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# Linear and Nonlinear Dust Acoustic Waves, Shocks and Stationary Structures in DC-Glow-Discharge Dusty Plasma Experiments

THE UNIVERSITY OF IOWA

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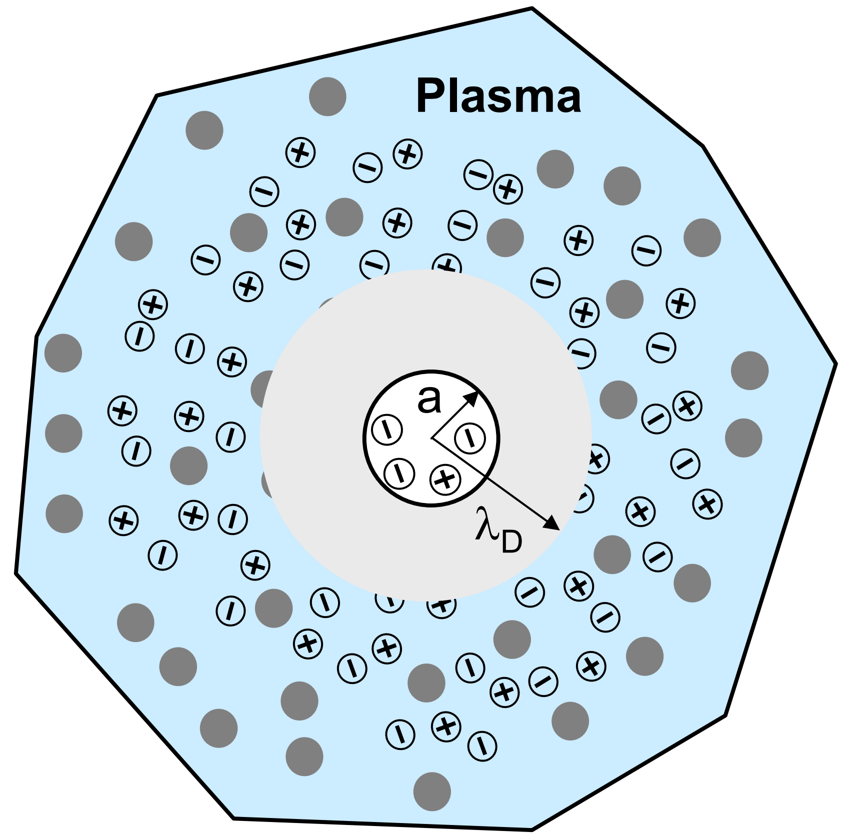
# Outline

- Introduction – What is a dusty plasma?
- What is a dust acoustic wave?
- How are DAW observed in the lab?
  - nonlinear DAW
  - dust acoustic shock waves
  - observations of linear DAW
- Structurization instability

# What is a dusty plasma?

- A four component system, consisting of electrons, ions, neutral atoms and micron size solid particles (dust)
- The dust is charged by collecting electrons and ions (more electrons)
- A particle with a = 1 μm in a plasma with $T_e$ = 2 eV and $T_i$ = 0.03 eV will have a Q ~ – 4000 e.
- Charged dust particles interacts collectively with the plasma



# The linear dust acoustic wave

- P. K. Shukla, 1st Capri Workshop on dusty plasmas,1989
- Rao, Shukla, Yu, Planet. Space Sci. 38, 543, 1990 (linear & nonlinear theory)

- **Dust Acoustic Wave** $\rightarrow$ A low frequency, compressional dust density wave

- **dust :** $m_d\,,\ Q_d = -eZ_d\,, n_d\,,\ u_d\,,\ T_d \ = 0 \ \rightarrow \ \frac{\partial n_d}{\partial t} = -n_{do}\frac{\partial u_d}{\partial x}; \qquad \frac{\partial u_d}{\partial t} = \frac{eZ_d}{m_d}\frac{\partial \varphi}{\partial x}$

- **electrons/ions :** Boltzmann equilibrium $\rightarrow \ n_{e(i)} = n_{e(i)0}\left(\pm e\varphi / kT_{e(i)}\right)$

- **charge neutrality :** $n_i = n_e + Z_d n_d \ \rightarrow \ \varphi = -\left(eZ_d \lambda_D^2 / \varepsilon_o\right) n_d; \quad \lambda_D^{-2} = \lambda_{De}^{-2} + \lambda_{Di}^{-2}$

- $\frac{\partial^2 n_d}{\partial x^2} = \frac{1}{C_{DA}^2}\frac{\partial^2 n_d}{\partial t^2} \rightarrow$ **dispersion relation**: $\quad \frac{\omega}{K} = C_{DA} = \lambda_D \omega_{pd}$

# Dust acoustic speed

$$C_{DA} = \lambda_D \omega_{pd} \approx \lambda_{Di} \omega_{pd}, \text{ for } T_i << T_e$$

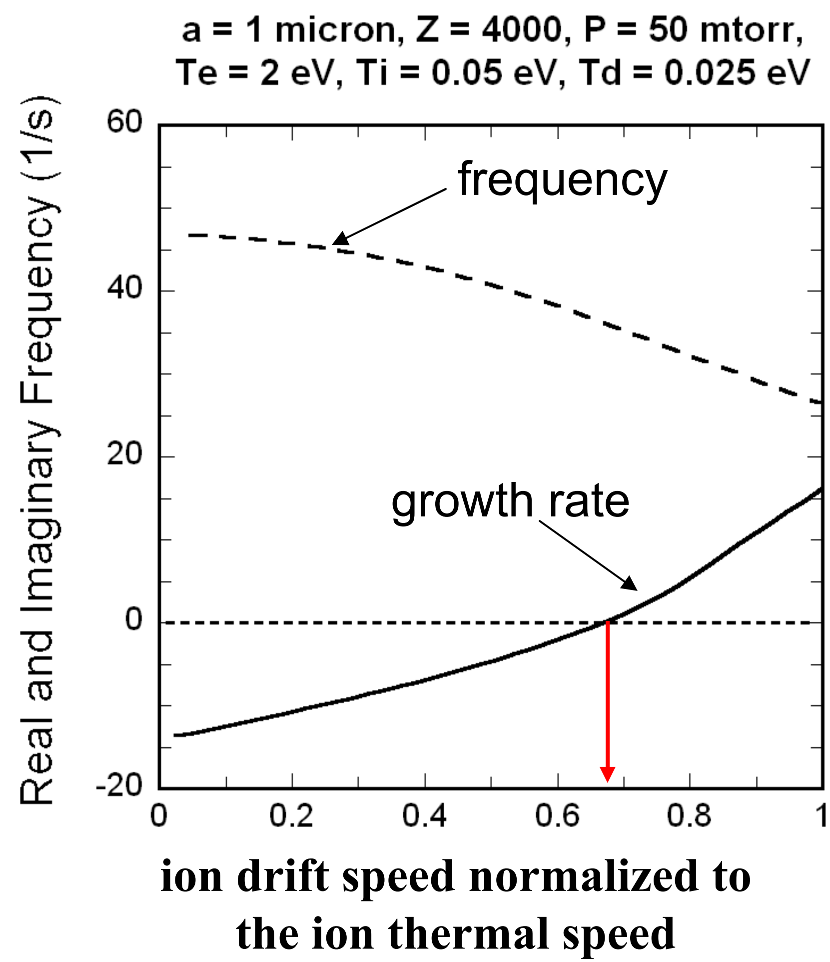
$$C_{DA} = \sqrt{\frac{n_d}{n_i} \frac{Z^2 k T_i}{M}}$$

For a “typical” laboratory dusty plasma:

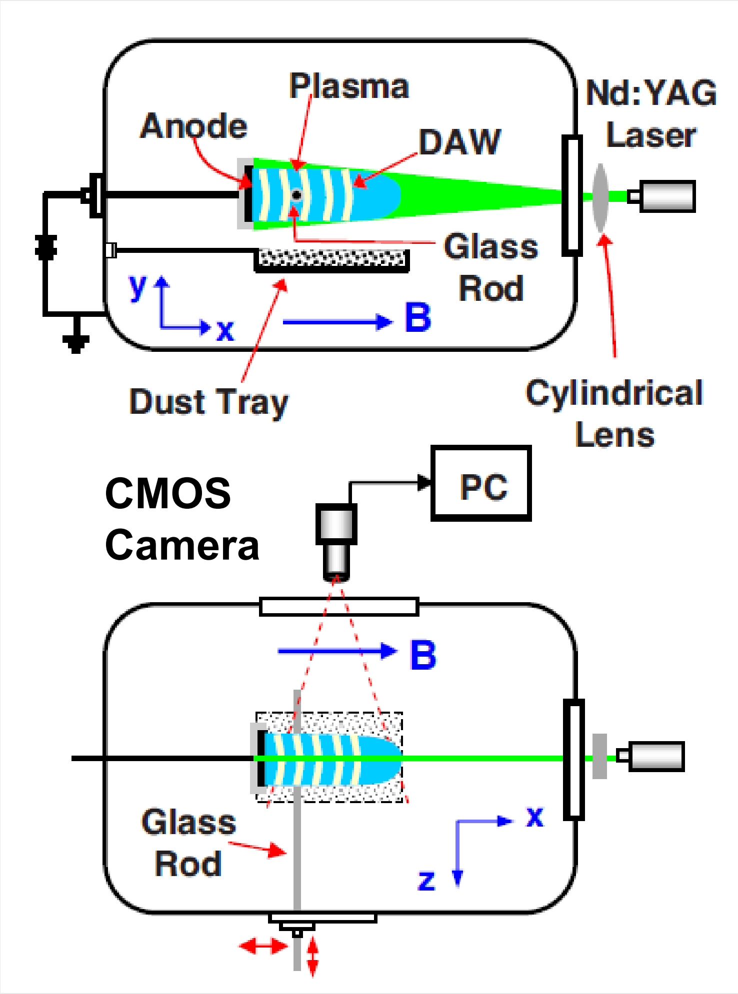
- $T_e$ = 2.5 eV, $T_i$ = 0.025 eV
- Dust diameter = 1 $\mu$m (glass)
- $m_d \sim 10^{-15}$ kg, $Z_d \sim 2000$, $n_{do}/n_{io} \sim 10^{-4}$
- $C_{DA} \sim 5$ cm/s, $\lambda \sim 1$ cm → $f \sim 5$ Hz

