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Discoveries in Dusty Plasmas

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Discoveries in Dusty Plasmas: 20 Years of the Dust Acoustic Wave

AS-ICTP, Trieste, 25 August 2009

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OUTLINE

- A. INTRODUCTION
- B. PROPERTIES OF DUSTY PLASMAS
- C. DUST CHARGING
- D. NEW WAVES/NEW INSTABILITIES
- E. NEW FORCES: WAKE FIELDS
- F. NONLINEAR STRUCTURES: MACH CONES, DIA SHOCKS, VOIDS, VORTICES
- G. CONCLUSION

INTRODUCTION

- OCCURRENCE OF DUSTY PLASMAS: IN SPACE NEBULAS, MOLECULAR CLOUDS, SUPERNOVAE, SATURN RINGS, MARTIAN ENVIRONMENTS AND COMETARY TAILS
- IN UPPER ATMOSPHERE AND NOCTILUCENT CLOUDS IN POLAR MESOSPHERE
- IN COMMERCIAL PLASMA ETCHING REACTORS: MICROELECTRONICS & NANOTECHNOLOGY
- NEW MATERIALS: DUST-PLASMA CRYSTALS
- IN FUSION REACTORS: IN MANY TOKAMAKS AND IN ITER
- IN MICROBIOLOGY AND DESINFECTION IN MEDICINE/DENTAL TREATMENT

DUSTY PLASMA DEFINITION

- ❑ DUSTY PLASMAS ARE MULTI-COMPONENT PLASMAS
- ❑ THEY CONTAIN ELECTRONS, IONS, NEUTRAL ATOMS/MOLECULES, AND MICRO-PARTICLES/CHARGED DUST GRAINS
- ❑ THEY ARE SIGNIFICANTLY DIFFERENT FROM THE USUAL ELECTRON-ION PLASMAS
- ❑ DUST CHARGING AS A DYNAMICAL VARIABLE
- ❑ NEW SPACE AND TIME SCALES ASSOCIATED WITH DUST PARTICLE MOTION

Rev. Mod. Phys. 81, 25 (2009) [20 pages]

