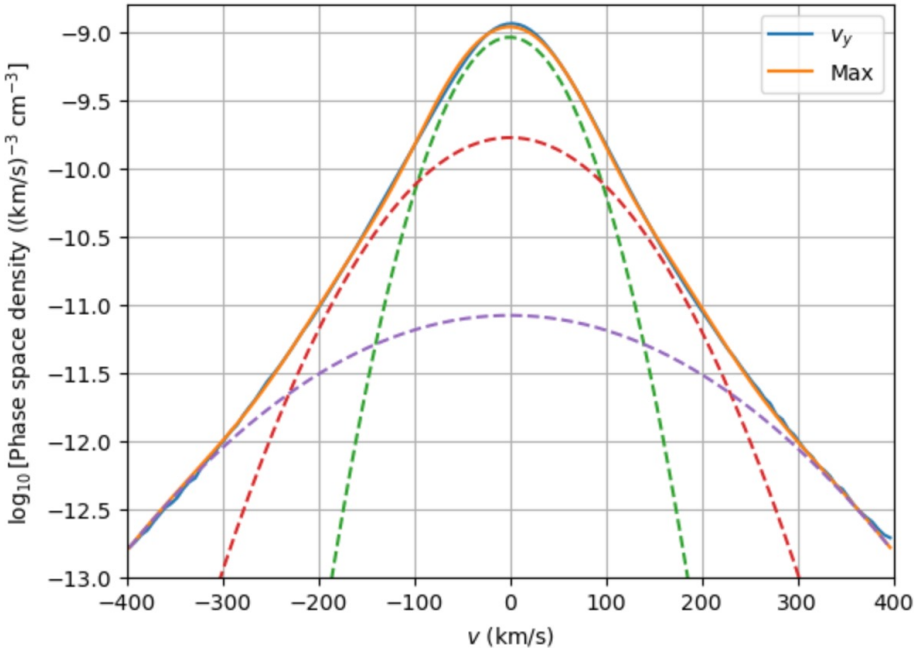
- Plasma Science (PLS) on Voyager 2 can measure thermal ions parameters. Temperature decreases close to the TS, and then remains roughly constant throughout the heliosheath, which does not apparently support turbulent heating.
- However, PLS mostly measures ions with radially outward velocities; and only the core ions close to the peak of the distribution can be detected.



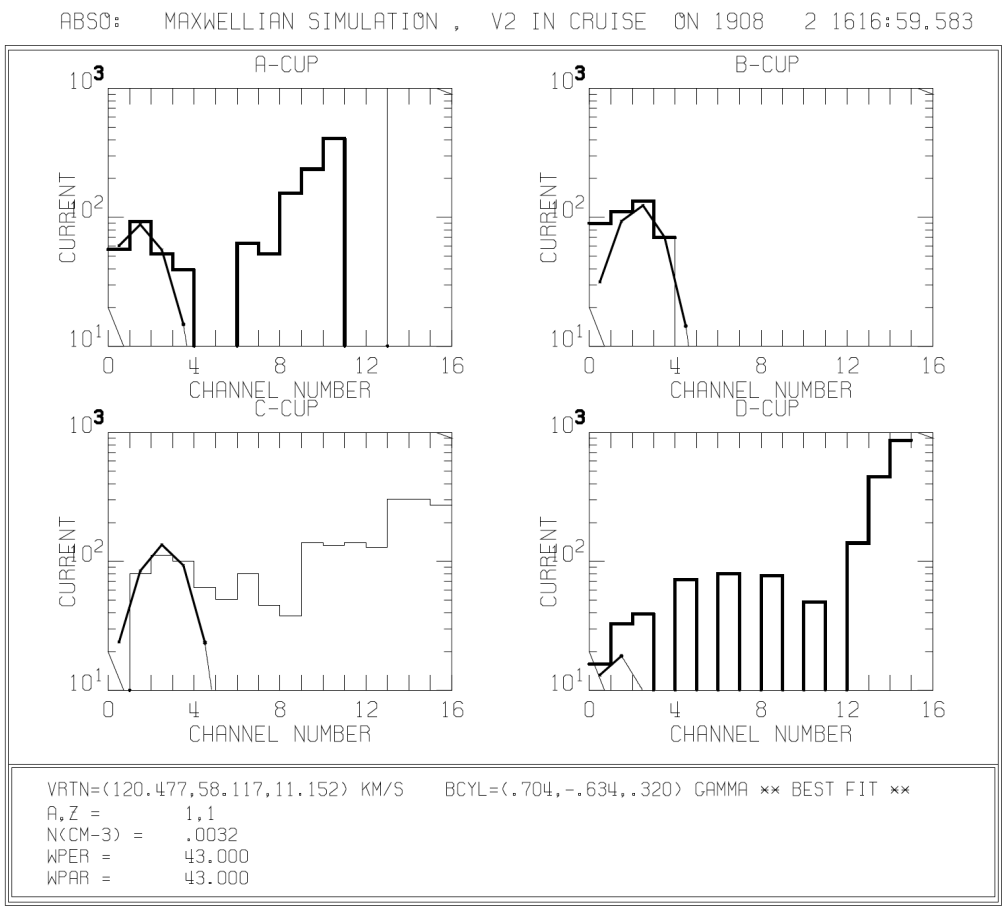
Richardson et al. (2022)