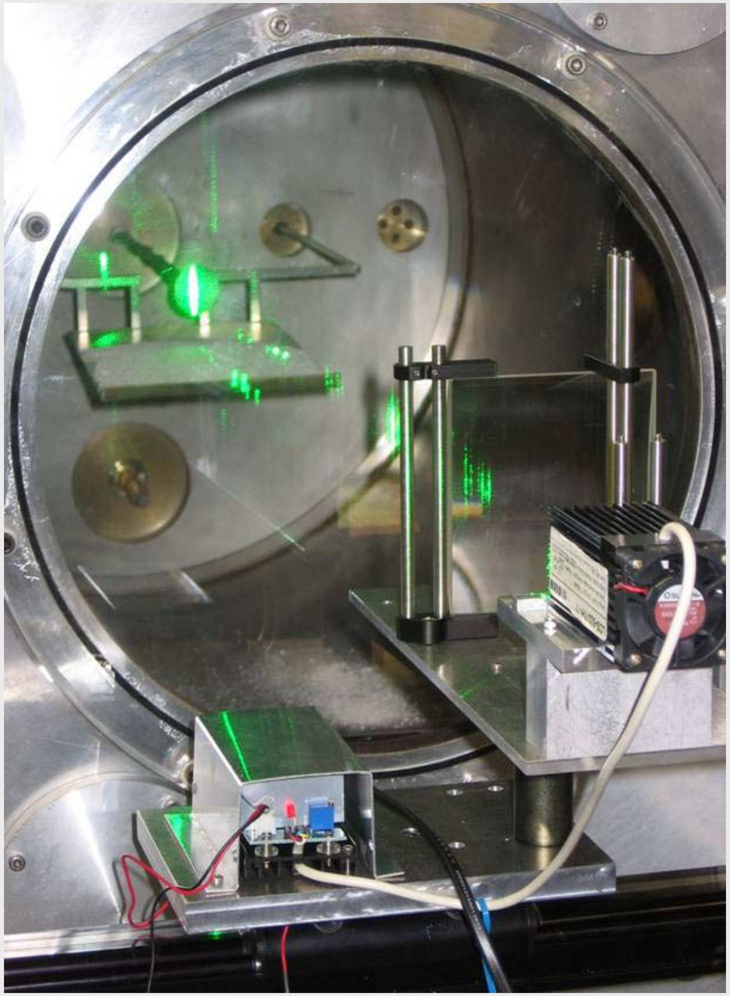
# Excitation of the DAW

- The DAW can be excited by an ion-dust streaming instability
- Instability occurs for relatively modest ion drifts that are typically present in discharge plasmas
- This instability can be analyzed using either kinetic theory, or fluid theory, treating the dust as a third plasma component
- Using fluid theory, the instability can be analyzed, with the ion drift resulting from a balance of a zero order E and ion-neutral collisions



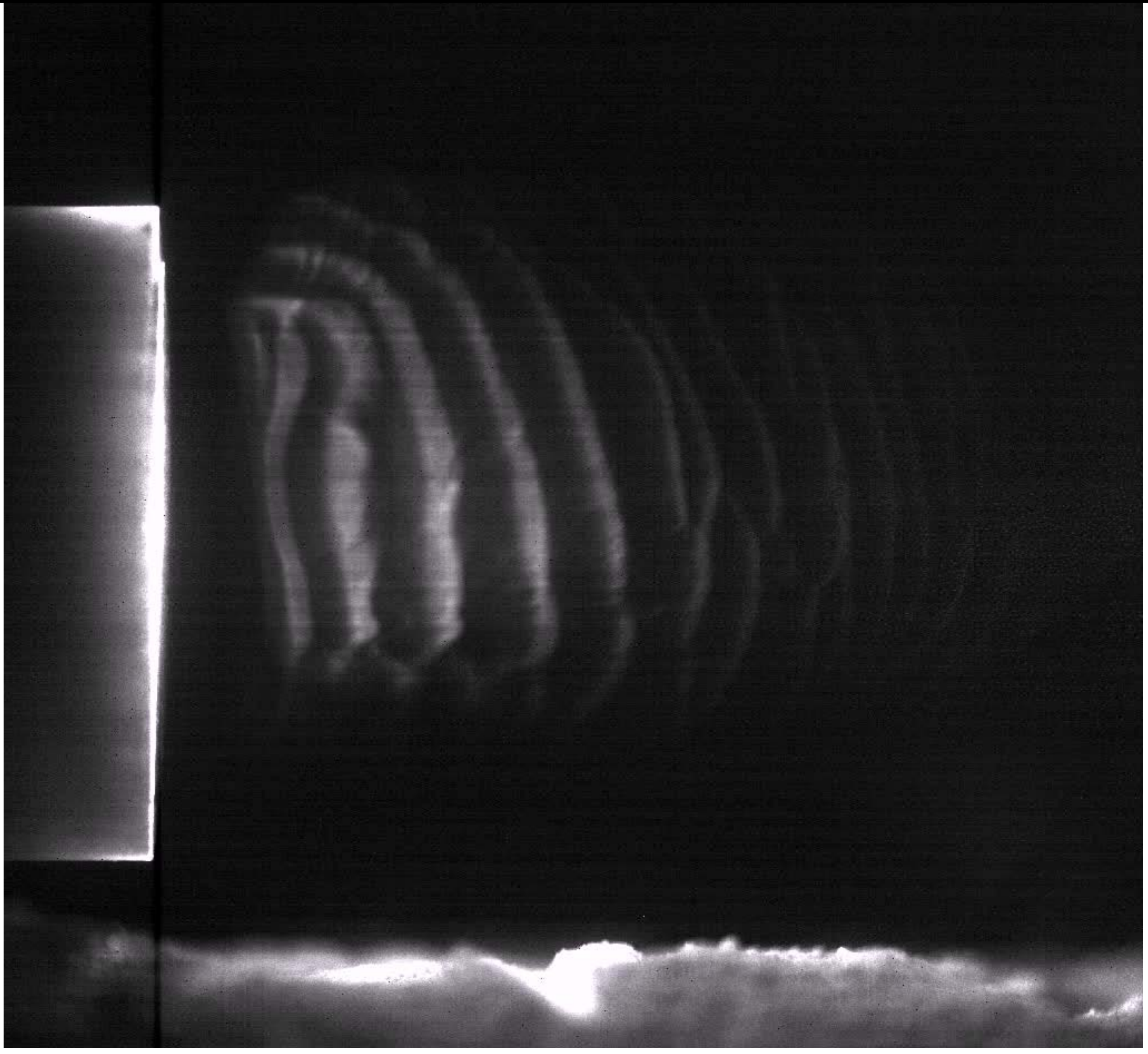
# Dusty plasma device



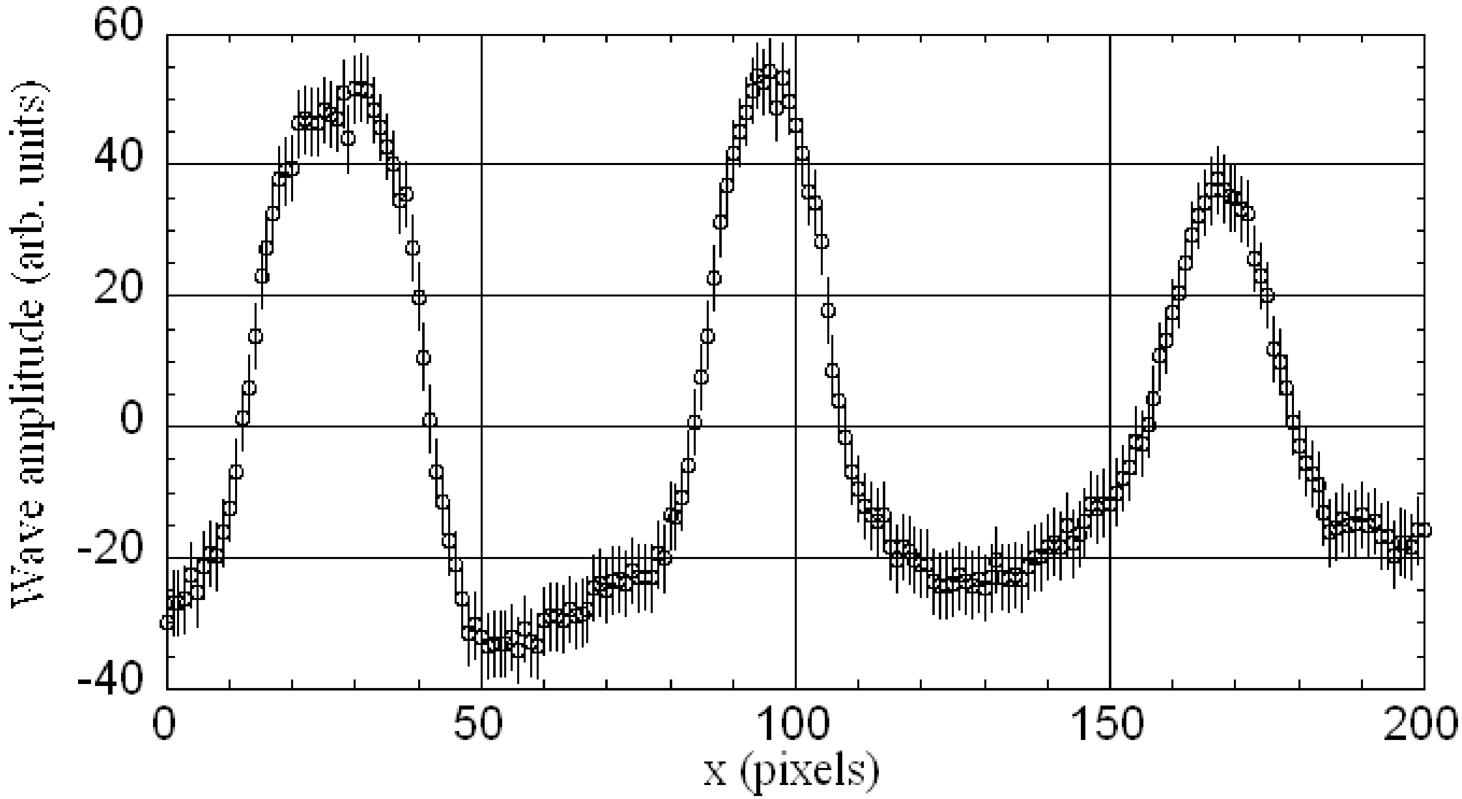



**Dust:** kaolin powder (μm), glass spheres (1 μm), iron spheres (μm)
**Plasma:** argon, 10 – 20 Pa, $n_i \sim 10^{15}\ m^{-3}$, $T_e \approx 100\ T_i \approx 2\text{-}3$ eV

