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SIMULATIONS OF ION HEATING IN THE PRESHEATH DUE TO ION-ACOUSTIC INSTABILITIES

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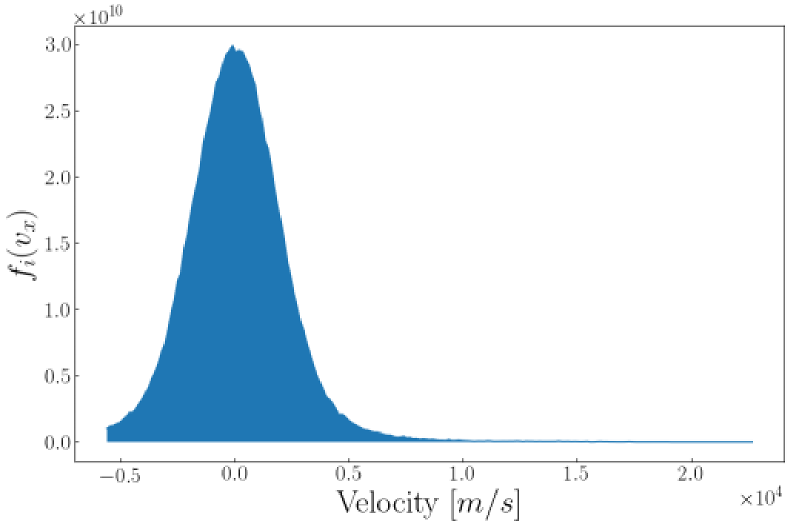
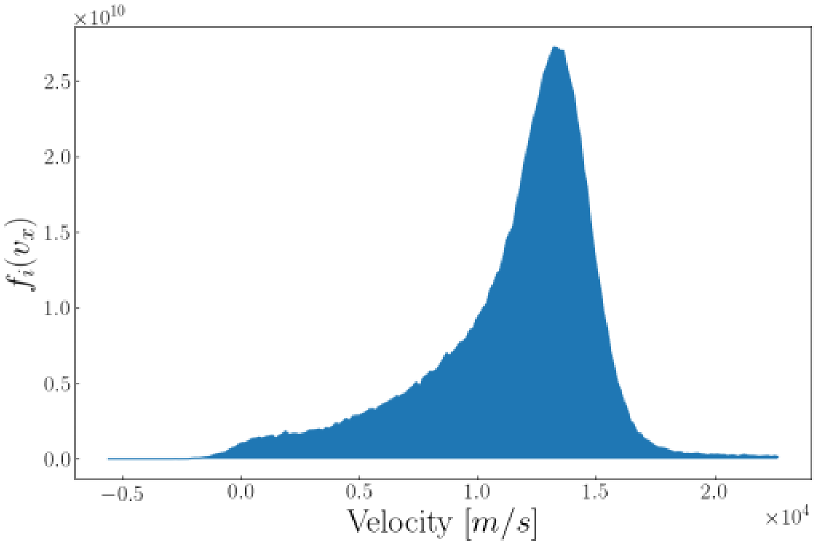
KNOWN: ION-NEUTRAL COLLISION LEAD TO ION HEATING IN THE PRESEHATH

- **Ionization and charge-exchange collisions in the presheath produce low-velocity ions broadening the ion velocity distribution function (IVDF)**
  - **expected to be negligible at pressures < 0.1 mTorr (L = 0.5 m; i-n mfp = 1-10 m)**