Colloquium: Fundamentals of dust-plasma interactions

Abstract | **References (293)** | No Citing Articles

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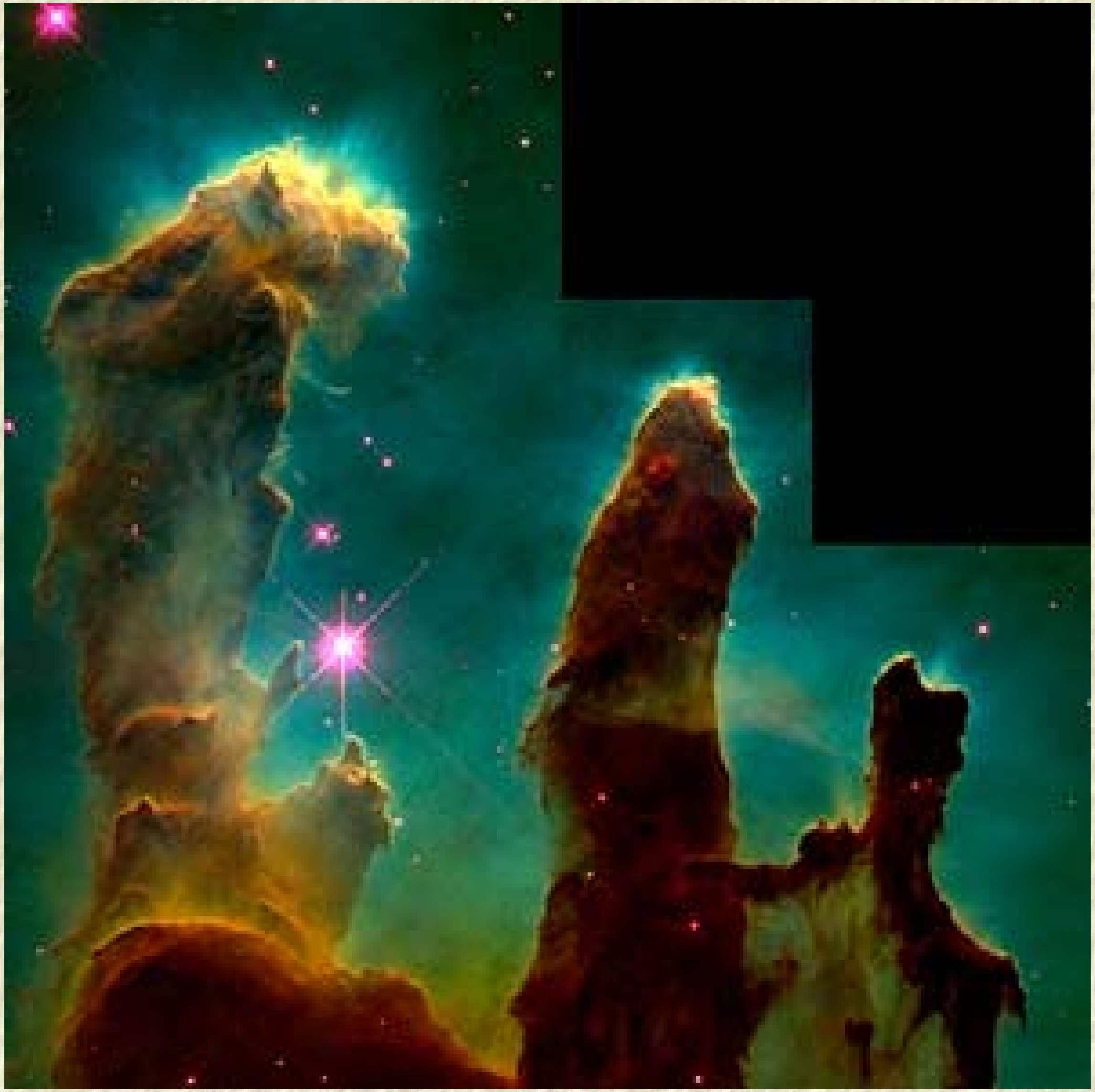
Published 7 January 2009