# A spontaneously excited dust acoustic wave

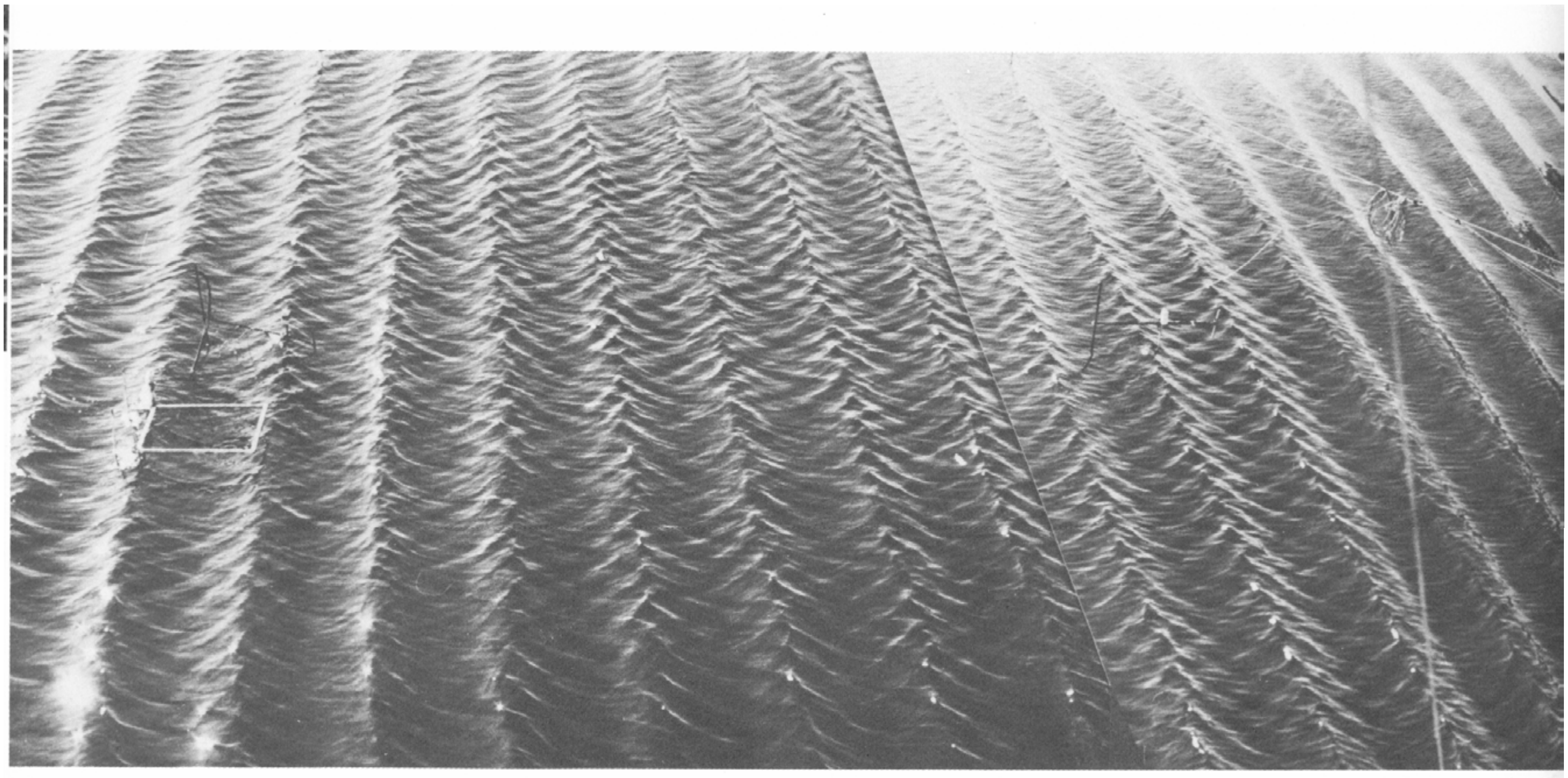


# Typical dust acoustic waveform




* Crests are sharper and troughs are flatter ➔ nonlinear
* Similar to deep ocean waves

# nonlinear waves in a water tank



# $2^{nd}$ order (Stokes) wave theory

- Perturbation analysis: expand $\eta = (n, v, \varphi)$ as a series in the small parameter, ε to second order: $\eta = \eta_0 + \varepsilon\,\eta_1 + \varepsilon^2\,\eta_2$
- Insert into momentum and continuity equations

$$\underbrace{\frac{\partial^2 n_2}{\partial x^2} - \frac{1}{C_{da}^2}\frac{\partial^2 n_2}{\partial t^2}}_{\text{2nd order quantities}} = \underbrace{A\frac{\partial^2 n_1^2}{\partial x^2} + B\frac{\partial^2 v_1^2}{\partial x^2} + C\frac{\partial^2 (n_1 v_1)}{\partial x \partial t}}_{\text{Products of 1st order quantities}}$$

2nd order quantities

Products of $1^{st}$ order quantities

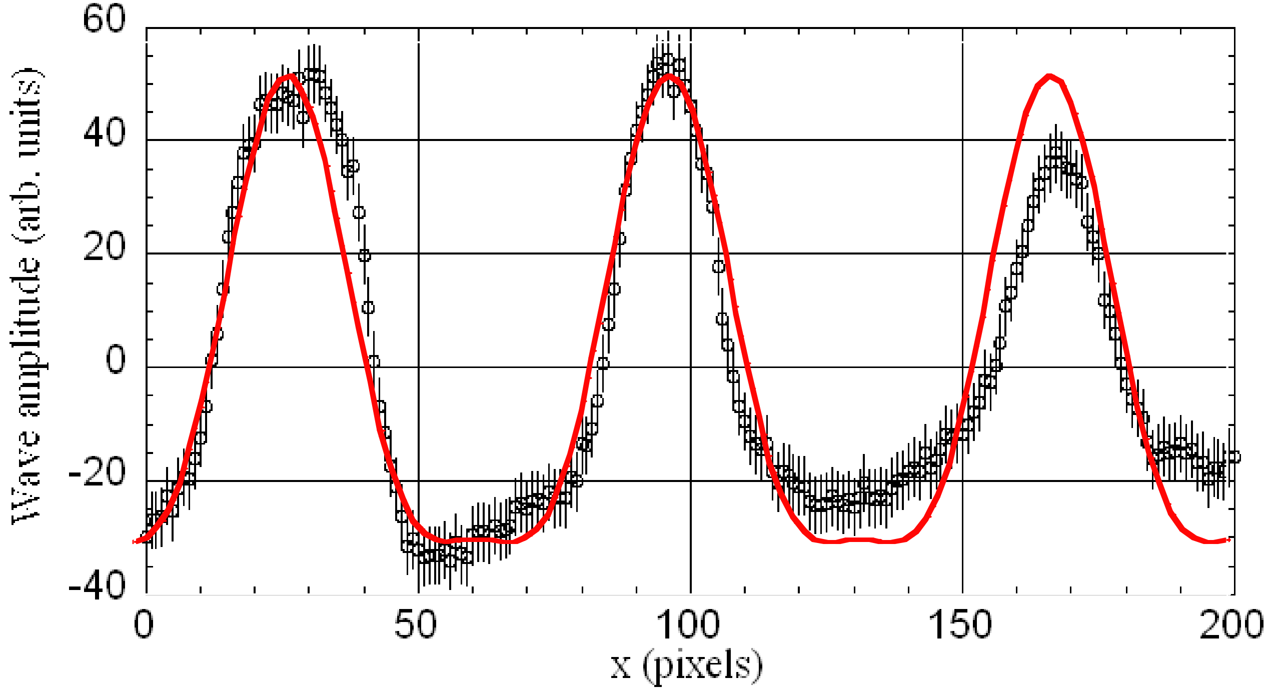
<u>SOLUTION</u>

$$\eta(x,t) = \eta_{01}\cos(kx - \omega t) + \eta_{02}\cos\left[2\left(kx - \omega t\right)\right]$$

Nonlinearity generates $2^{nd}$ harmonic term

# Nonlinear dust acoustic wave

$$\eta(x,0) = \eta_{01}\cos(kx+\varphi) + \eta_{02}\cos[2(kx+\varphi)]$$

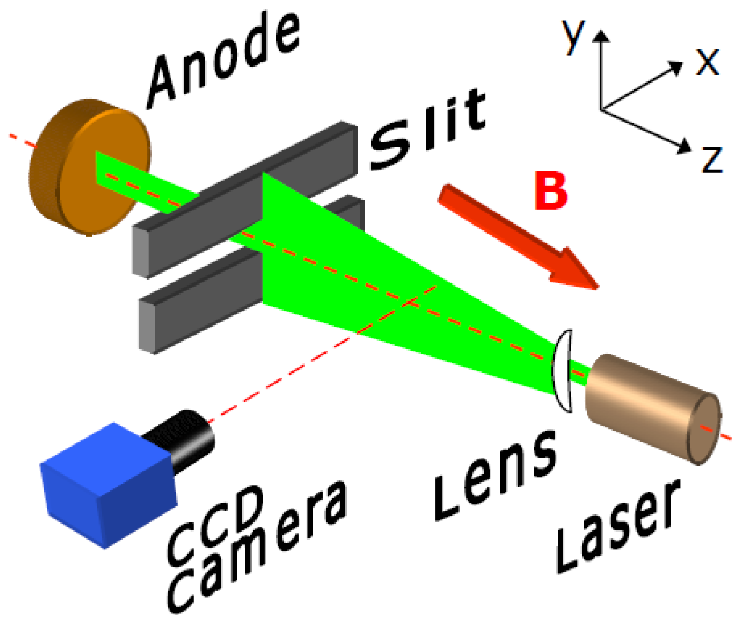



➔ Second order wave theory can account, qualitatively, for the nonlinear dust acoustic waves.

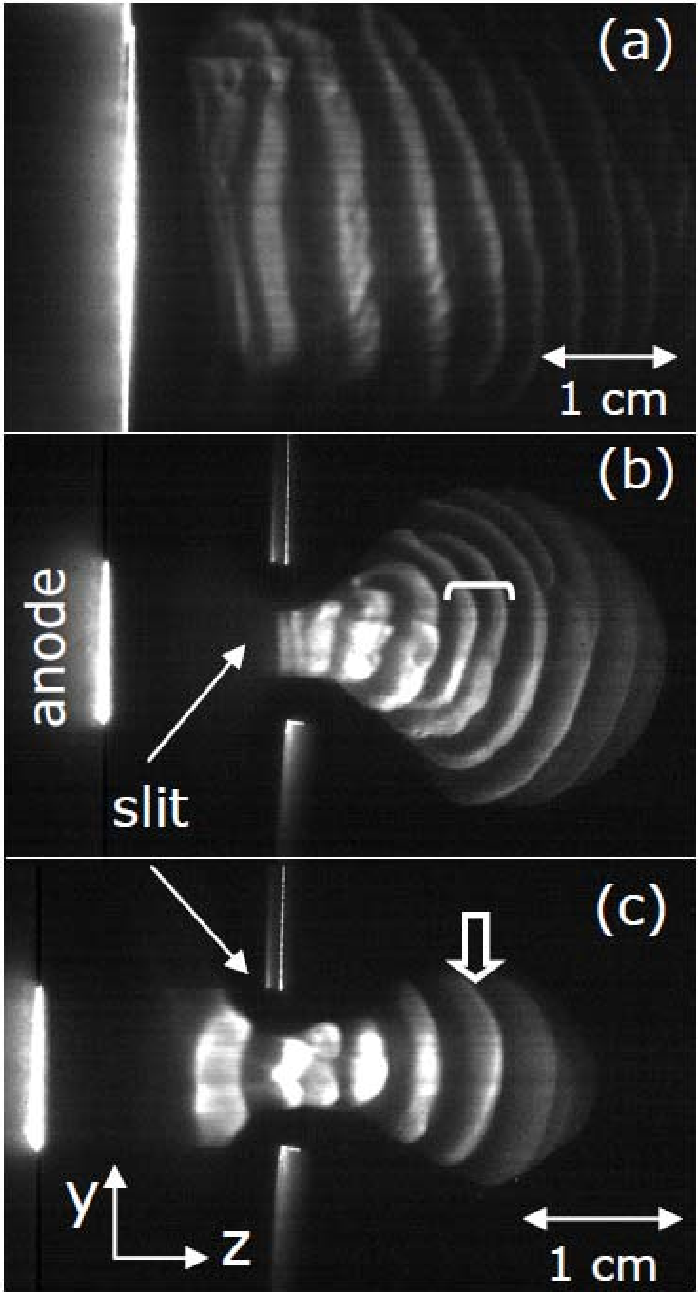
# Dust acoustic shock waves

- Certain features in Saturn's rings may be attributed to dust acoustic waves
- DASW may provide trigger to initiate the condensation of small dust grains into larger ones in dust molecular clouds
- Since DASW can be imaged with fast video cameras, they may be used as a model system to study nonlinear acoustic wave phenomena