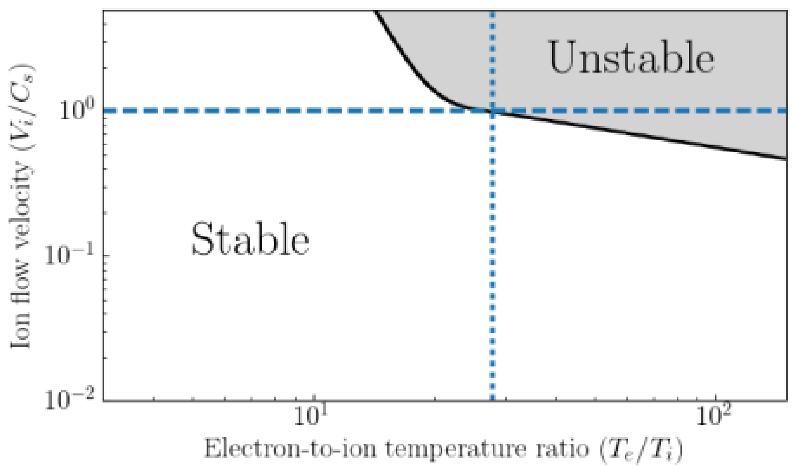
- **Example of IVDF in bulk**

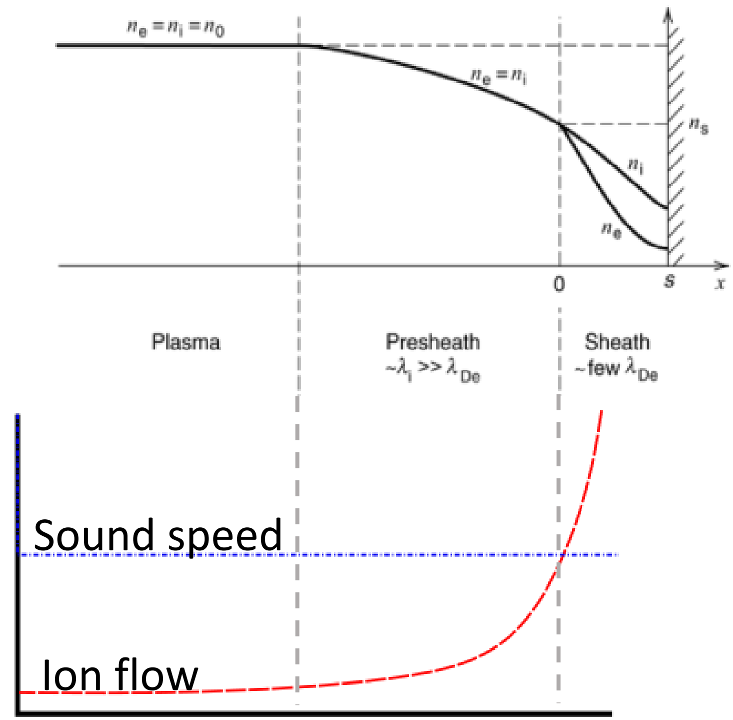


- **Example of IVDF in presheath**

ION-ACOUSTIC INSTABILITIES CAN INCREASE COLLISIONS BETWEEN e^- & i^+, HEATING i^+

- **Ion-acoustic instabilities are excited when the ion velocity is near the sound speed and the electron-to-ion temperature ratio is high**
  - **For ions near room temperature, the minimum electron temperature to excite instability is 0.7 eV**





