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Simulation of ion-acoustic wave excitation, reflection, and wave-particle scattering in the presheath

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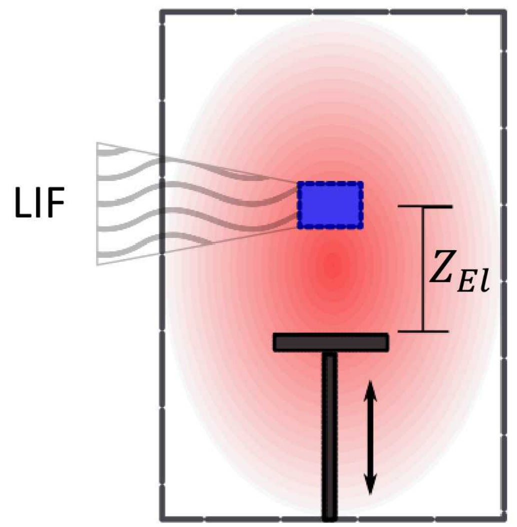
Ion-acoustic fluctuations (IAFs) observed in an ion presheath

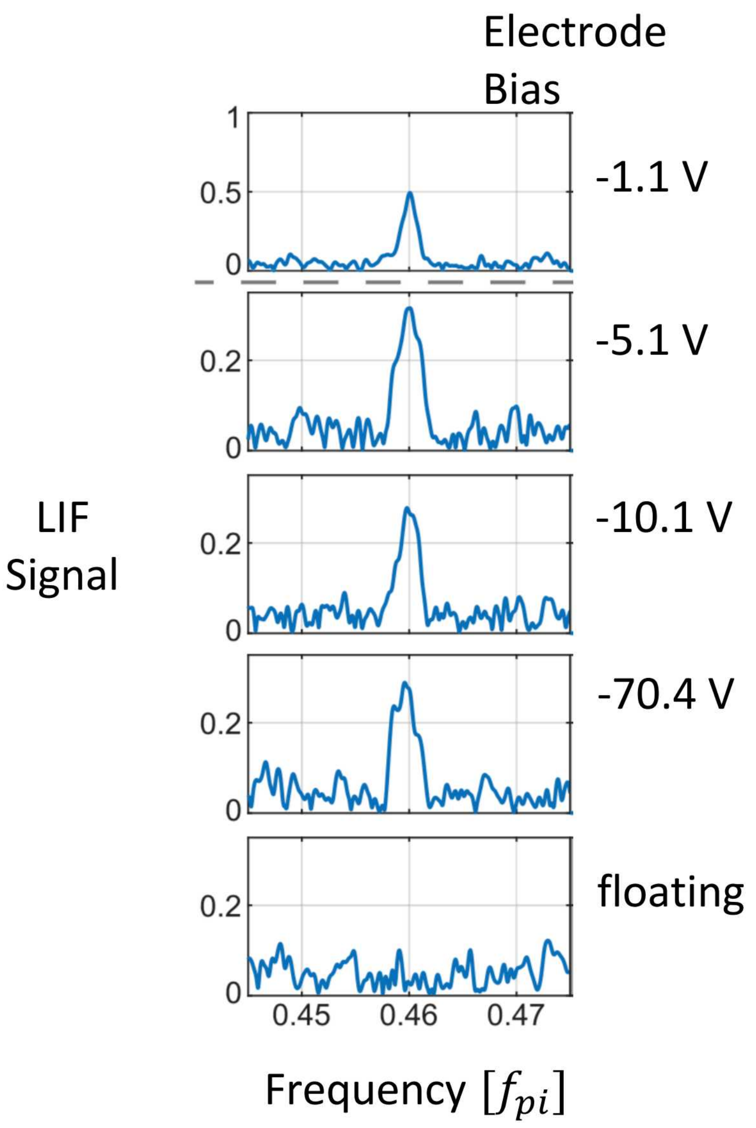


Blue = LIF viewing volume

Grey = Movable, biased Electrode

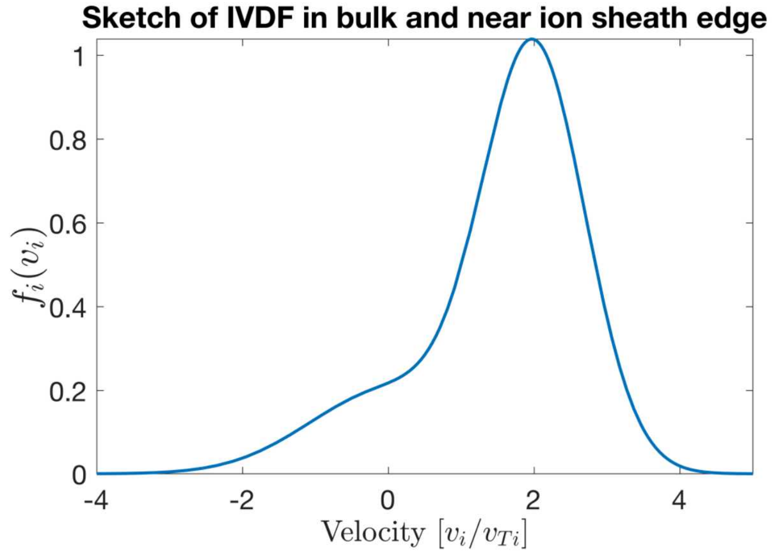
- Ion acoustic fluctuations were measured using laser-induced-fluorescence in an Ar-e plasma
  - $n_0 \sim 9 \times 10^8 cm^{-3}$ $T_e \sim 5\ eV$
- The fluctuations were measured far from the electrode, around the entrance to the presheath
  - $Z_{El} \sim 6\ cm$ $\lambda_{De} \sim .06\ cm$
- $^{Z_{El}}/_{\lambda_{De}} \sim 100$

Hood R, et Al. *Phys. of Plasmas.* **27** (2020) 053509



Expect non-thermal distributions in the presheath, but thermal distributions have been measured

- Ion velocity distribution function (IVDF or $f_i(v_i)$)
  - Expected: IVDF has a flow shift and a "fat" low-velocity ($v_i \ll v_{Ti}$) tail
  - Measured: IVDF is as expected in most of the ion presheath, but can be thermalized near the sheath edge