EAGLE NEBULA



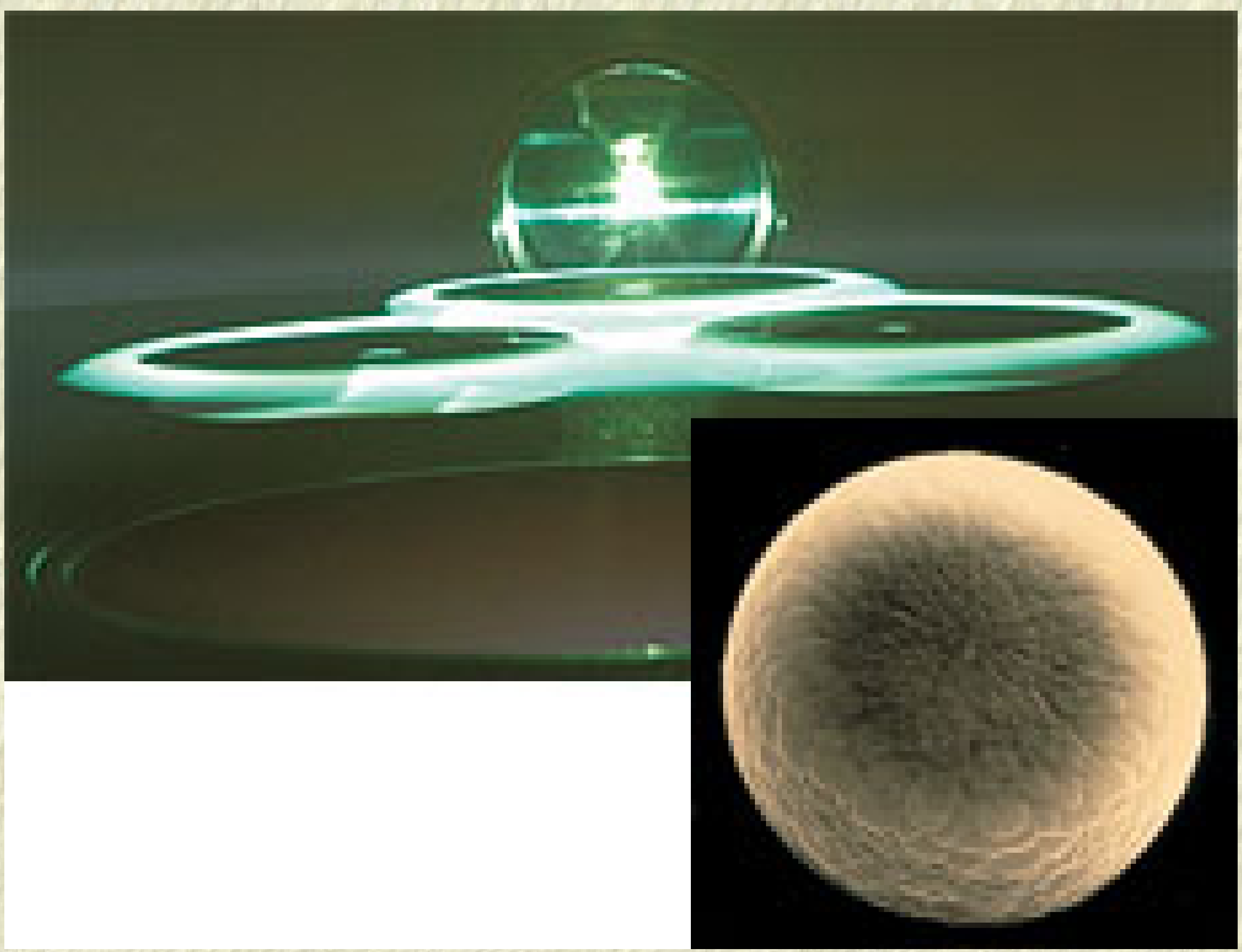
SATURN RINGS

HALE-BOPP & HYAKUTAKE

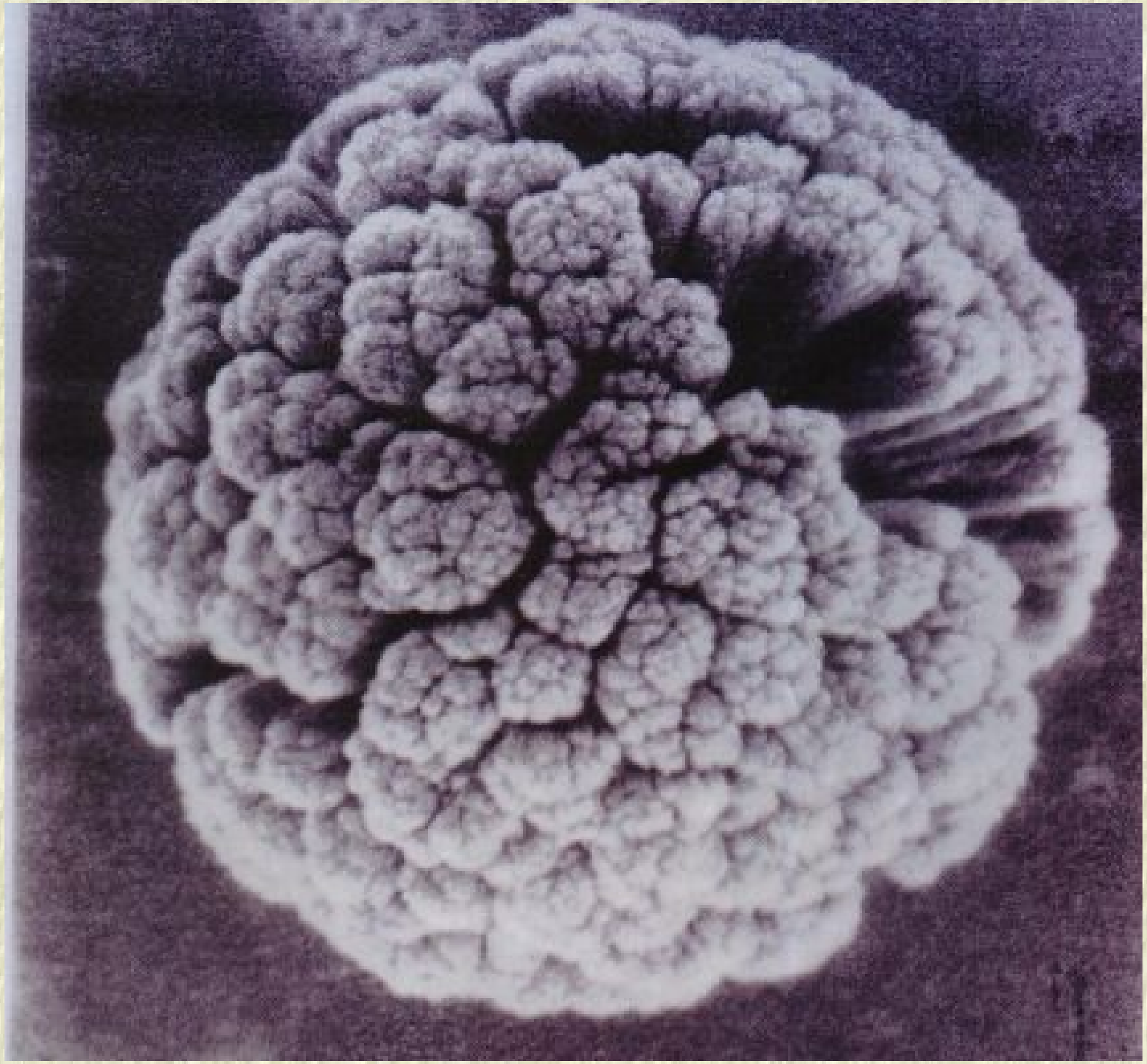