- **sketch of the density and ion flow speed through the presheath**

M. Lieberman and A. Lichtenberg. *Principles of Plasma Discharges and Material Processing*. Wiley (2005)

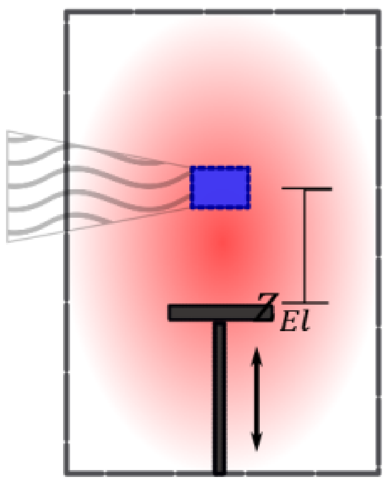
ION-ACOUSTIC FLUCTUATIONS HAVE BEEN MEASURED IN THE PRESHEATH

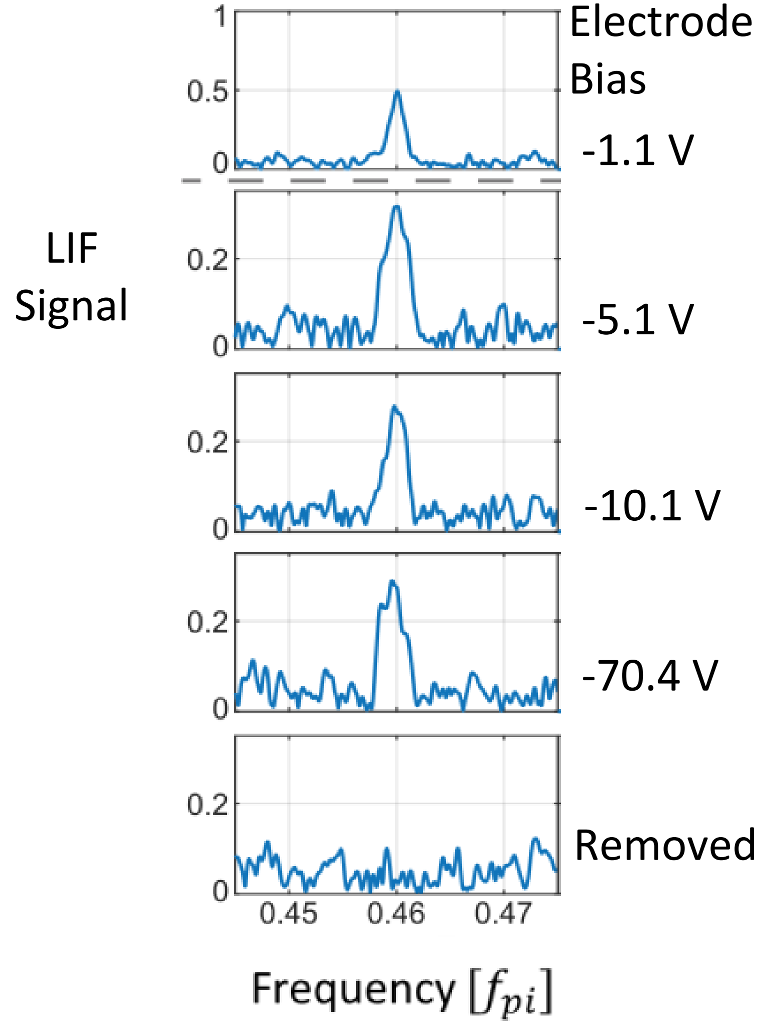
- **Fluctuations were measured in an e-Ar plasma using laser-induced-fluorescence (LIF)**
  - **density ~ 9 × 10^8 /cc**
  - **electron temperature ~ 5 eV**
  - **measurements were made about 100 debye lengths from a biased electrode (Z_{El} ~ 6 cm)**

Blue = LIF viewing volume

Grey = Movable, biased Electrode

Hood R, et al. *Physics of Plasmas.* **27** (2020) 053509





HYPOTHESIS: ION-ACOUSTIC INSTABILITIES EXCITED NEAR THE SHEATH EDGE LEAD TO ION HEATING

- **Use PIC sims to test the hypothesis**
- **Instabilities can enhance the energy exchange between the ions and electrons, heating the ions since $T_e > T_i$**
  - **Test by changing T_e across the threshold for instability (T_e = 0.7 eV)**
  - **Test by calculating electron-ion energy exchange rate using the ion temperature equation**
  - **Test if instabilities are present by comparing to a uniform plasma simulation**
- **Instabilities reflect off of the sheath, heating ions far from the sheath**
  - **Test by computing energy in fluctuations moving toward and away from sheath**

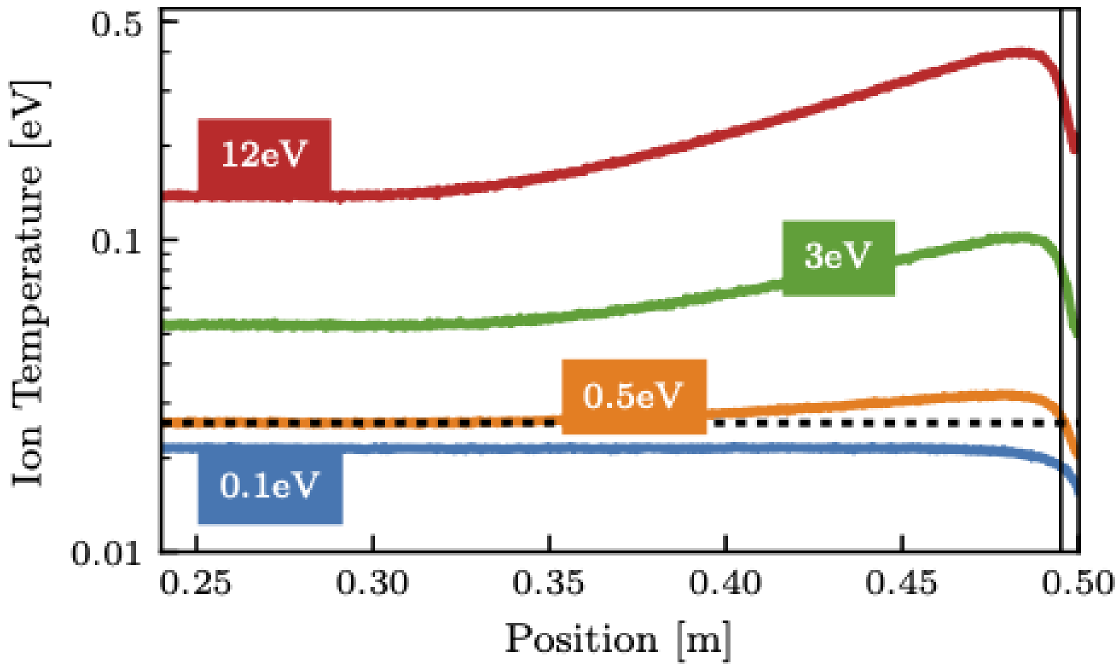
PARTICLE-IN-CELL SIMULATIONS WITH ABSORBING BOUNDARY CONDITIONS PRODUCE A PRESHEATH