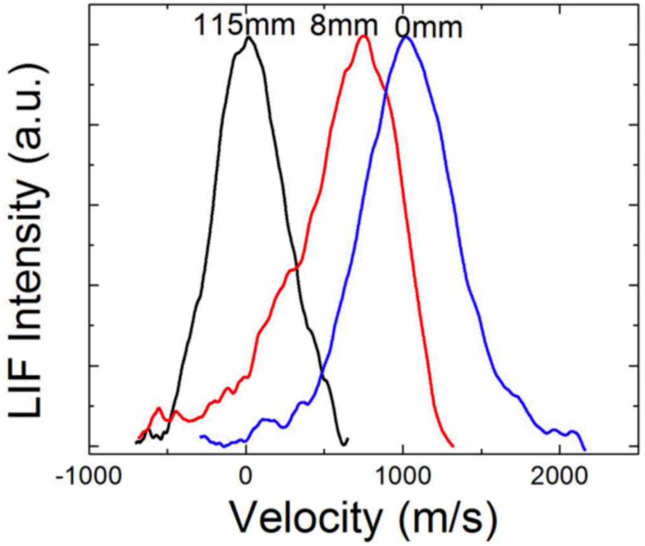
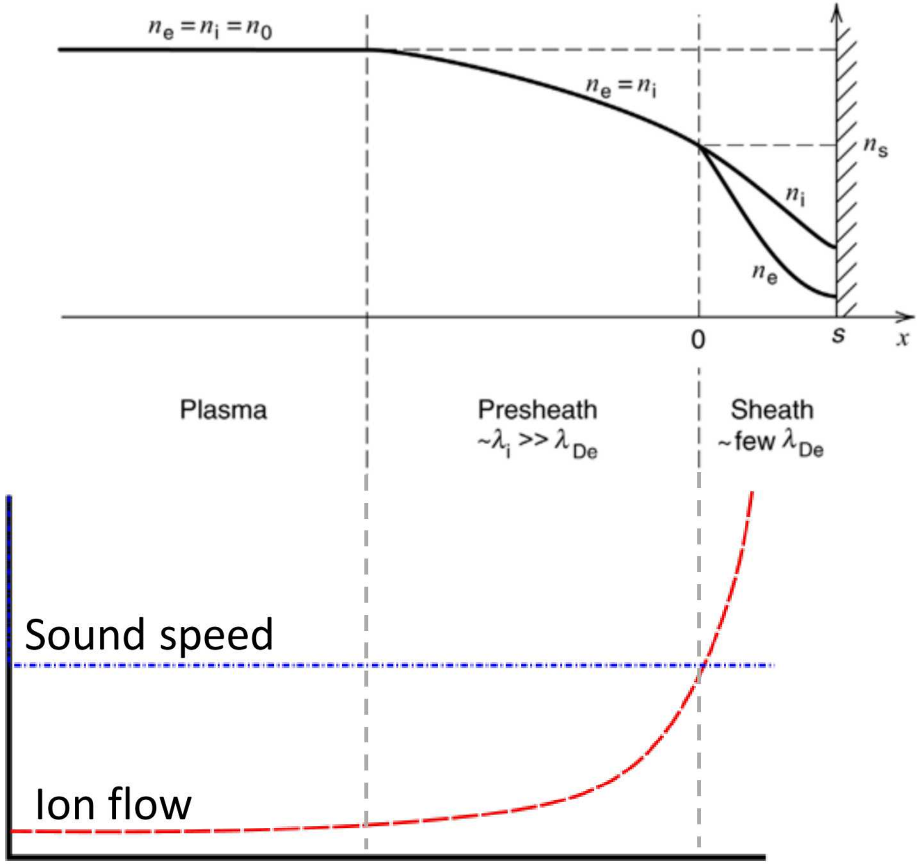


Figure 2. ivdfs of Xe II ions in a $P = 0.13$ mTorr, $T_e = 1.7$ eV, $n_e = 3.5 \times 10^9$ cm^{-3} xenon plasma at varying distances from the sheath edge.

C. Yip, N. Hershkowitz and G. Severn. *Plasma Sources Sci. Technol.* **24** (2015) 015018

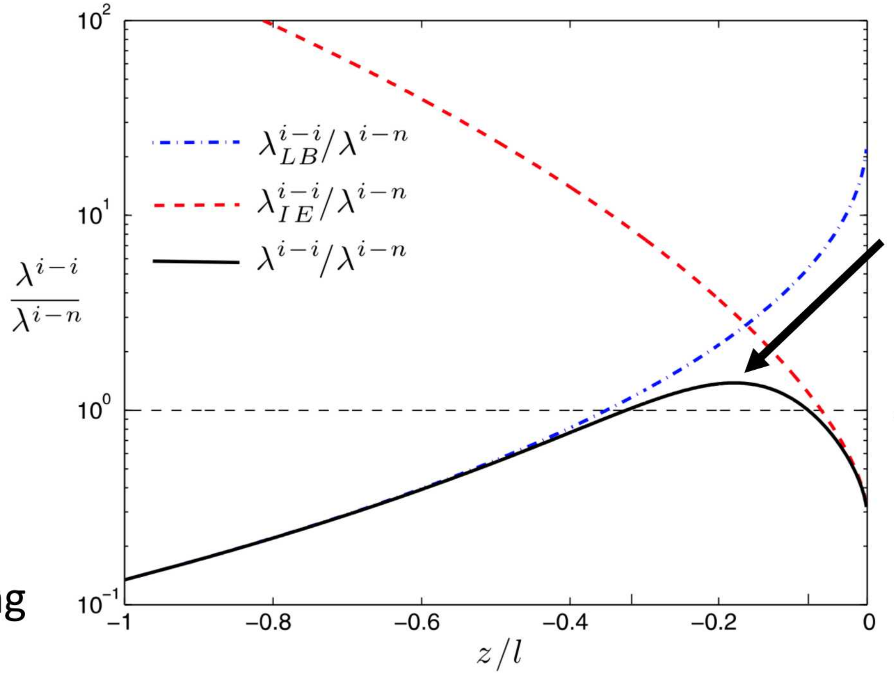
IAFs are predicted to affect collisions in the ion presheath



- Wave-particle interactions can increase $i - i$ scattering
  - IVDF could be thermalized near the sheath edge
  - This effect is consistent with experiments

C. Yip, N. Hershkowitz and G. Severn. *Plasma Sources Sci. Technol.* **24** (2015) 015018

N. Claire. *Physics of Plasmas.* **13** (2006) 062103



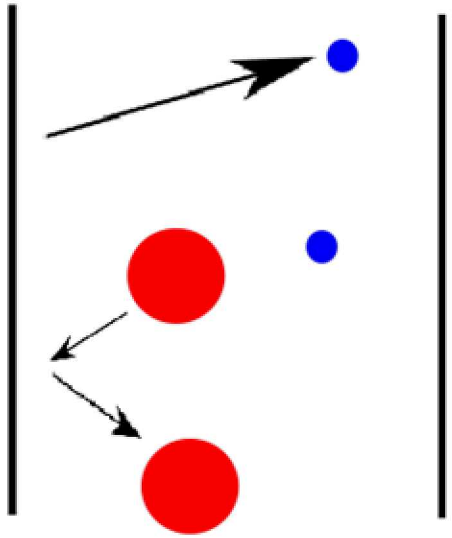
$i - i$ mean-free-path compared to $i - n$ mean-free-path throughout the presheath toward the sheath edge ($\frac{z}{l} = 0$)