Fit to PLS data

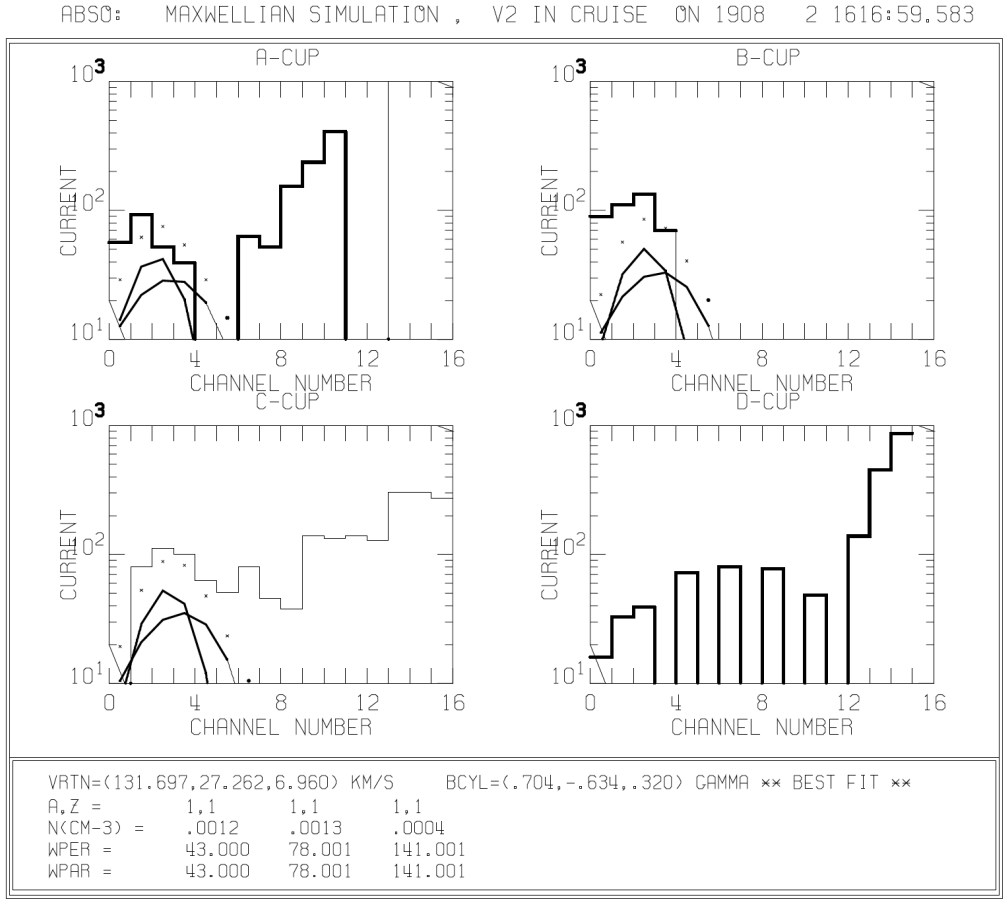
- To obtain plasma parameters (density, velocity vector, and temperature), a Maxwellian fit was applied to PLS data.
- Thermal ion distribution from the hybrid simulation can be represented reasonably well as the sum of three Maxwellians.
- The fitted three-Maxwellian distribution with fixed densities and temperature is then fed to the PLS fit procedure with the flow velocity as free parameters.