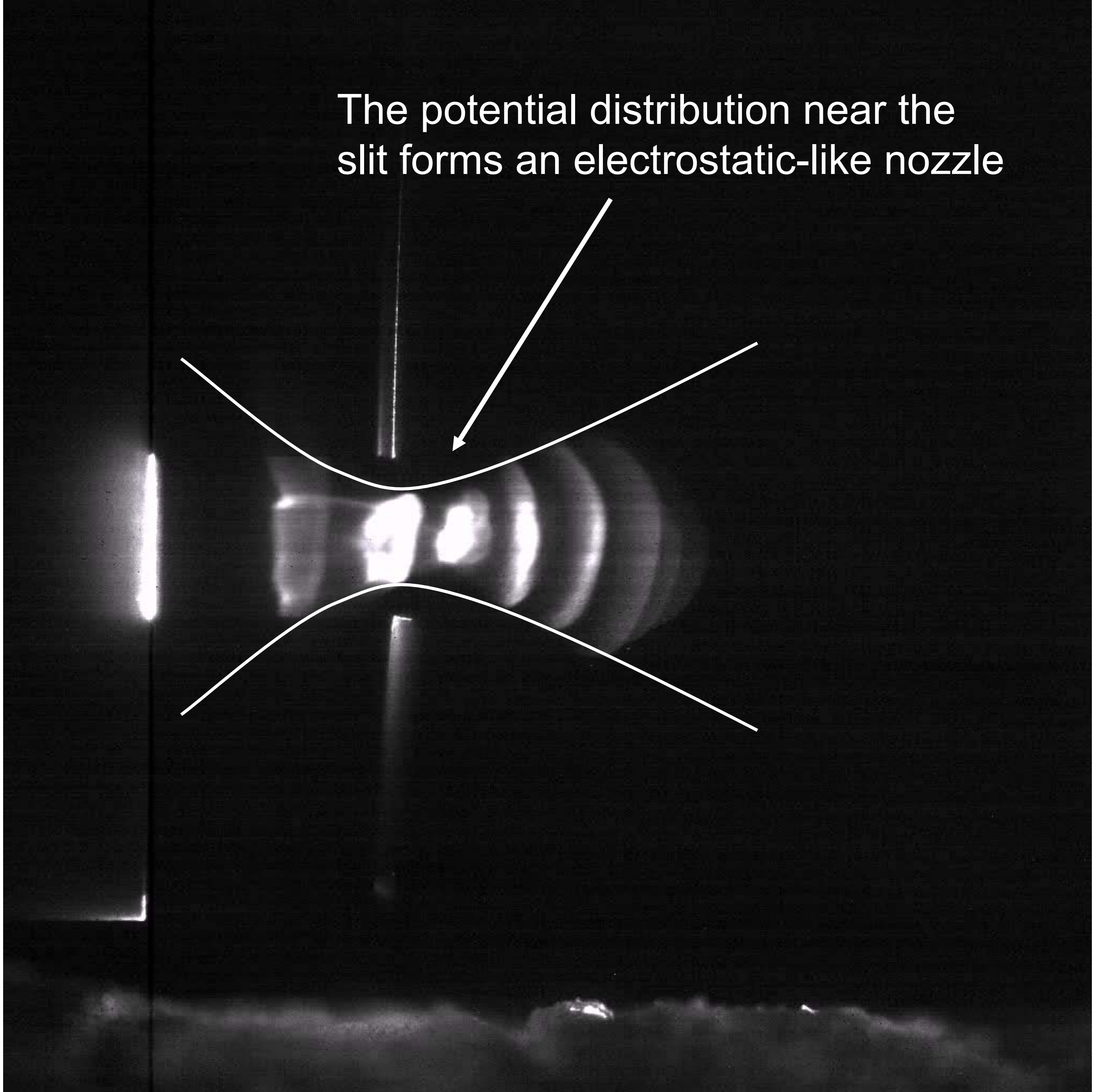
# DA Shocks



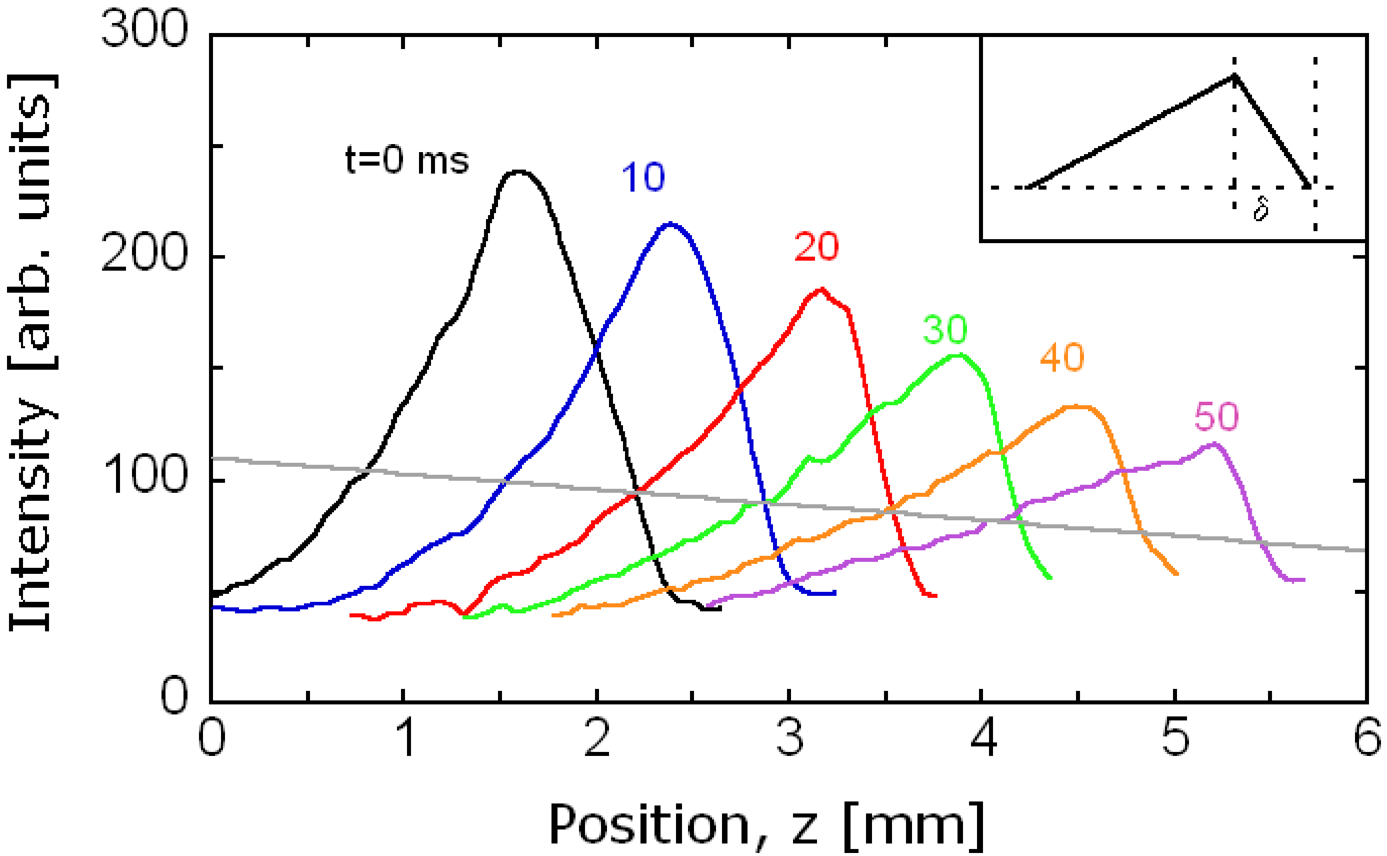
Anode
Slit
y
x
z
B
Lens
Laser
CCD
Camera