- $\frac{\lambda^{i-i}}{\lambda^{i-n}} < 1$ implies possible IVDF thermalization

S. D. Baalrud and C. C. Hegna. *Plasma Sources Sci. Technol.* **20** (2011) 025013

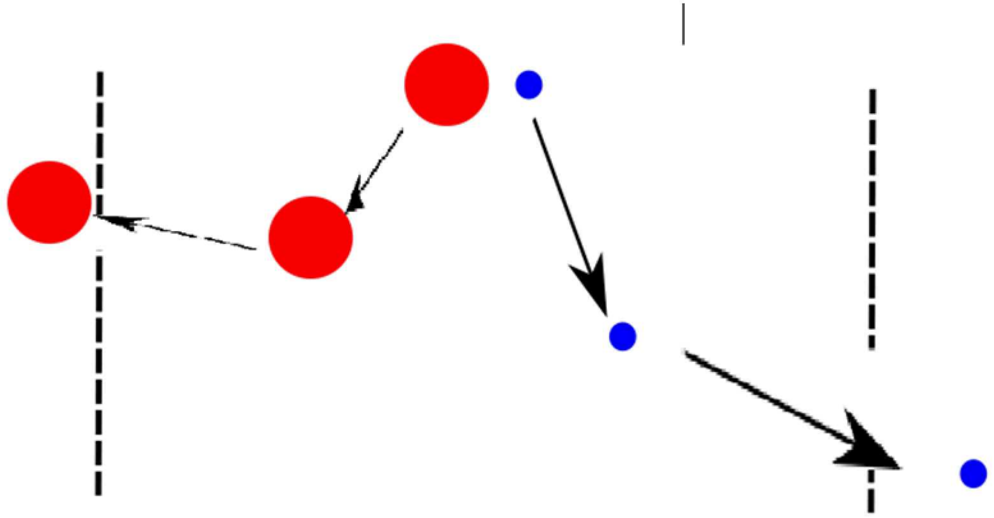
These predictions can be tested by comparing two types of PIC simulations

Uniform Plasma



One simulation with specular boundary conditions where a set number of particles are introduced once and no particles are added or removed afterward

Flowing Plasma



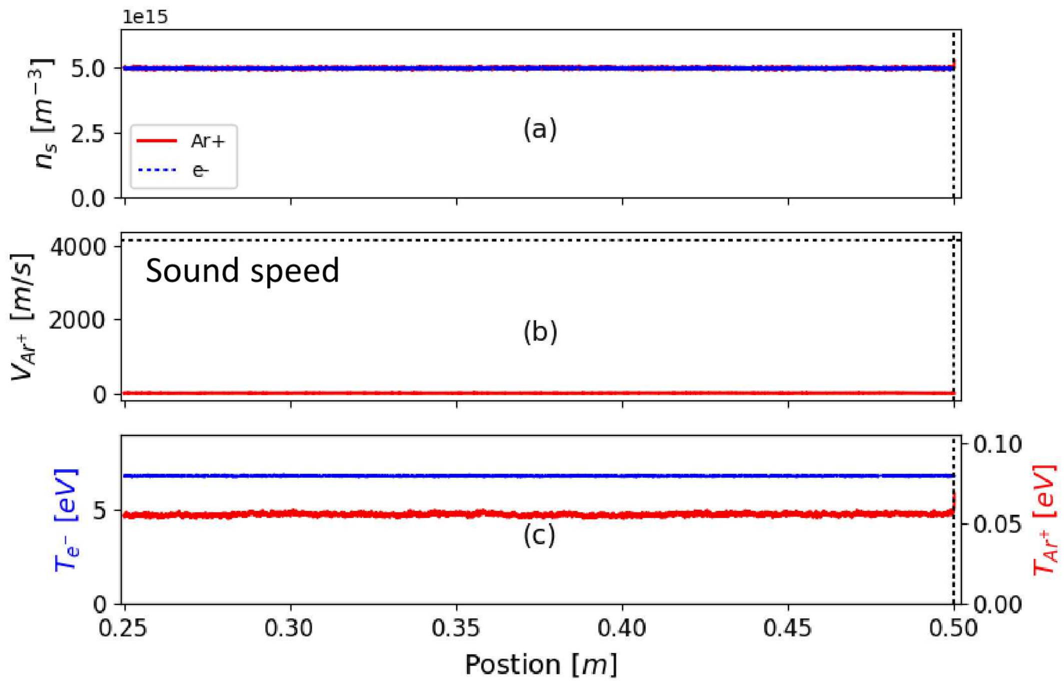
Another where particles are constantly introduced to the domain and are permanently removed once they reach a boundary

Aleph can simulate a low temperature plasma

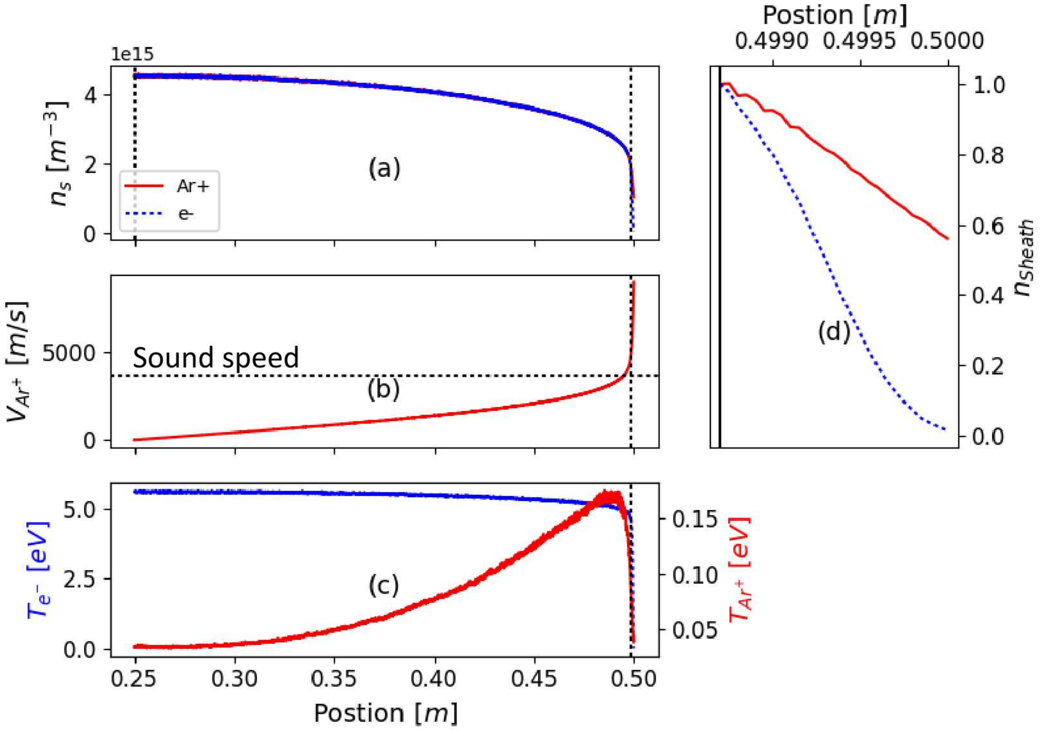
- Simulations had 1 dimension for particle positions and 3 for velocities (1D3V)
- Two species = electrons and singly charged argon ions
- Particles are deposited at a fixed rate, uniformly throughout the domain
- Collisions with neutrals can be included with the direct simulation Monte-Carlo method (DSMC)
- The domains were 50 cm long and contained 10,000 cells each ~$\lambda_{De}/5$
- $n_0 \sim 5 \times 10^9 cm^{-3}$ $T_e \sim 6\ eV$ $\lambda_{De} \sim .025\ cm$