Fit to PLS data



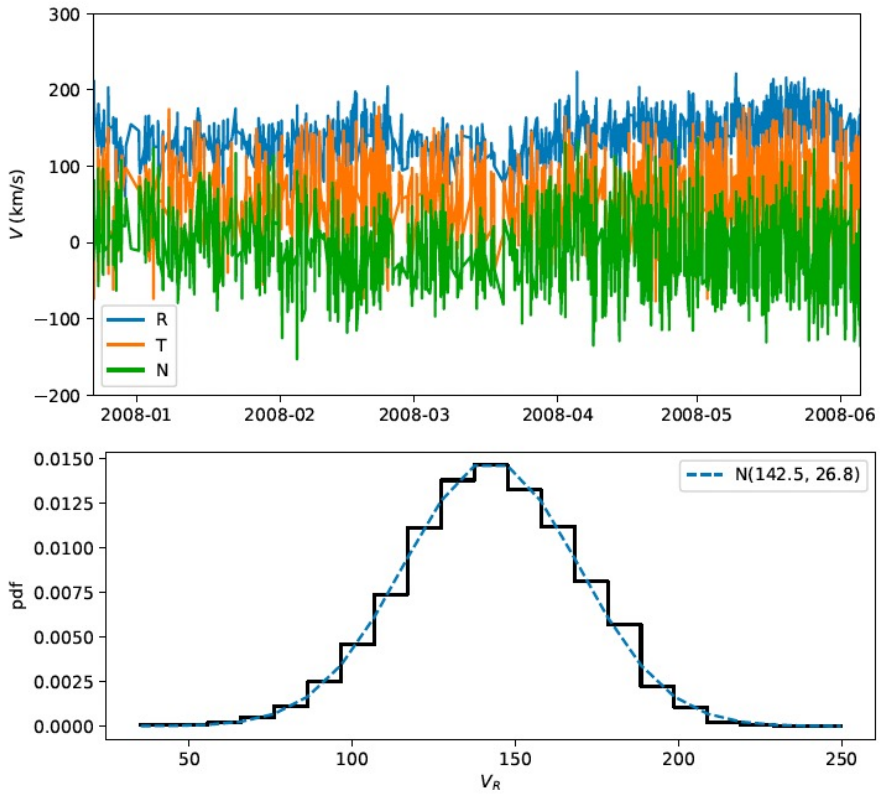
Single Maxwellian fit.



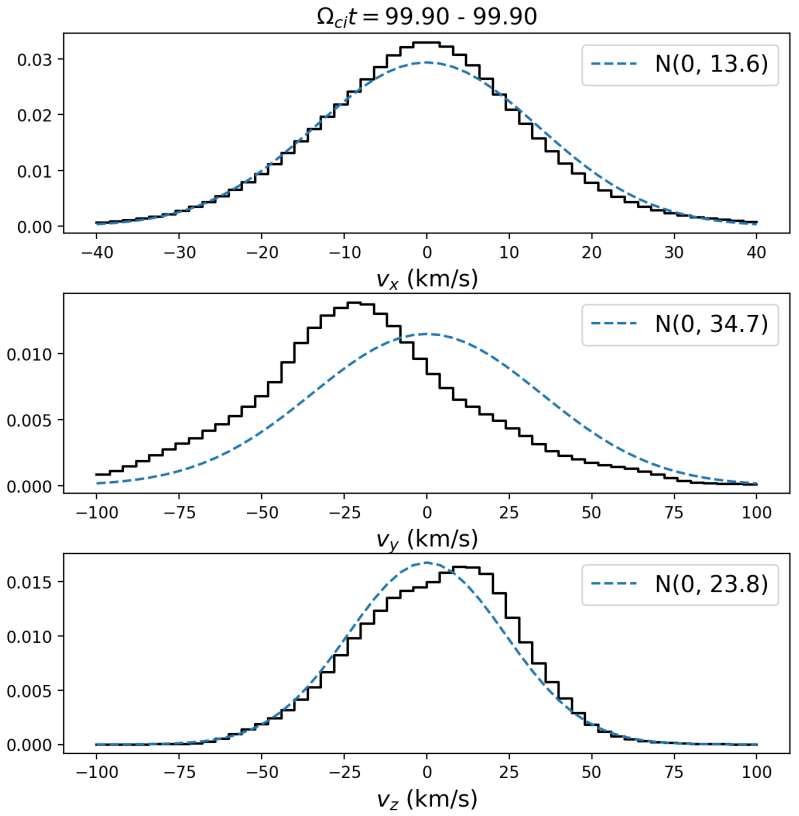
Sum of 3 Maxwellian, fixed density and temperature

Velocity fluctuations with PLS

- Velocity fluctuation, R ~ 27 km/s, T/N ~ 40 km/s.