- 1D simulations with 3 velocity dimensions using Aleph
  - 50 cm long domain
  - 1,600 cells
  - T_e/n_0 constant; Debye length constant (0.07 cm)
- 2 types of particles: electrons and He ions
- plasma sourced uniform in space and constant in time
  - represents uniform ionization by primary electrons

$T_e^s(eV)$	$T_e(eV)$	$n_0(\#/m^3)$
0.1	0.08	1×10^{13}
0.2	0.16	2×10^{13}
0.5	0.41	5×10^{13}
0.8	0.65	8×10^{13}
1.5	1.25	1.5×10^{14}
3	2.58	3×10^{14}
6	5.40	6×10^{14}
12	11.50	1.2×10^{15}
24	25.10	2.4×10^{15}
48	42.80	4.8×10^{15}

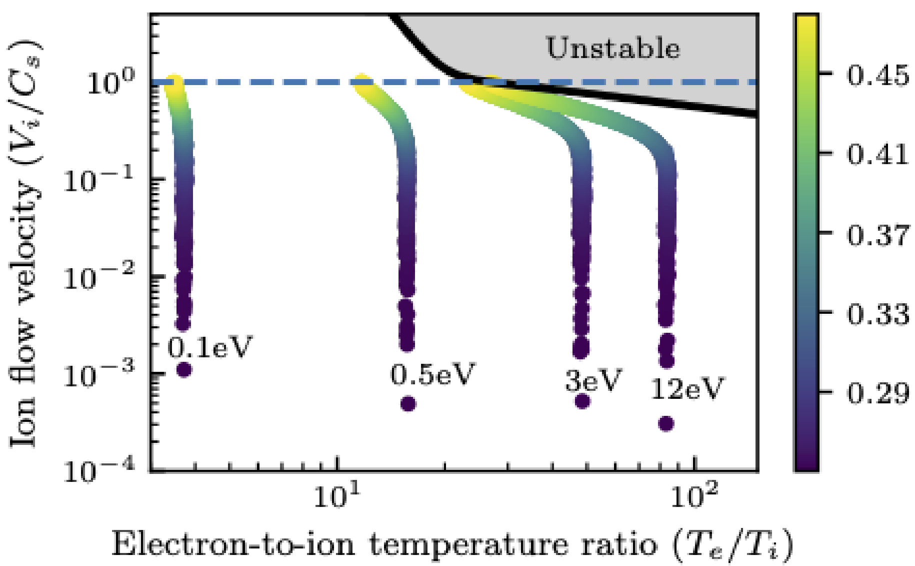
- Source electron temperature, steady-state electron temperature, plasma density