Specular and absorbing boundary conditions simulate uniform and experimental plasmas

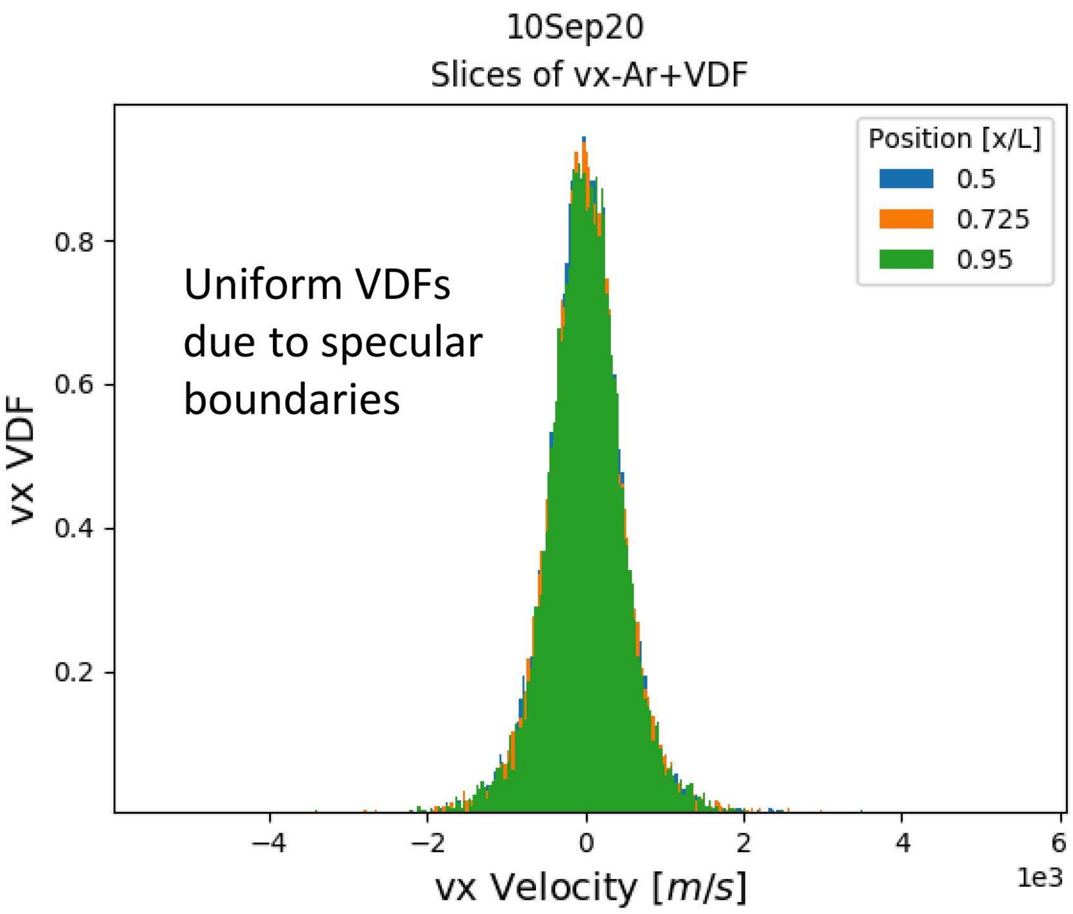
Uniform Plasma

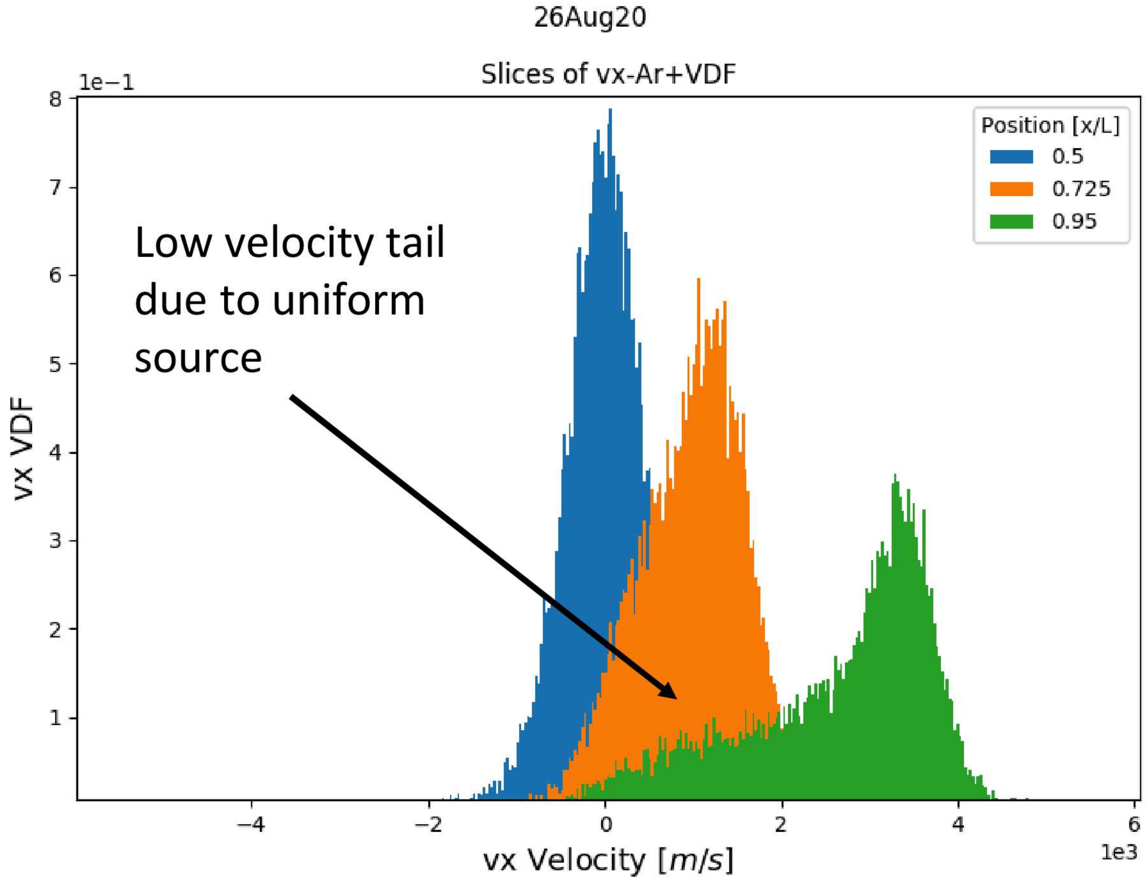


Flowing Plasma



IVDFs exhibit expected properties in both



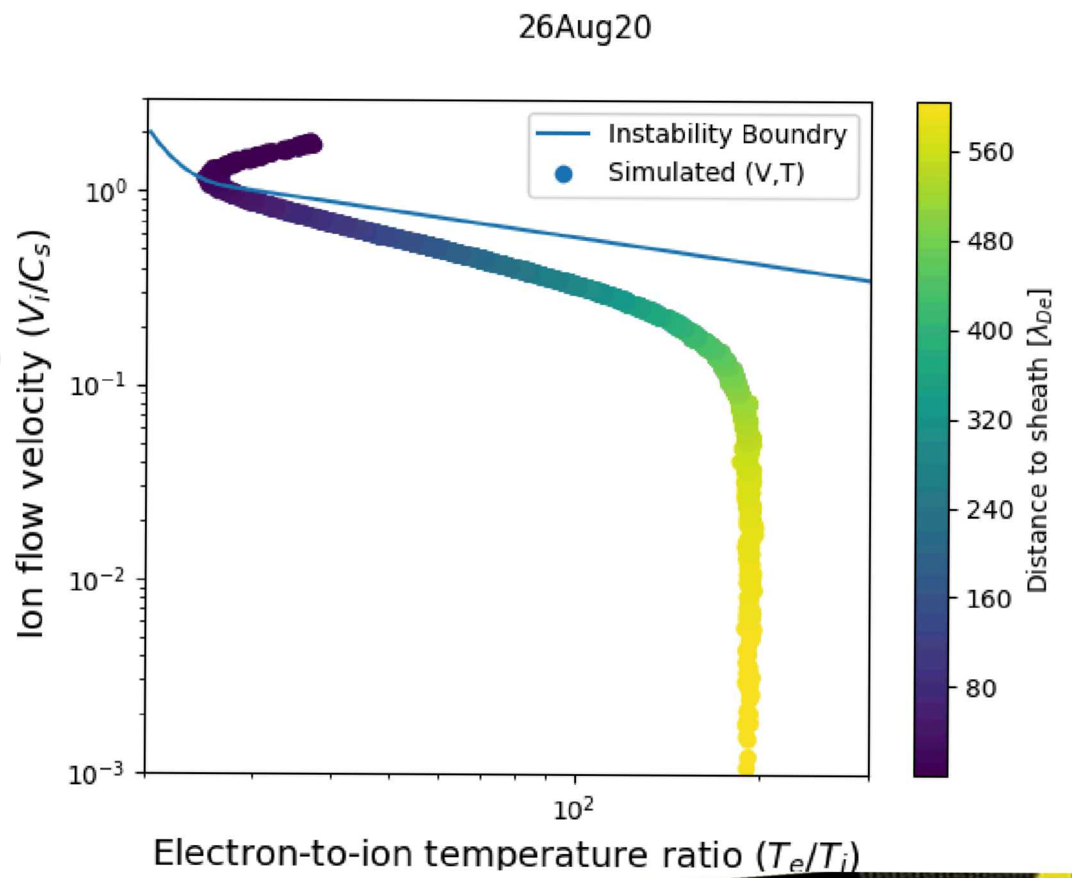