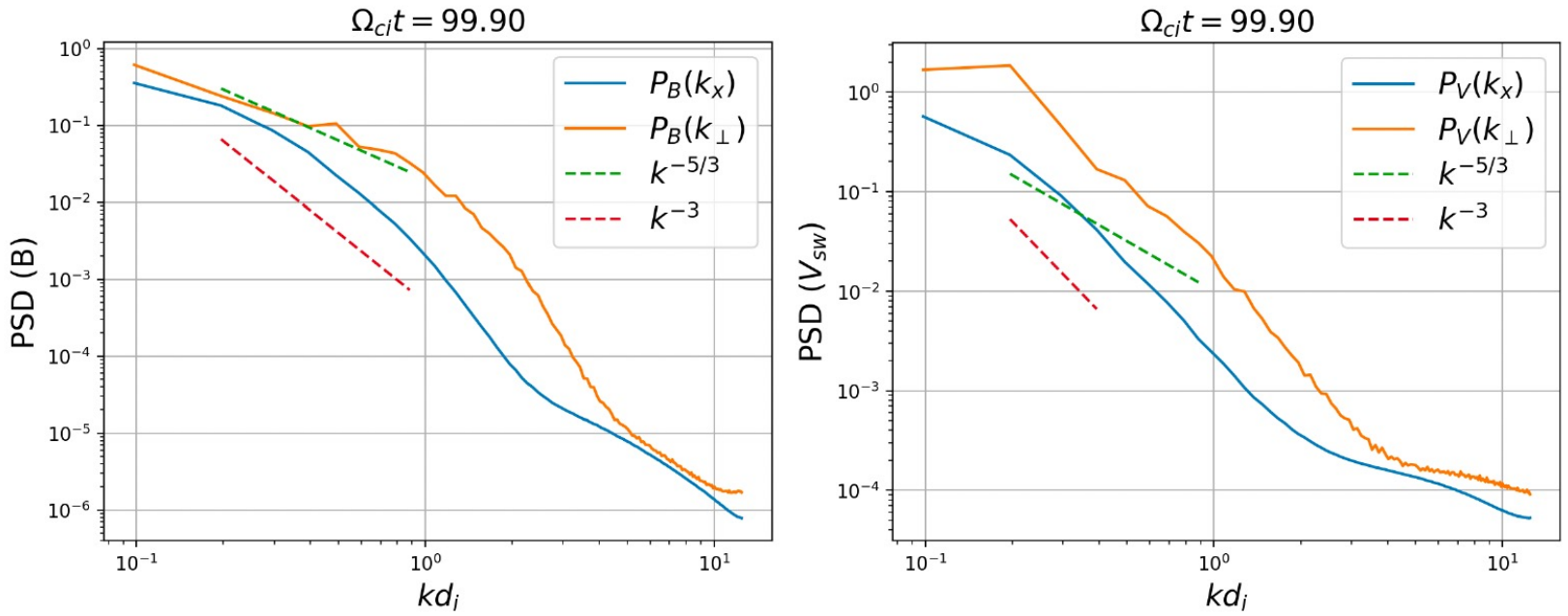
PLS data



Simulation

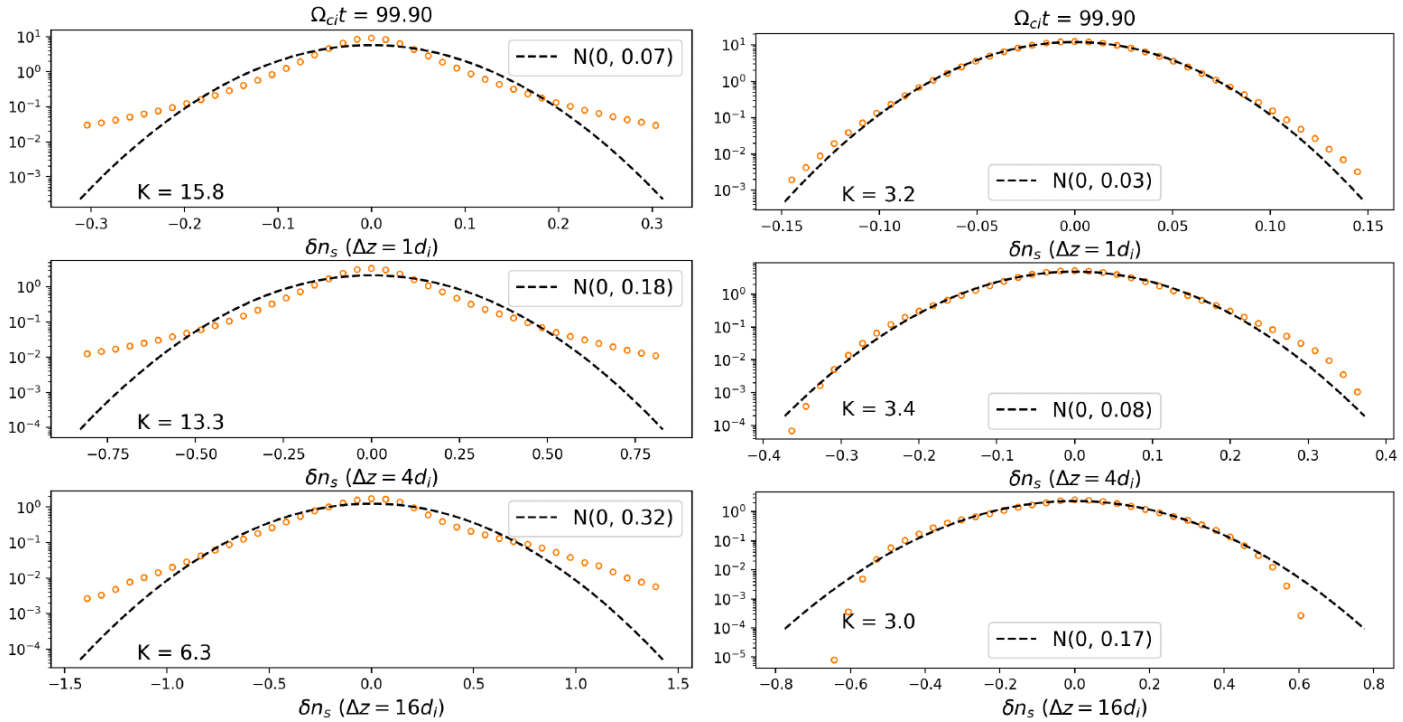
Turbulent spectrum

- Turbulent cascade appears stronger in magnetic than kinetic spectrum.