SIGNIFICANT ION HEATING IN THE PRESHEATH, WHEN T_e IS ABOVE THRESHOLD FOR INSTABILITY

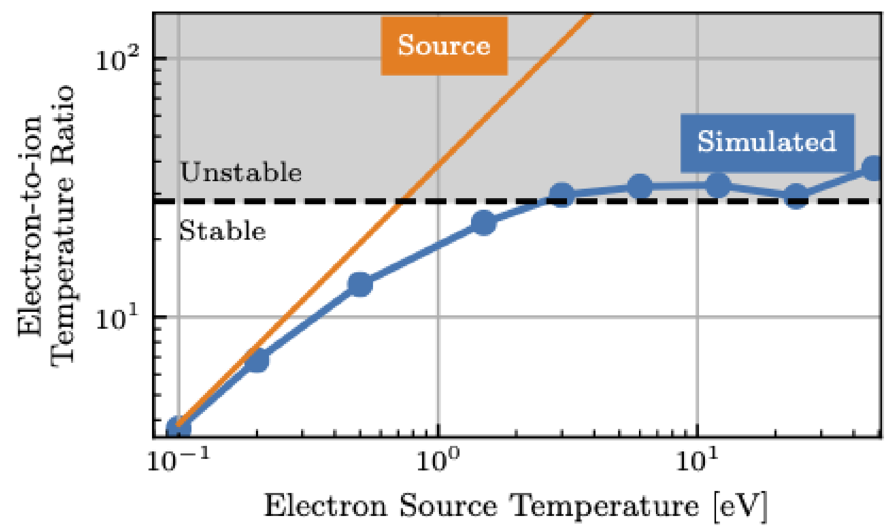


- **Simulated ion temperature from the center (0.25 m) to the sheath edge (vertical line). Horizontal dashed line is the ion source temperature (0.26 eV).**

T_e/T_i AT THE SHEATH EDGE LOCKS TO THE THRESHOLD VALUE WHEN T_e IS ABOVE 0.7 eV



- Simulated average ion velocity and temperature ratio from the center (black) to sheath edge (yellow)

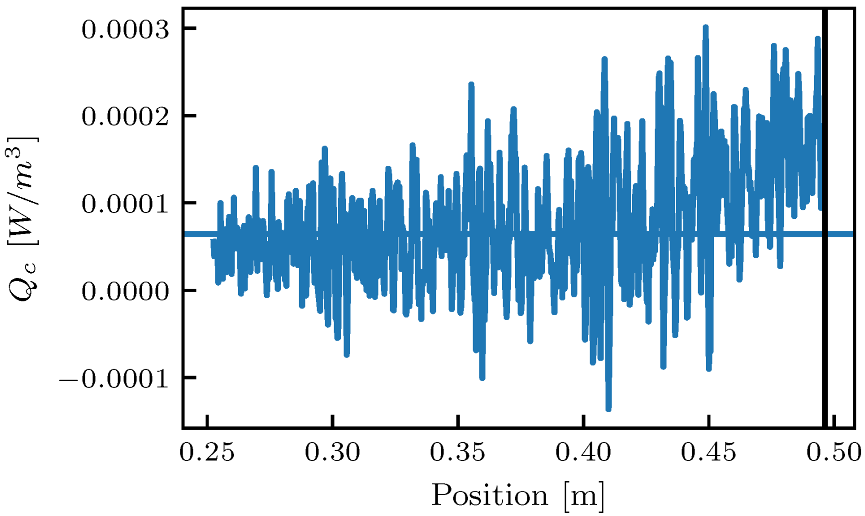


- Simulated electron-to-ion temperature ratio at the sheath edge for different source electron temperatures

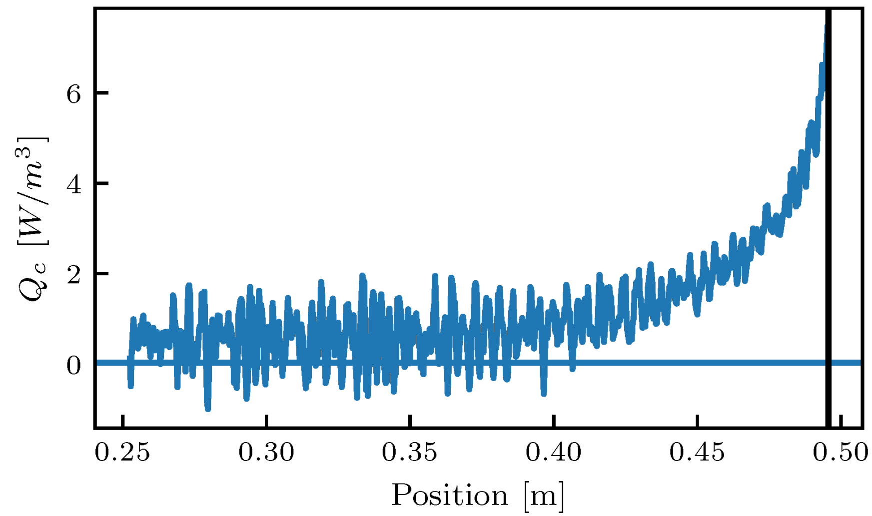
- **Instabilities determine the ion temperature at the sheath edge**
  $T_i = T_e/28$