Linear dielectric theory predicts instability in the simulation containing the presheath

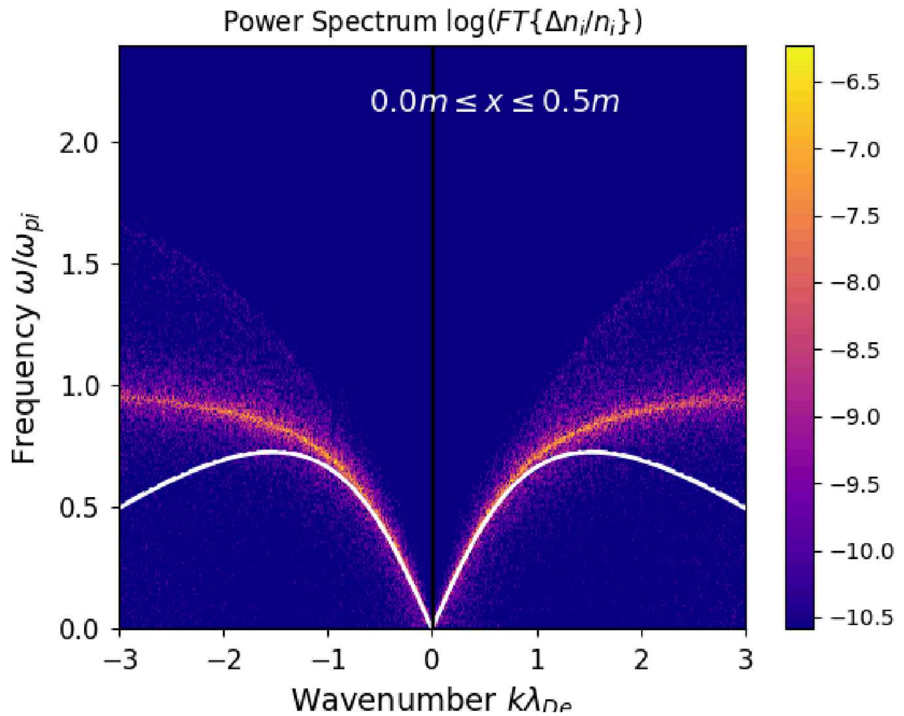
- The instability boundary (unstable above) is calculated from the growth rate (γ) and simulated $\left(\frac{T_e}{T_i}, \frac{V_i}{C_s}\right)$ are compared