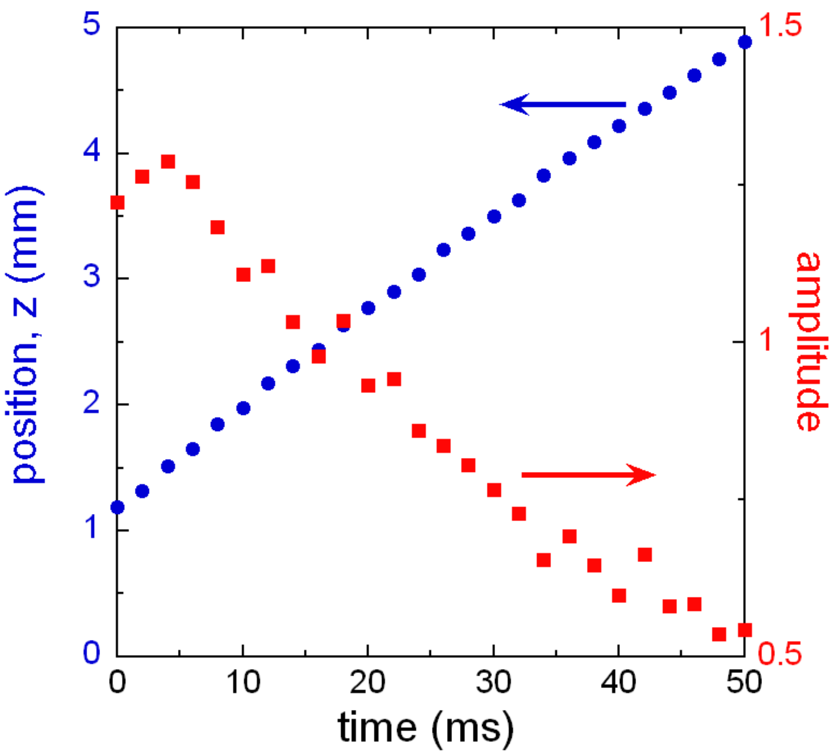
(a)
1 cm
(b)
anode
slit
(c)
y
z
1 cm

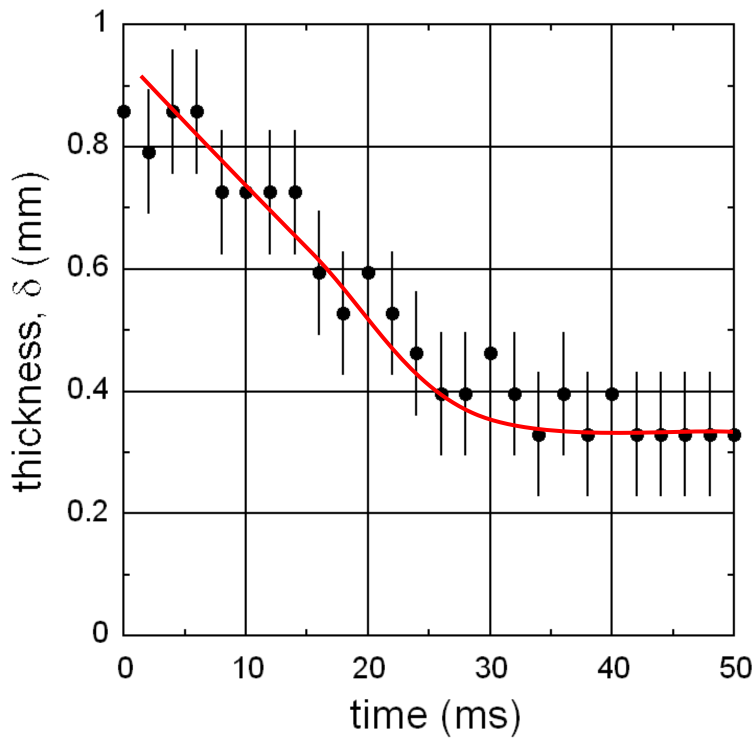

The potential distribution near the
slit forms an electrostatic-like nozzle

# Steepening of shock wave



# Shock position, amplitude and thickness




$$M = \frac{V_s}{C_{DA}} \gtrsim 1$$

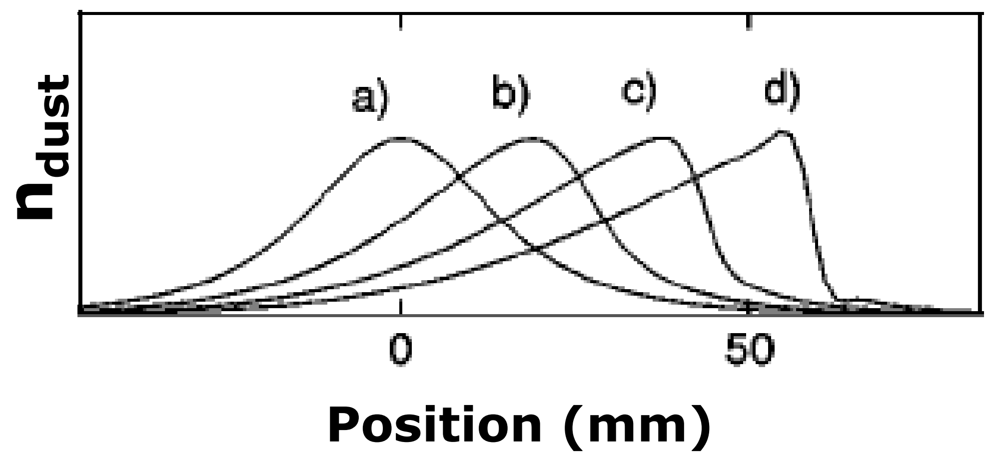
# Shock amplitude and thickness

- Amplitude falls off as $\sim r^{-1}$
- For cylindrical shock, amplitude $\sim r^{-1/2}$
- Faster falloff may indicates dissipation
- Shock width: $\delta \approx$ 0.3 mm
- mean-free path for dust-neutral collisions: $\lambda_{dn} \sim$ 0.1 mm
- Other mechanisms affecting shock width
  - Strong coupling effects
  - Dust charge variation

# Theory: Eliasson & Shukla

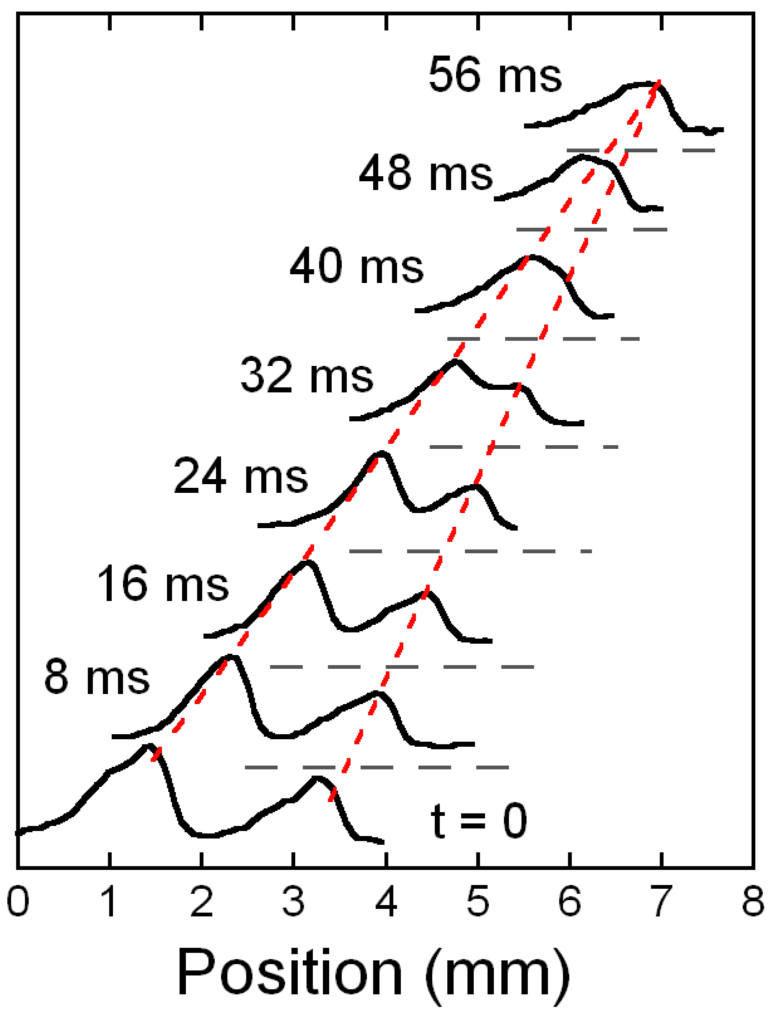
## *Phys. Rev. E 69, 067401 (2004)*

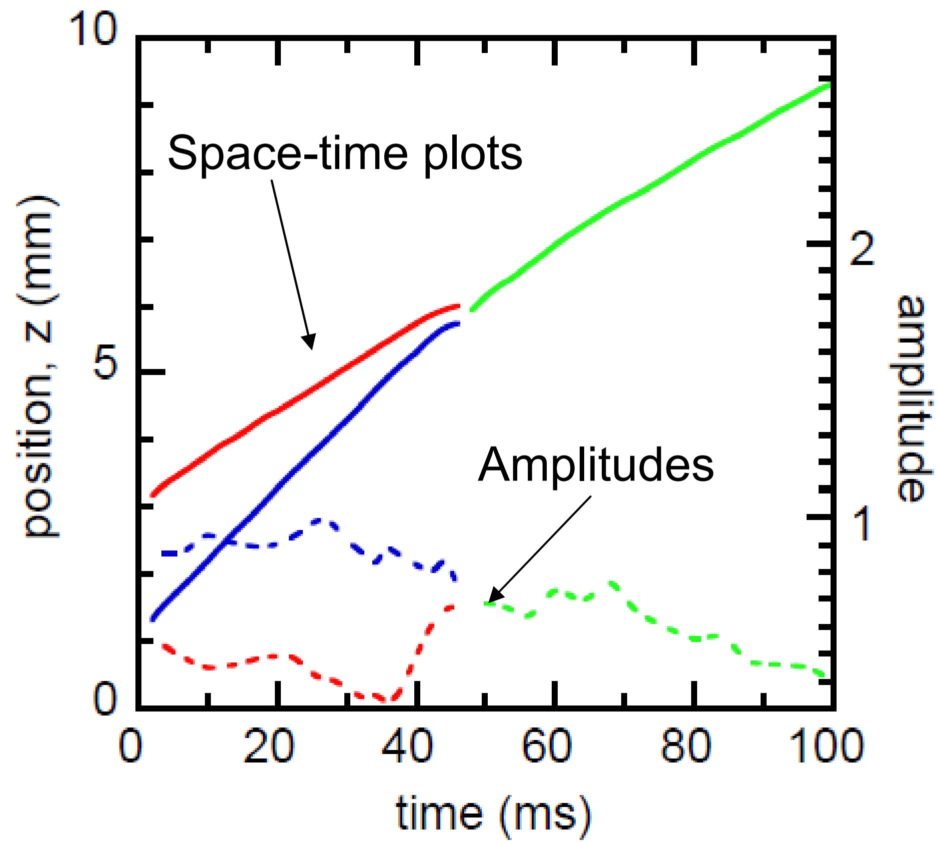
- Nonstationary solutions of fully nonlinear nondispersive DAWs in a dusty plasma




- Numerical calculations for our experimental parameters were performed, validating the observed shock velocity and steepening