INSTABILITIES ENHANCE ELECTRON-ION ENERGY EXCHANGE

No instabilities expected T_e = 0.1 eV



Instabilities expected T_e = 6 eV

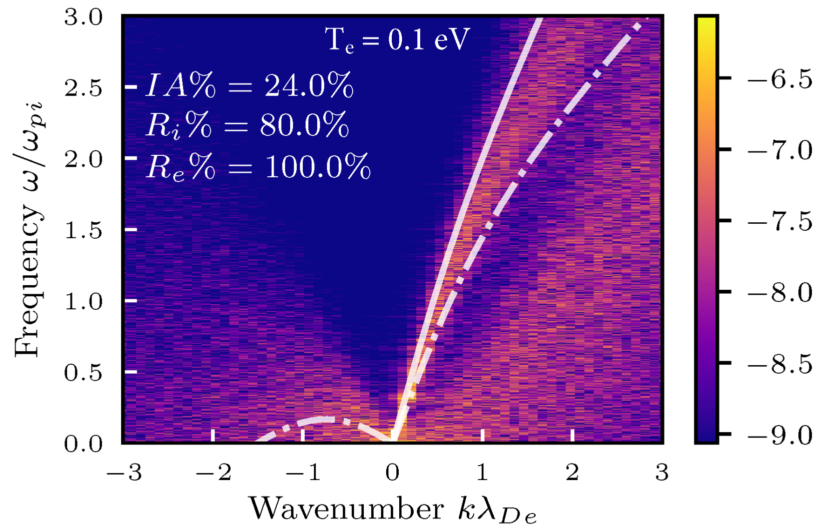


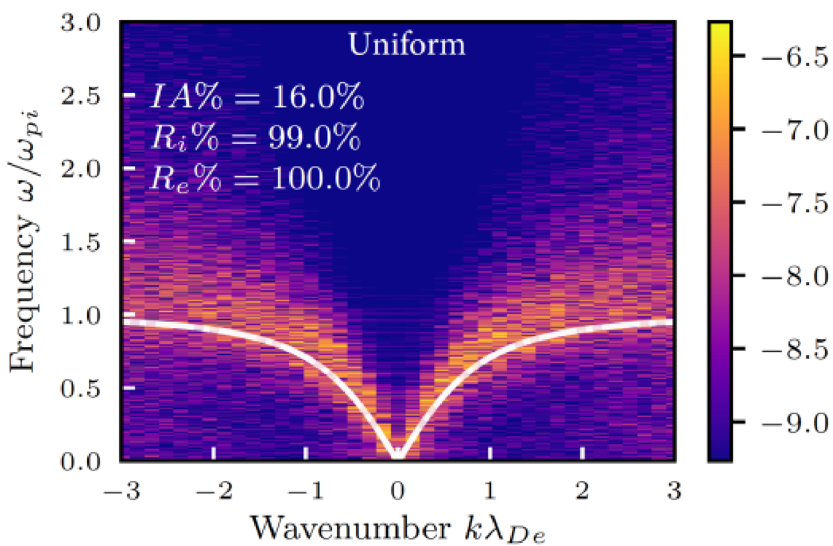
$$\frac{3}{2}n_iV_i^x\frac{\mathrm{d}T_i^x}{\mathrm{d}x}+n_iT_i^x\frac{\mathrm{d}V_i^x}{\mathrm{d}x}+\frac{\mathrm{d}q_i^x}{\mathrm{d}x}+\pi_i^{xx}\frac{\mathrm{d}V_i^x}{\mathrm{d}x}=Q_c+\frac{3}{2}\nu_i^s n_i T_i^s$$