MESOSPHERIC NOCTILUCENT CLOUDS

T. W. Backhouse, Meterol. Mag. **20**, 133 (1885).

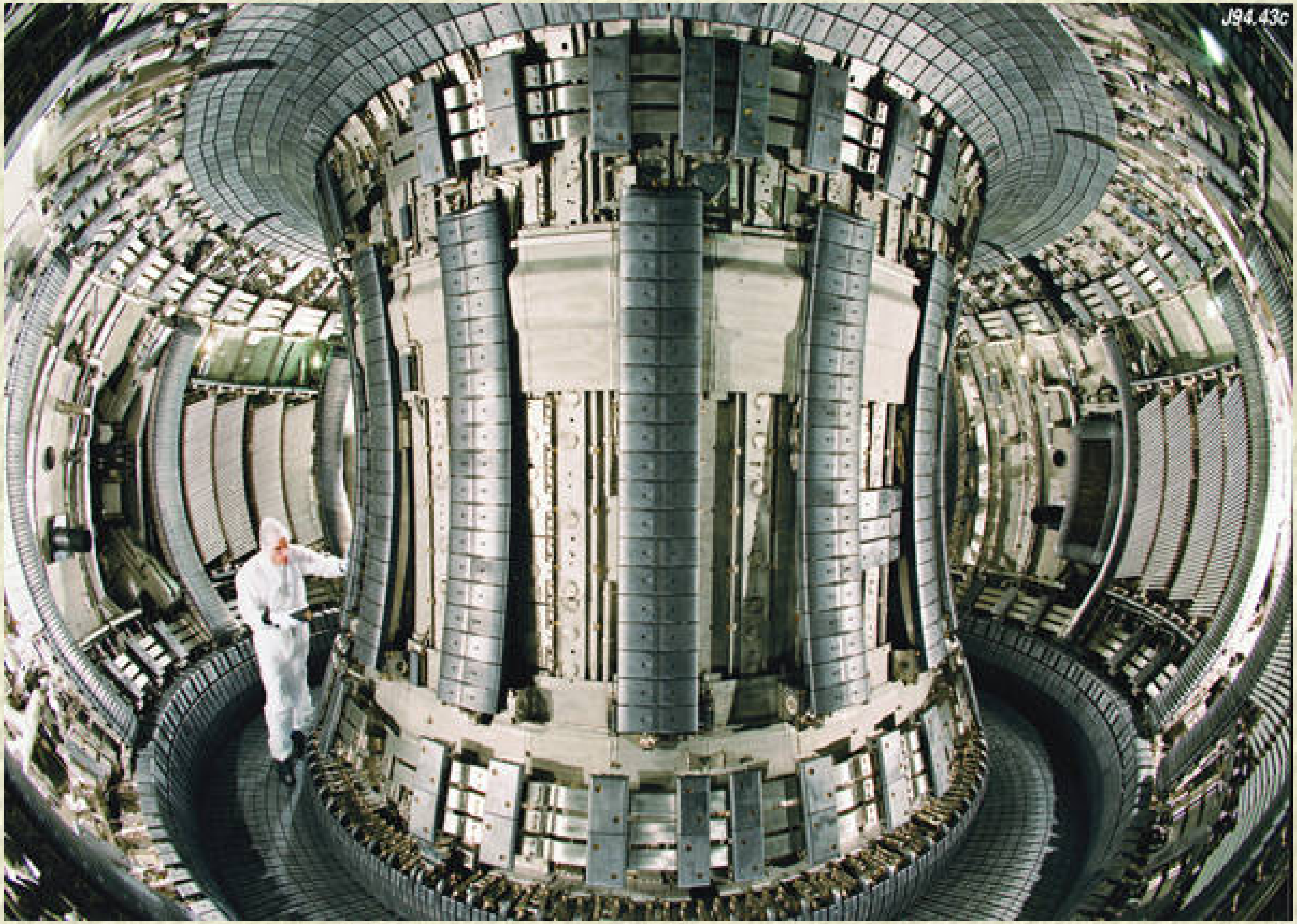