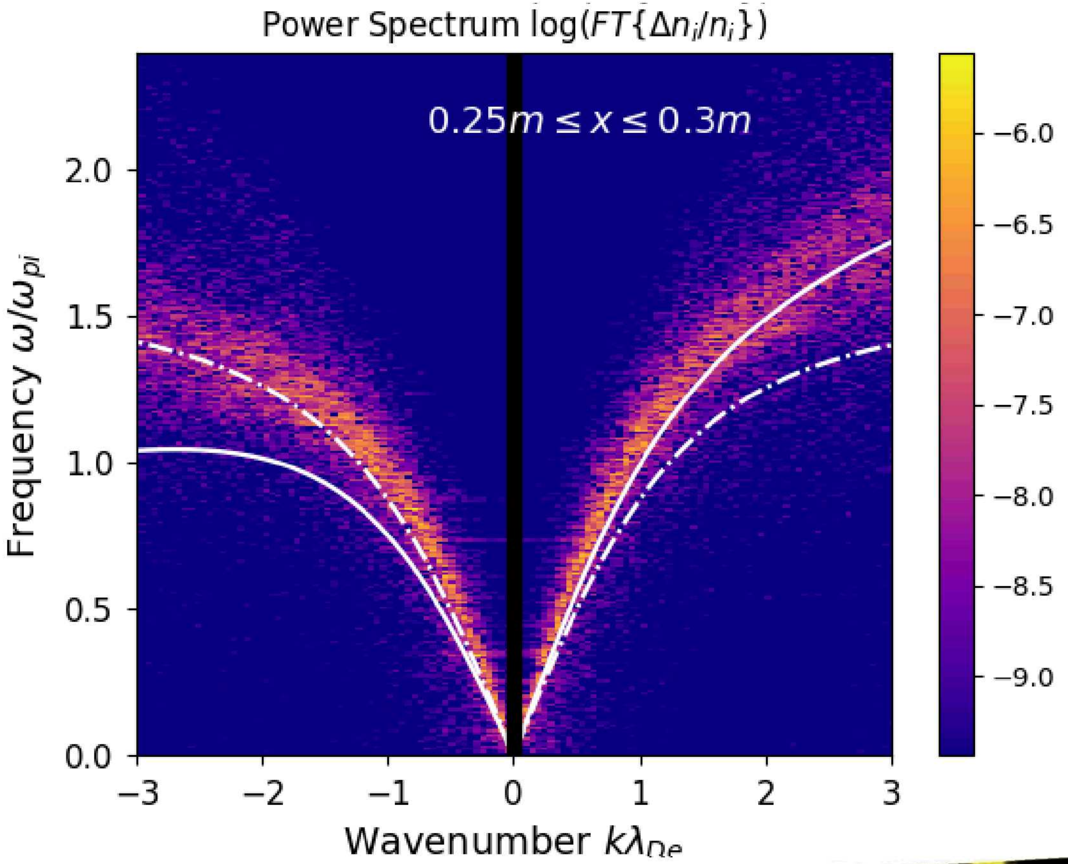
- $$\gamma = \frac{-kC_s\sqrt{\pi/8}}{\left(1+k^2\lambda_{De}^2\right)^2}\left\{\begin{array}{c}\left(\frac{T_e}{T_i}\right)^{3/2} exp\left(\frac{-T_e/T_i}{2\left(1+k^2\lambda_{De}^2\right)}\right) \\ +\left(\frac{m_e}{m_i}\right)^{3/2}\left(1-\frac{V_i}{C_s}\sqrt{1+k^2\lambda_{De}^2}\right)\end{array}\right\}$$

- The region that is predicted to be unstable is small $\sim 24\ \lambda_{De}$



Fluctuations are present throughout entire plasma, but also in the uniform plasma