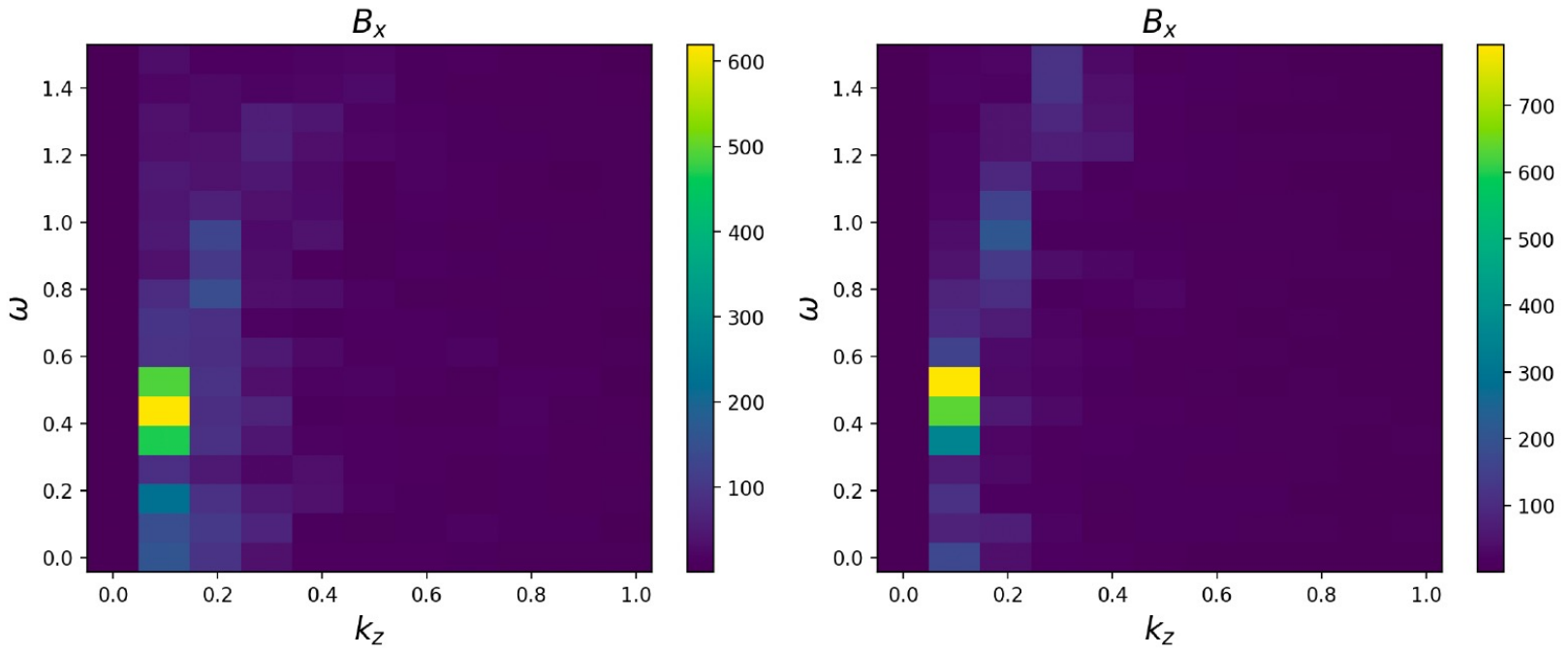
Intermittency

- Intermittency appears stronger in the simulation with compressive driving (left panel), possibly related to the shocklets.



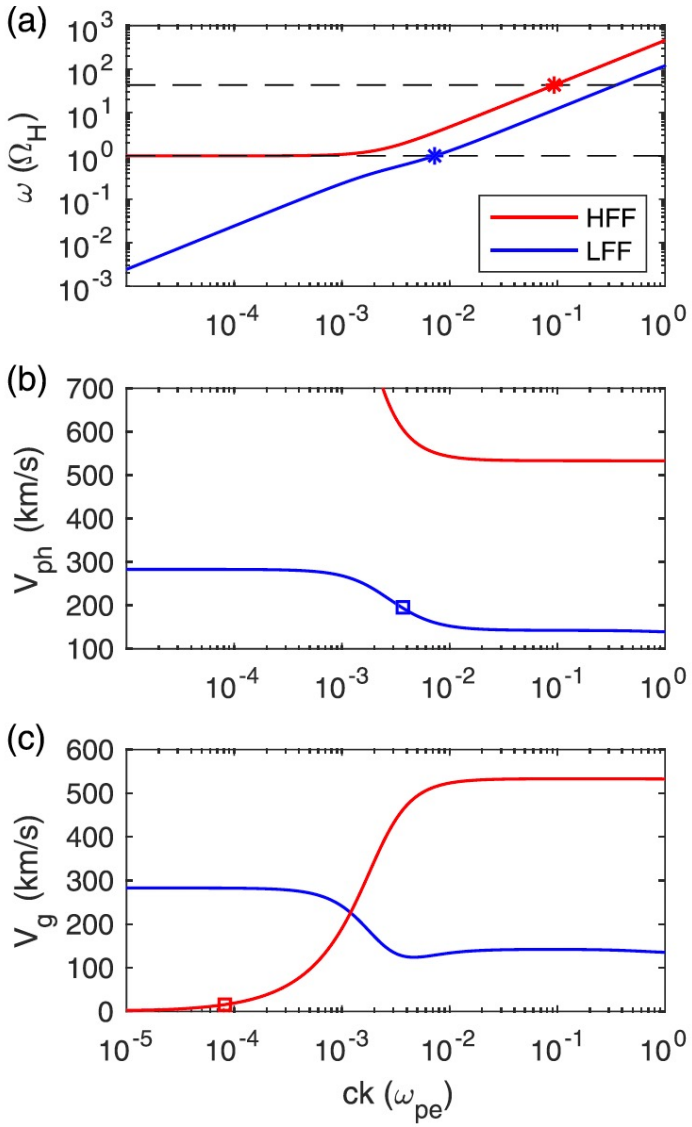
$\omega - k$ spectrum

- Possible multi-fluid wave signatures.



SW + PUI

Single Maxwellian.



Zieger et al. (2020)

Summary

- Turbulence in the heliosheath causes heating of solar wind ions and velocity fluctuations, both of which may increase observed low-energy ENA fluxes ~ 100 eV. However, the effects are likely not strong enough to completely explain the gap between models and observations.
- The heating and velocity fluctuation are consistent with Voyager 2 PLS measurements within data uncertainties. New Horizons measurements of the full ion distribution will be important for understanding energetic neutral atoms.