MICROELECTRONICS



FORMATION OF DUST STRUCTURES

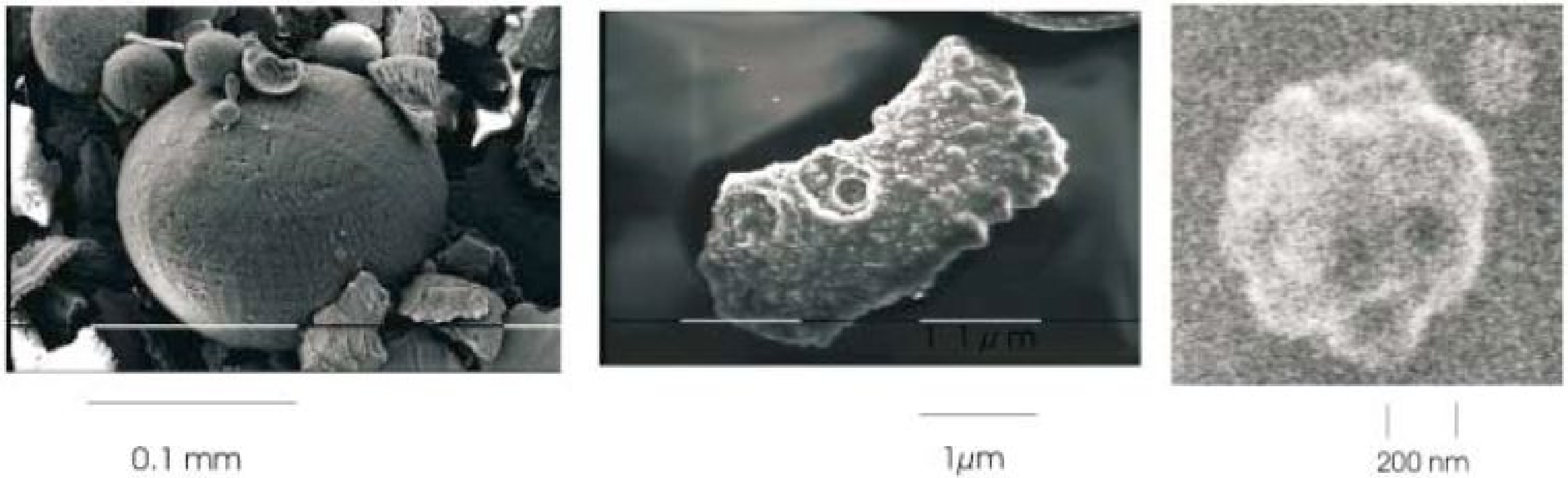


JET TOKAMAK



DUST IN FUSION DEVICES