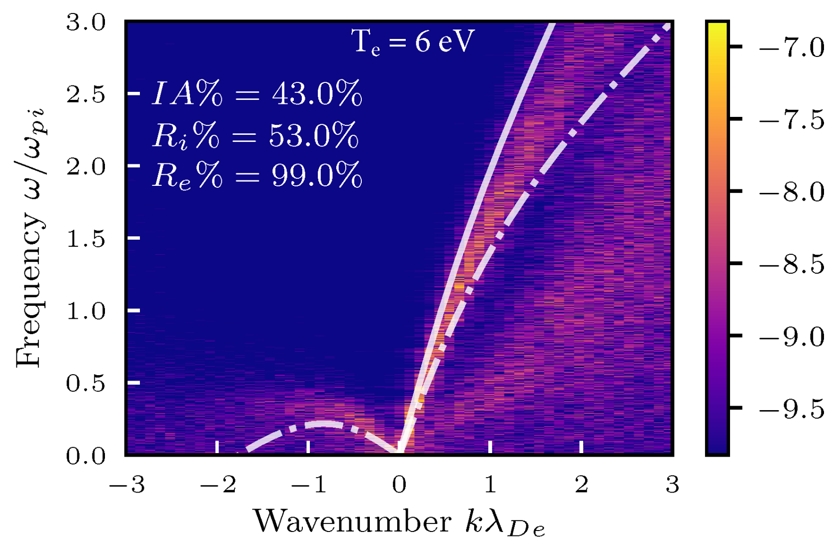
- Ion energy balance equation, where Q_c is the e-I energy exchange rate

INCREASED ION-ACOUSTIC ACTIVITY WHEN INSTABILITIES ARE PREDICTED

- **Uniform plasma simulated using reflecting boundaries and no sources**
  - **used as the baseline for the percentage of fluctuations that are ion-acoustic (near dispersion curves in white)**







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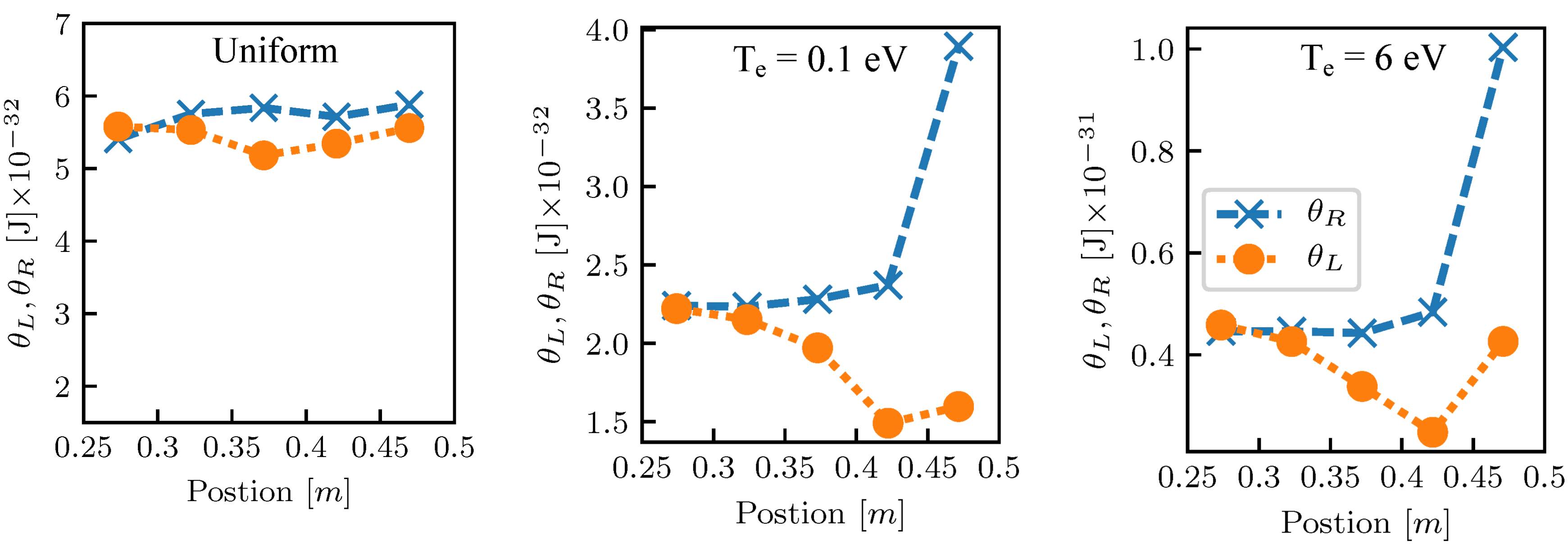
ION-ACOUSTIC FLUCTUATIONS ARE REFLECTED FROM THE SHEATH

$$\mathcal{E}(k) = V \int \frac{\hat{\rho}^2}{2\epsilon_0 k^2}\,\mathrm{d}\omega$$