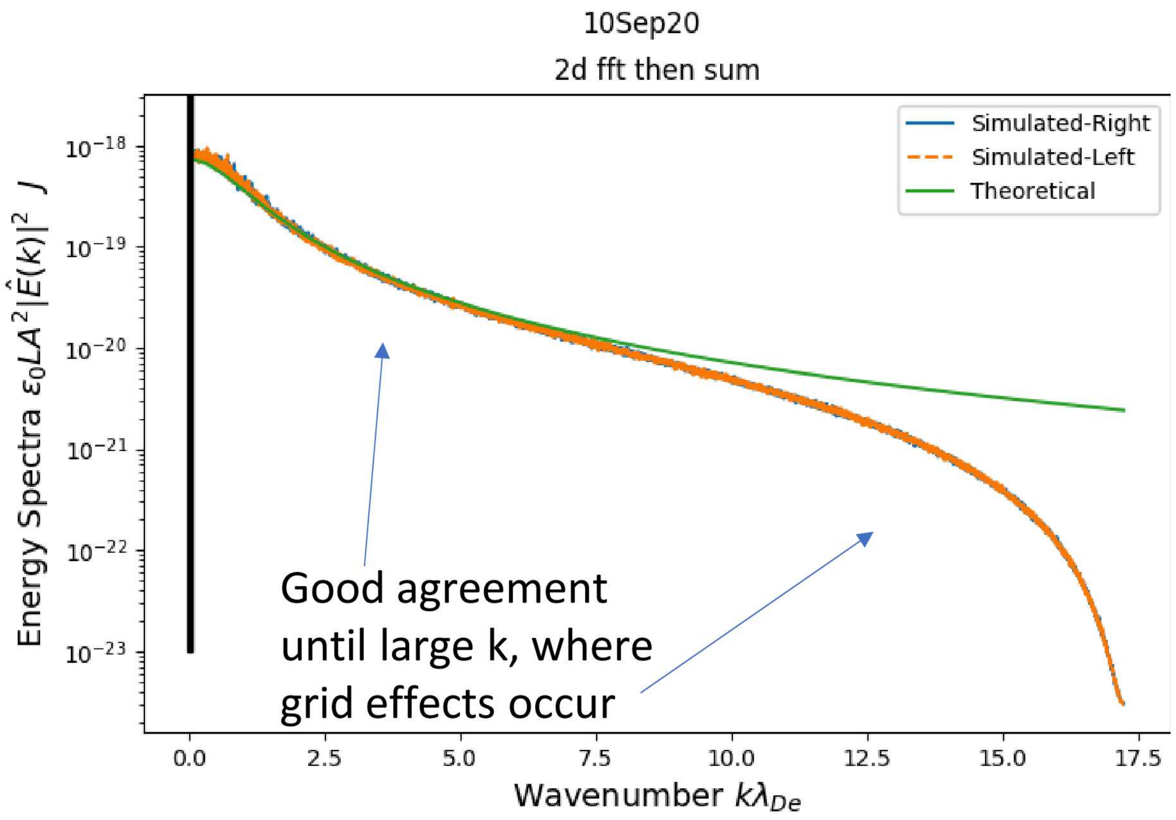


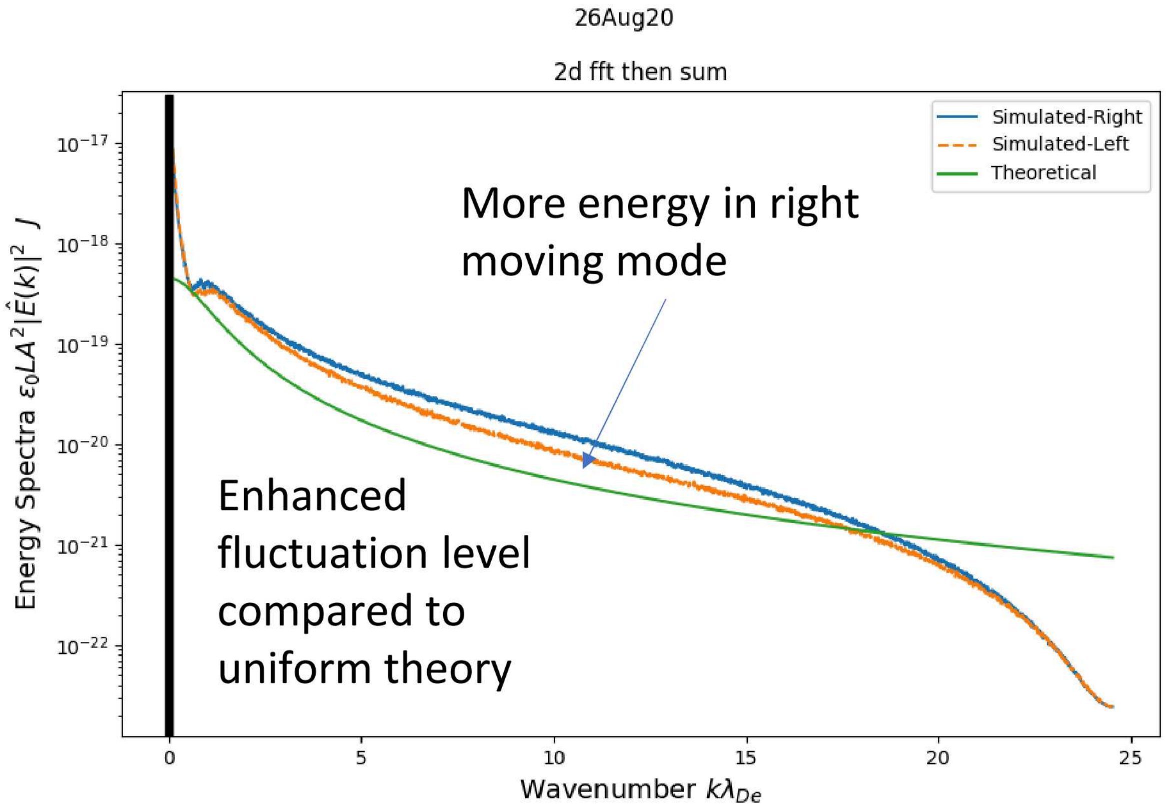


White lines = IA dispersion relation:

$$\omega = \mathbf{k} \cdot \mathbf{V_i} - \frac{kC_s}{\sqrt{1 + k^2 \lambda_{De}^2}}$$

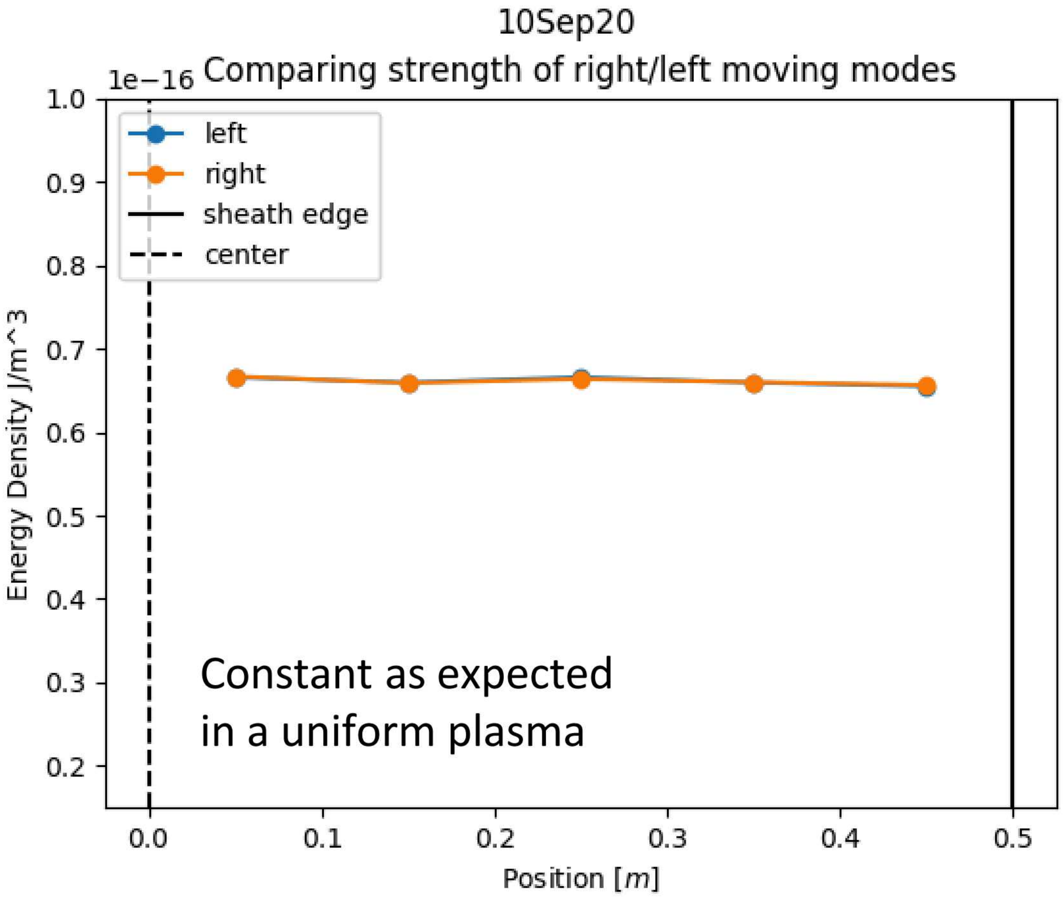
Spectral energy density indicates instability rather than thermal noise in the presheath