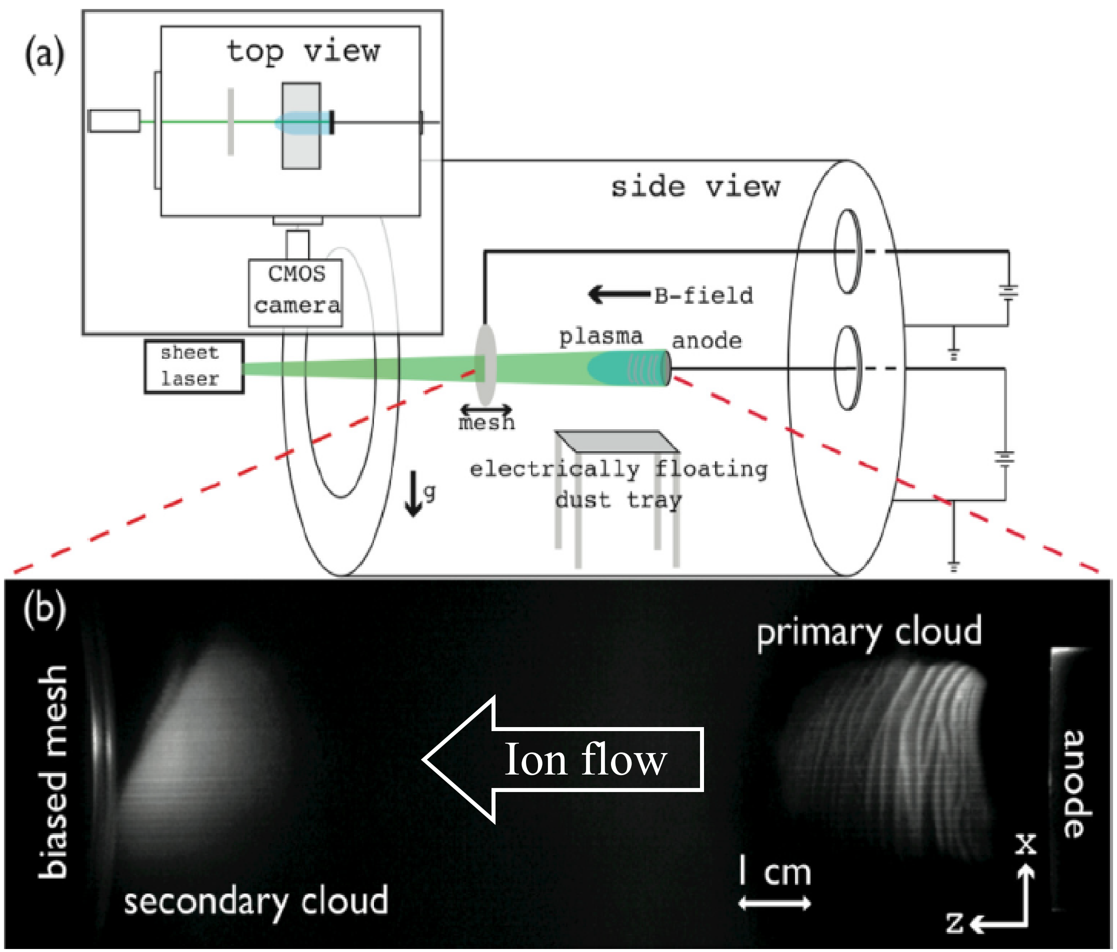
# Confluence of shock waves



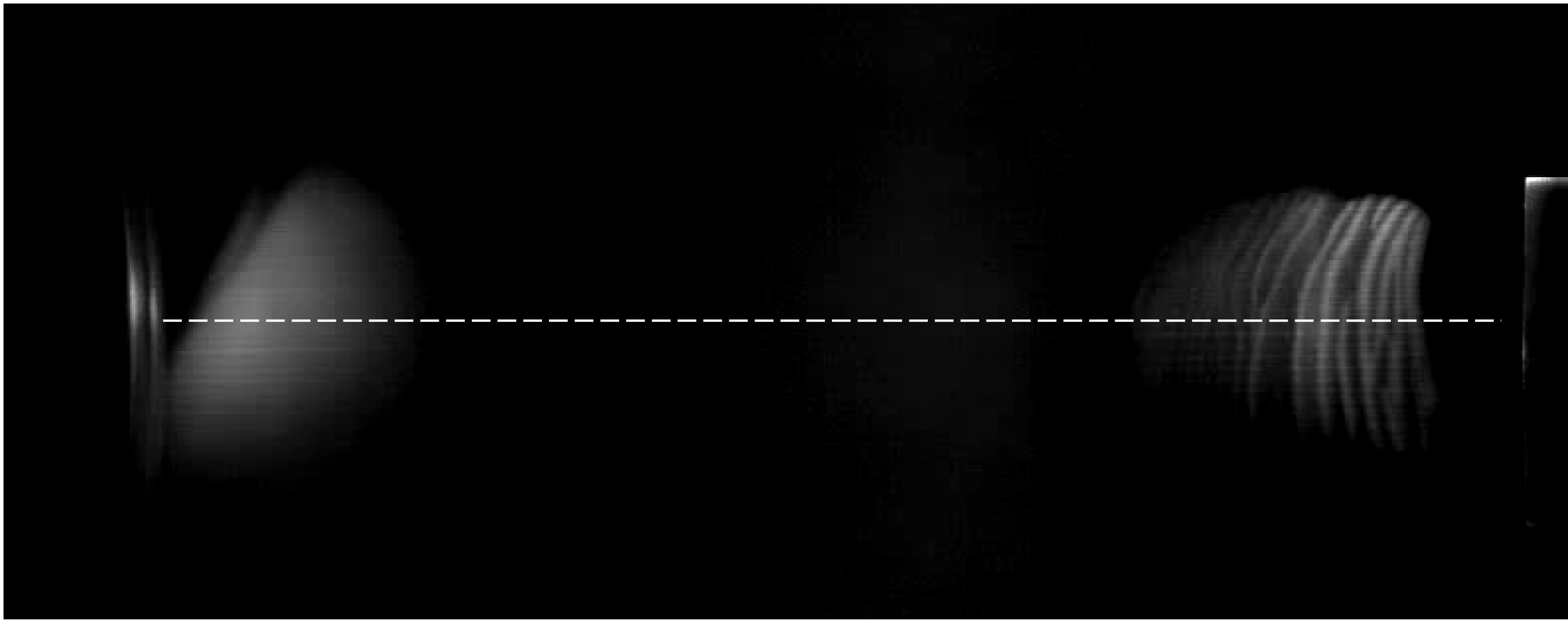




The faster shock overtakes and consumes the slower shock. This is a unique property of shocks

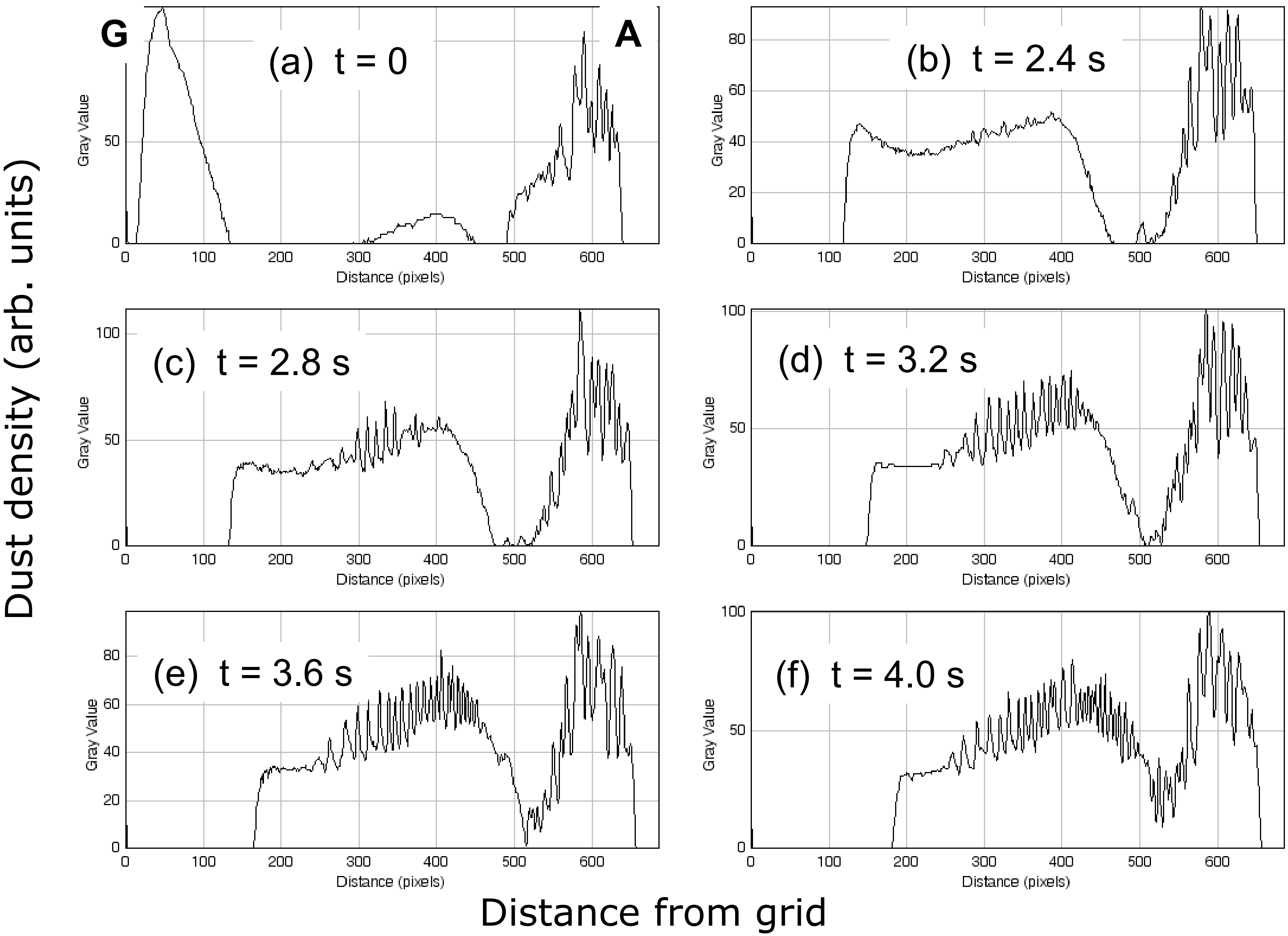
# DAWs in excited a drifting dust cloud




- A secondary dust suspension is trapped in the electrostatic potential formed by a biased grid placed 15 cm from the anode.
- When the bias on the grid is suddenly switched off, the grid returns to its floating potential, and the secondary cloud is released.
- The secondary cloud begins drifting toward the anode.
- When the center of cloud is about 10 cm from the anode, dust acoustic waves begin to be excited in the previously *quiescent* dust suspension.