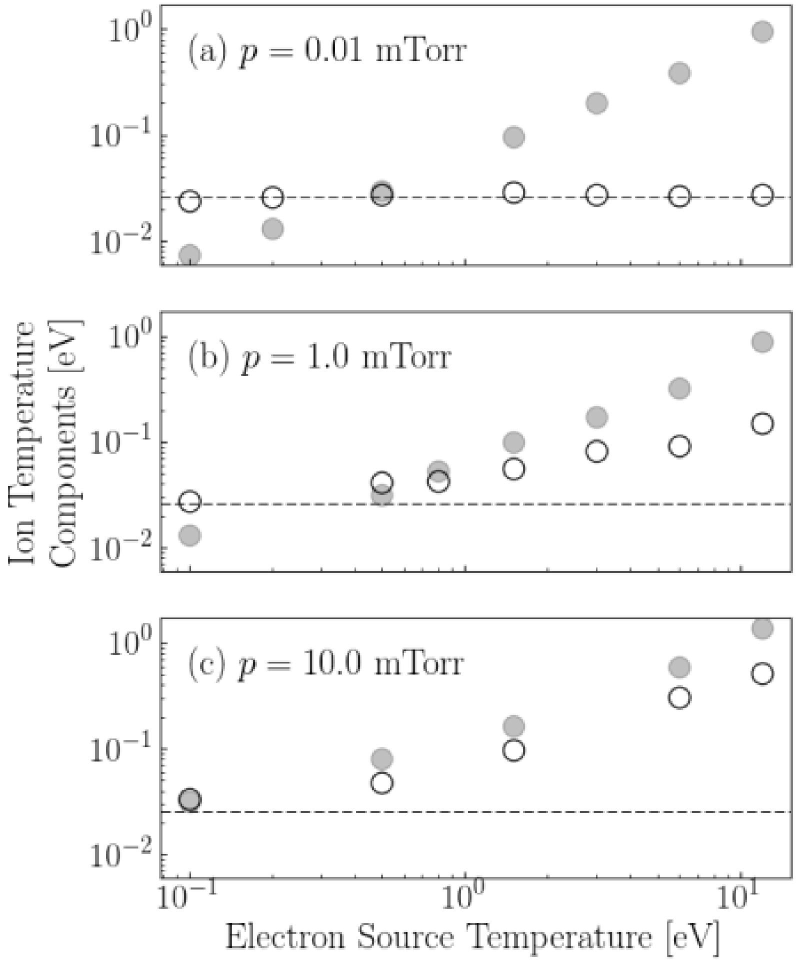
$$\theta_L = \frac{1}{n_i}\int_{IA,k<0} \mathcal{E}(k)\,\mathrm{d}k$$

$$\theta_R = \frac{1}{n_i}\int_{IA,k>0} \mathcal{E}(k)\,\mathrm{d}k$$



THE ION HEATING FROM THE INSTABILITIES IS OBSERVED TO BE HIGHLY ANISOTROPIC

- **At sub mTorr pressures (and T_e > 0.7 eV) instability heating dominates**
  - **heating only in parallel direction**
- **At pressures above 3 mTorr ionization and ion-neutral collisions determine ion heating**
  - **instabilities are damped by neutral collisions**
  - **heating isotropic**



CONCLUSIONS

- Instabilities set ion temperature at the sheath edge $T_i = T_e/28$
- Ion-acoustic instabilities are excited near the sheath-presheath boundary by the ion flow when T_e > 0.7 eV and at low pressures (<.1 mTorr)
- The electron-ion collisions rate is enhanced by the instabilities and the ions heat significantly
- The ion-acoustic fluctuation level is enhanced in simulations where instability is expected, consistent with the presence of instabilities
- Ion-acoustic fluctuations reflect from the sheath, a likely mechanism for the ion heating observed far from the sheath
- The instability heating is concentrated along 1 velocity dimension unlike the heating observed from neutral collisions at higher pressures (>1 mTorr)

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