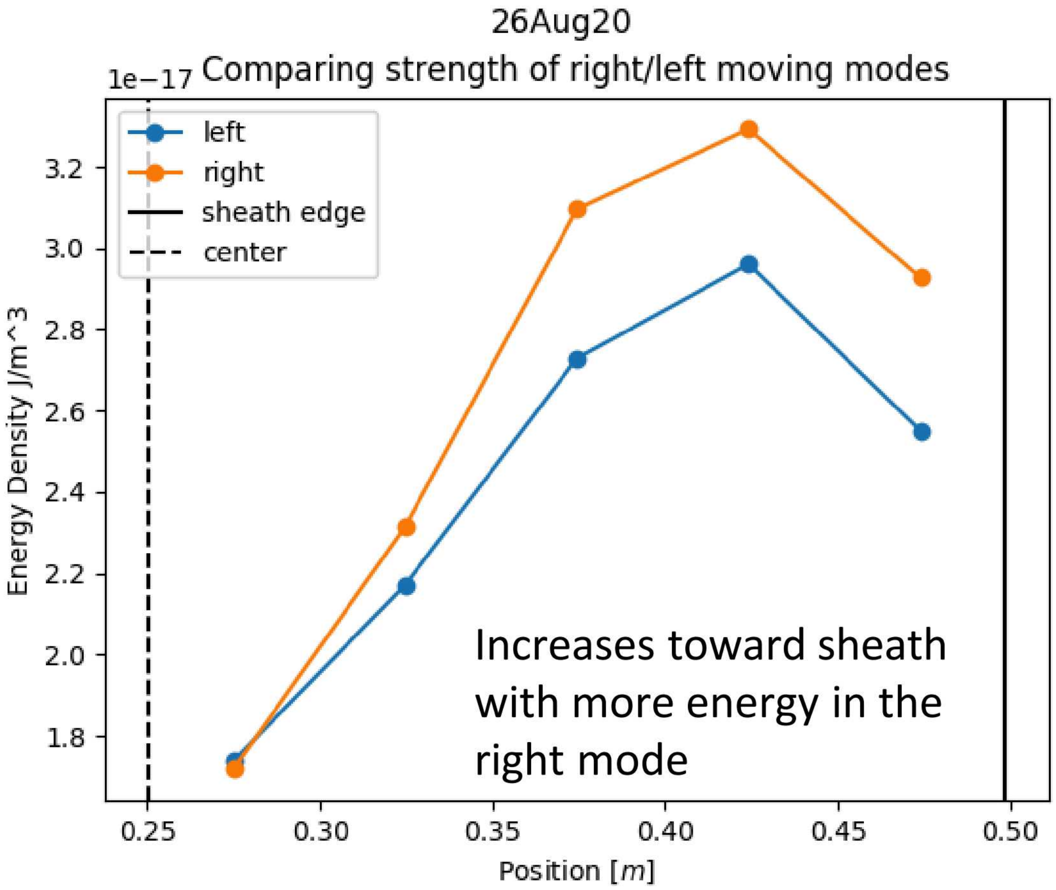




$$\frac{\epsilon_0\left|\hat{\mathbf{E}}(k)\right|}{2} = \frac{T_e}{2}\frac{1}{1+(k\lambda_{De})^2}$$

Simulations indicate significant IAF reflection





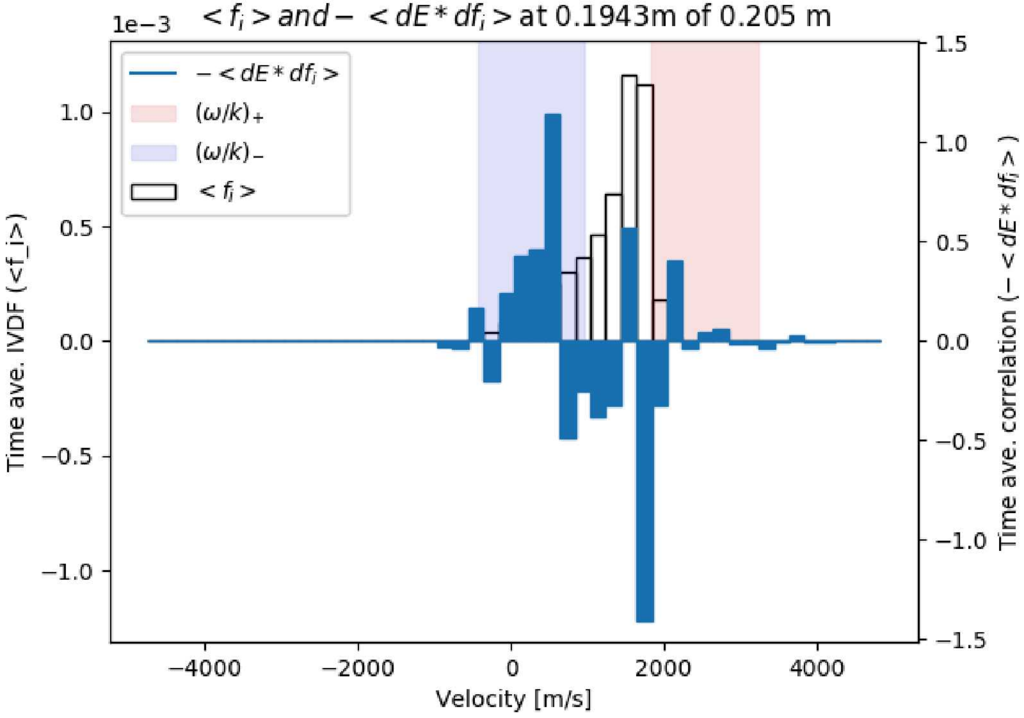
Ion-ion collisions frequency can be calculated from simulated data

The collision operator is related to the time average of VDF and E-field fluctuations

$$C(f) \propto \frac{\partial}{\partial v} < \delta f \; \delta \mathbf{E} >$$

$$\delta f = f(t) - \langle f \rangle, \; \delta \mathbf{E} = \mathbf{E}(t) - \langle \mathbf{E} \rangle$$

To do this we must have a well resolved δf, meaning many (~100) particles per cell or few cells



Conclusions

- Simulations of a uniform plasma and those of an ion presheath exhibit ion-acoustic fluctuations
- The fluctuations in the uniform simulation seem to be entirely thermal in nature, while those in the presheath are enhanced due to the ion-acoustic instability driven by the ions streaming out of the plasma