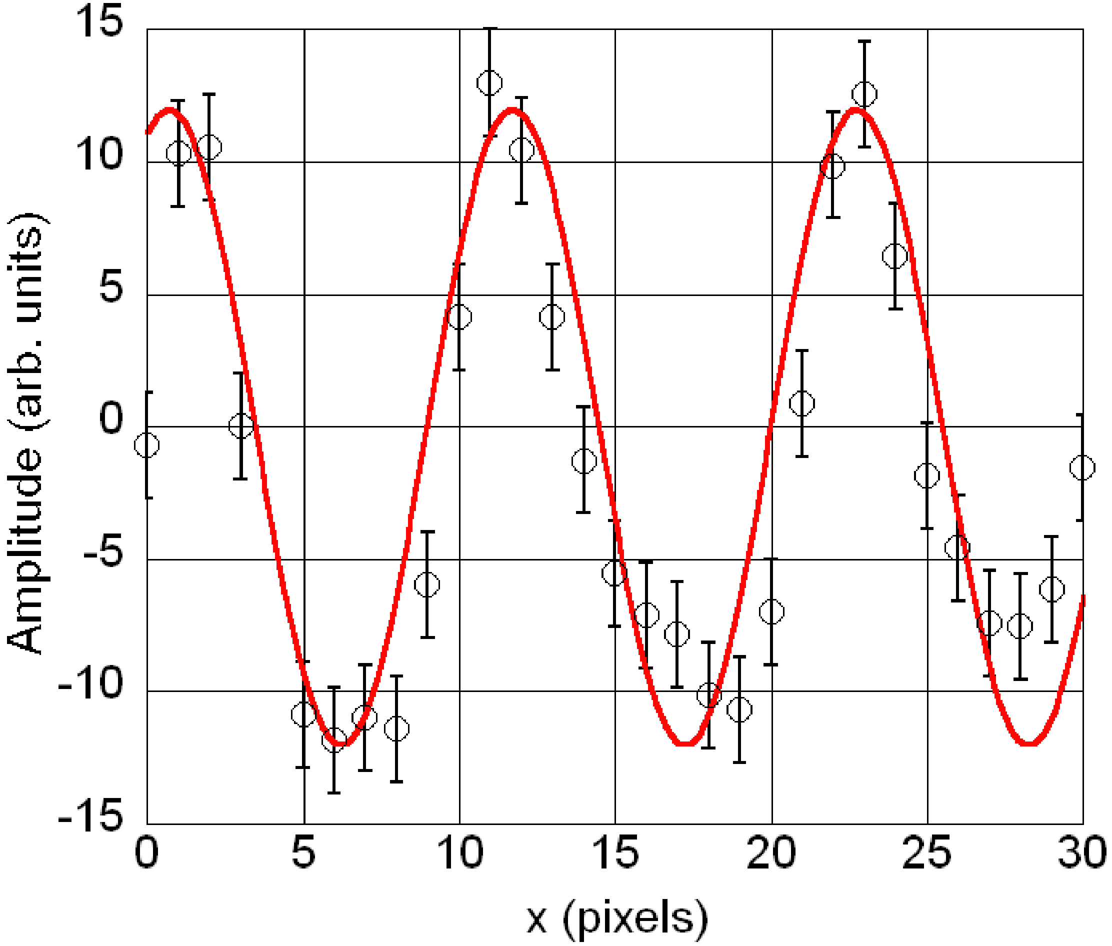


# DAW in drifting dust cloud

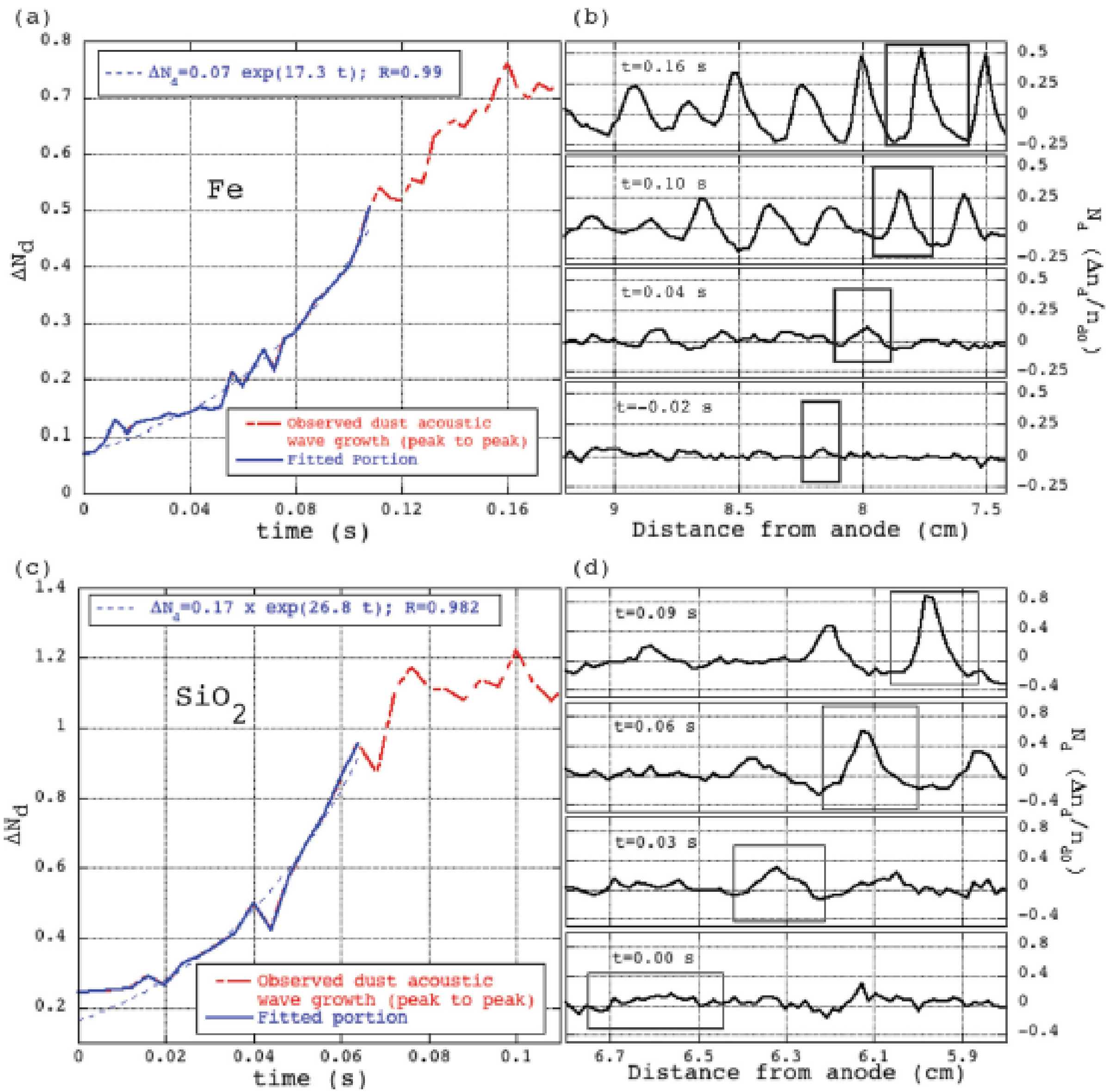


# ≈ linear dust acoustic waveform

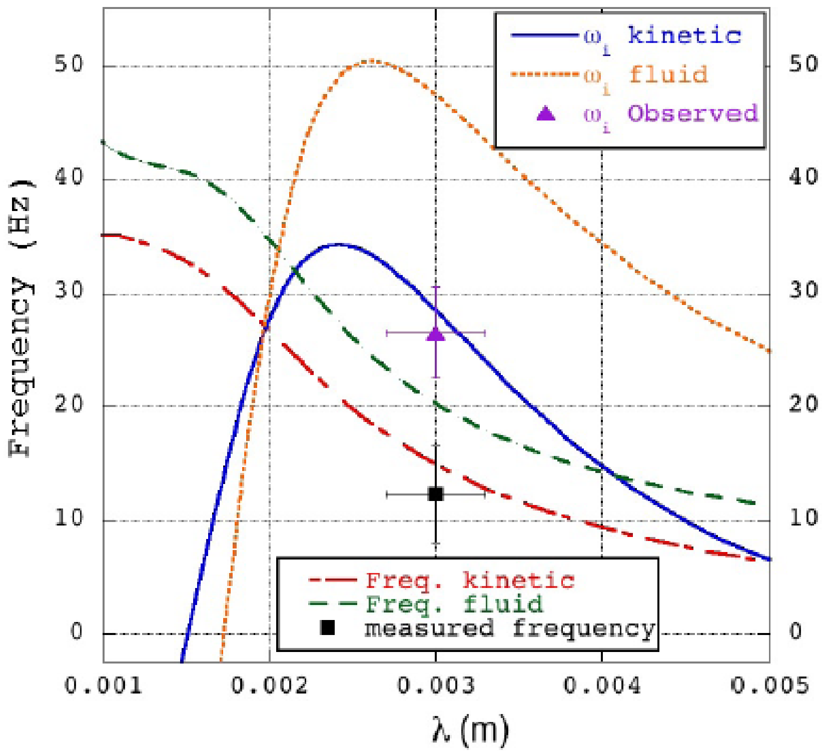
$$\delta n_d / n_d \approx 20\%$$



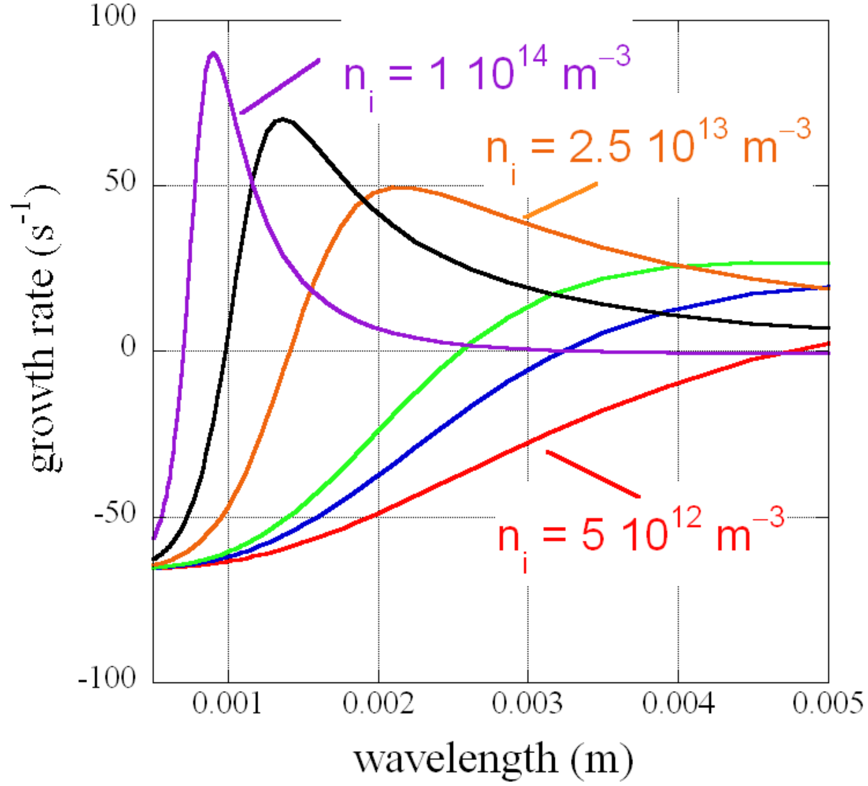
# Wave growth rate measurement



# Comparison to theory
## (0.5 μm glass spheres)




ion density dependence




- **Good agreement on the measured and calculated growth rates**
- **Theory also accounts for why the wave excitation begins at a location where the ion density is sufficient for growth**

# Dusty Plasma Structurization

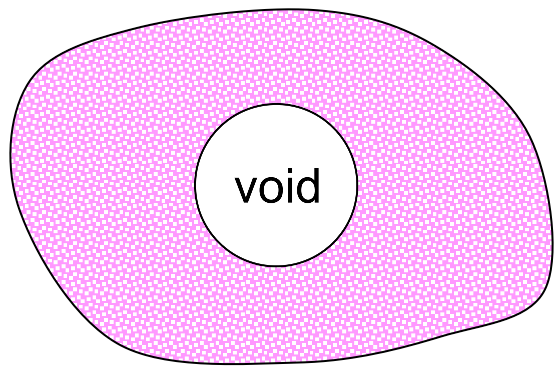
*Morfill &Tsytovich, Plasma Phys. Rep. 26, 727,2000*

- Formation of self-organized structures: dust clumps separated by dust voids
- non-propagating dust acoustic waves
- Due to constant flux of plasma on dust, dusty plasmas are *open* systems that are sustained by an ionization source
- This property makes dusty plasma susceptible to self-organization → the formation of structures
- *ionization / ion drag instability*

# Ionization / ion drag instability

**I.** A fluctuation decreases the dust density in region

**II.** Less absorption of electrons leads to higher electron density in region

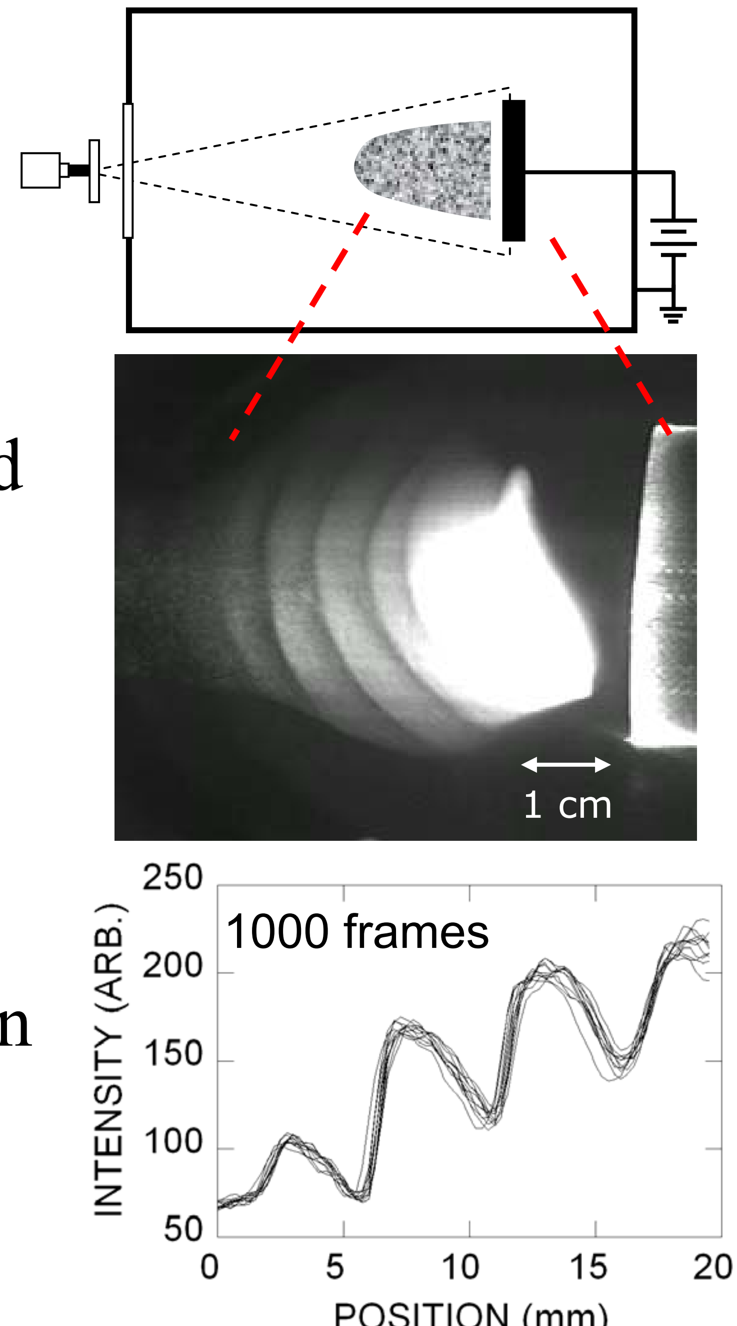



**III.** More electrons leads to higher ionization rate further increasing plasma density

**IV.** Increase in ion density leads to more dust being pushed out of region by the ion drag force

# Dust structurization

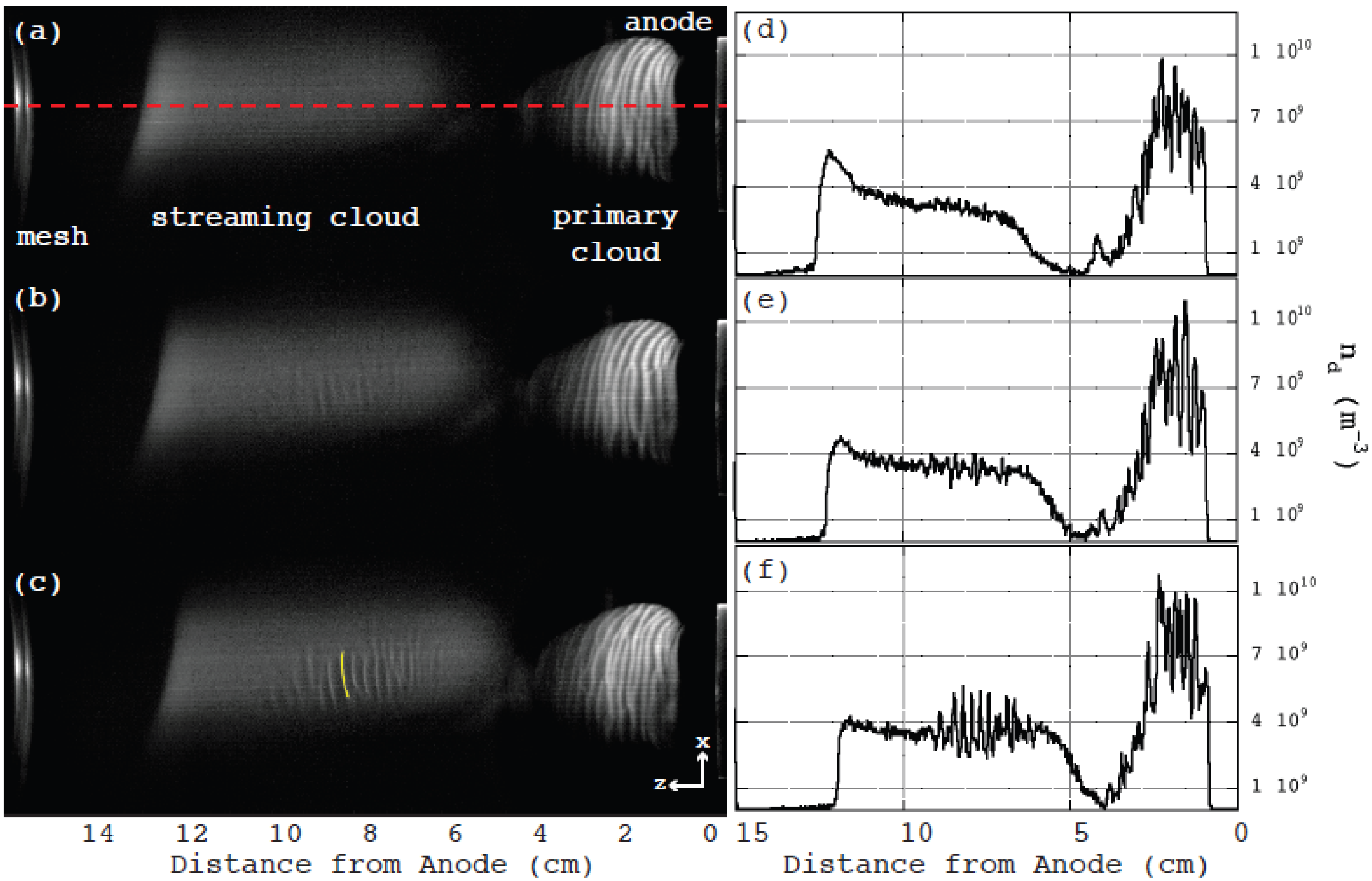
- For discharge currents ~ 1-10 mA, propagating DAWs are excited
- For currents > 15 mA, the dust cloud is spontaneously trans-formed into nested conical regions of high and low dust density that are *stationary and stable*
- This phenomena was observed with various types and sizes of dust and in argon and helium discharges
- Heinrich *et al*., PRE 84, 026403, 2011



# Summary

- Experiments on nonlinear dust acoustic waves have been described
- Dusty plasmas can be used to study basic acoustic and hydrodynamic behavior.

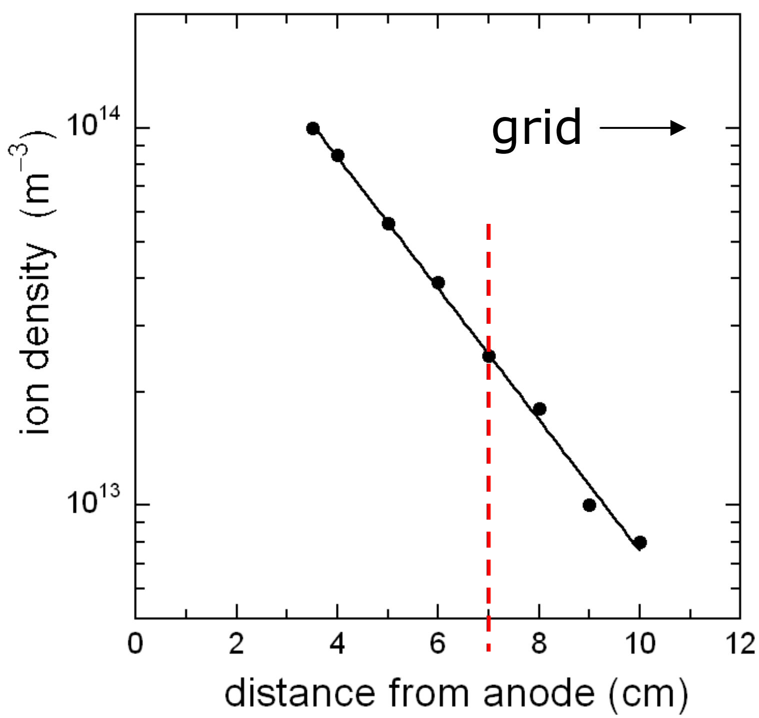
# extra slide



(a)
anode
mesh
streaming cloud
primary cloud
(b)
(c)
x
z
14 12 10 8 6 4 2 0
Distance from Anode (cm)
(d)
(e)
(f)
1 10^10
7 10^9
4 10^9
1 10^9
n_d (m^-3)
15 10 5 0
Distance from Anode (cm)

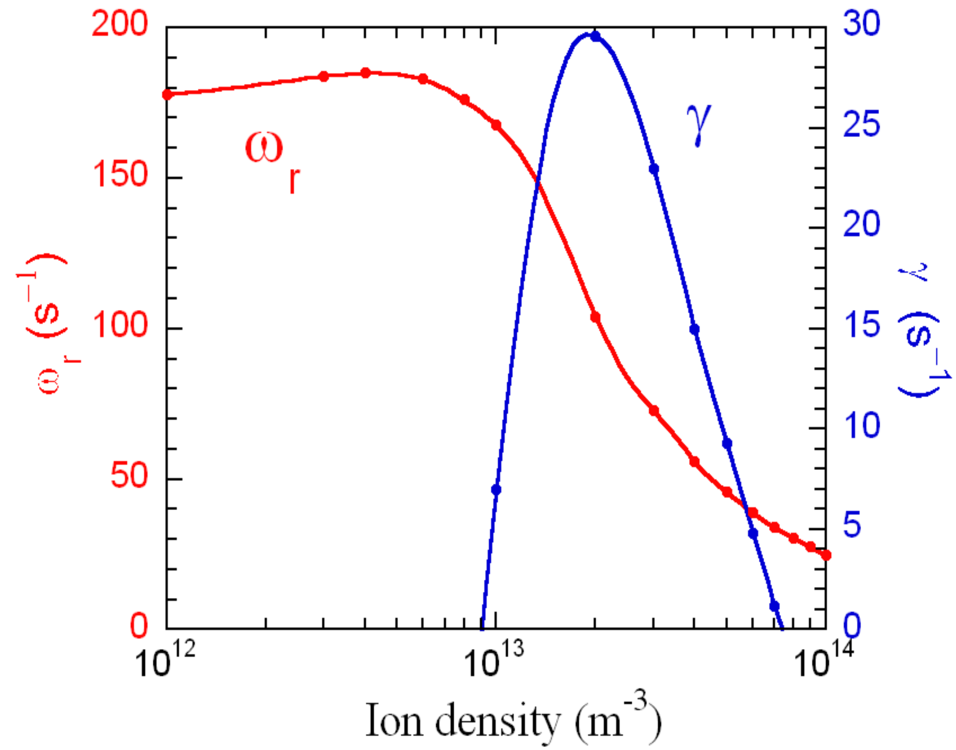
# extra slide-Onset of wave growth

1 micron glass spheres




Ion density increases toward the anode. Wave growth starts at ≈ 7 cm.

dispersion relation calculation




DAW unstable for ion densities > $10^{13}$ m$^{-3}$