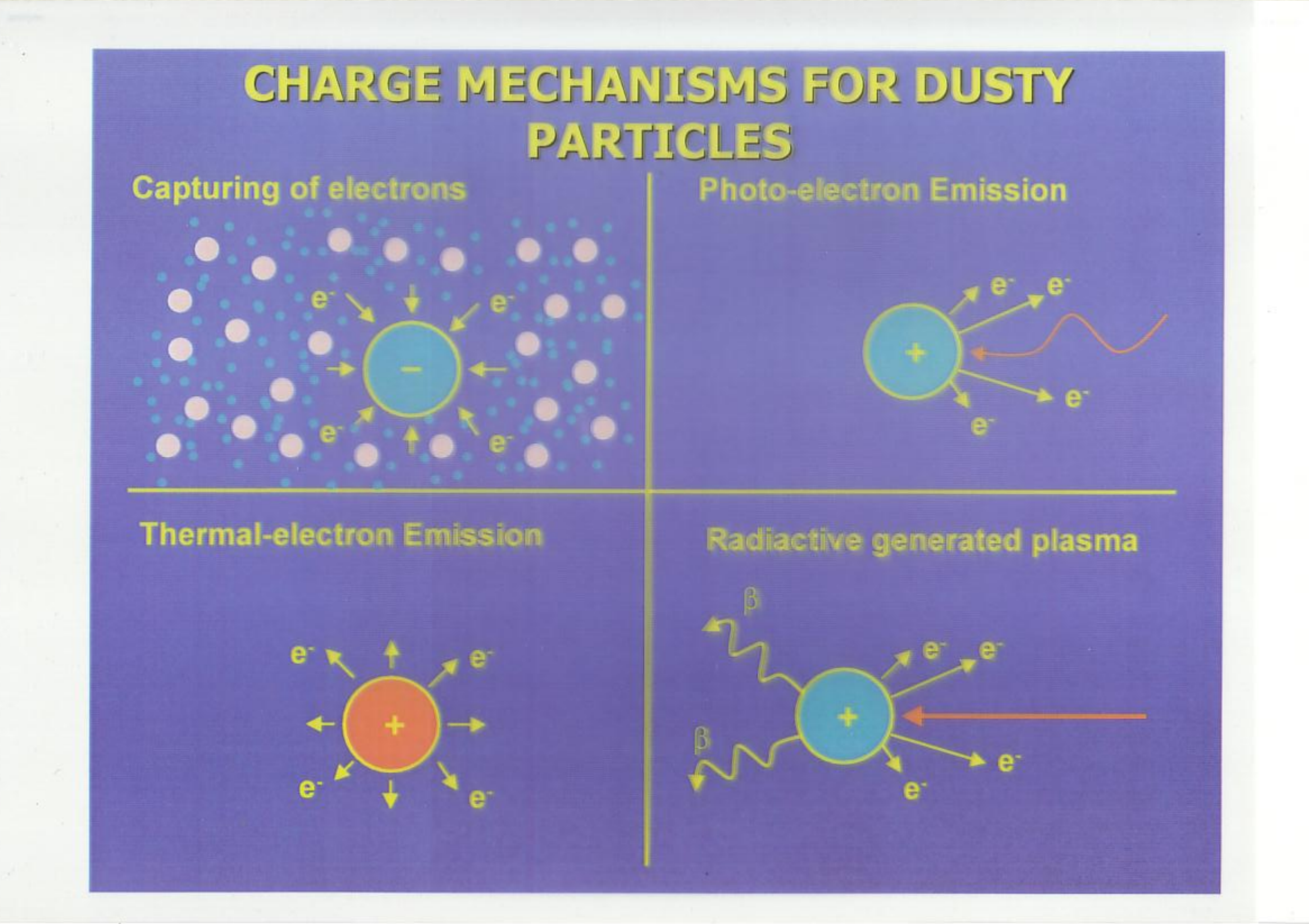
- Significant amount of dust particles is observed in the chambers of fusion devices



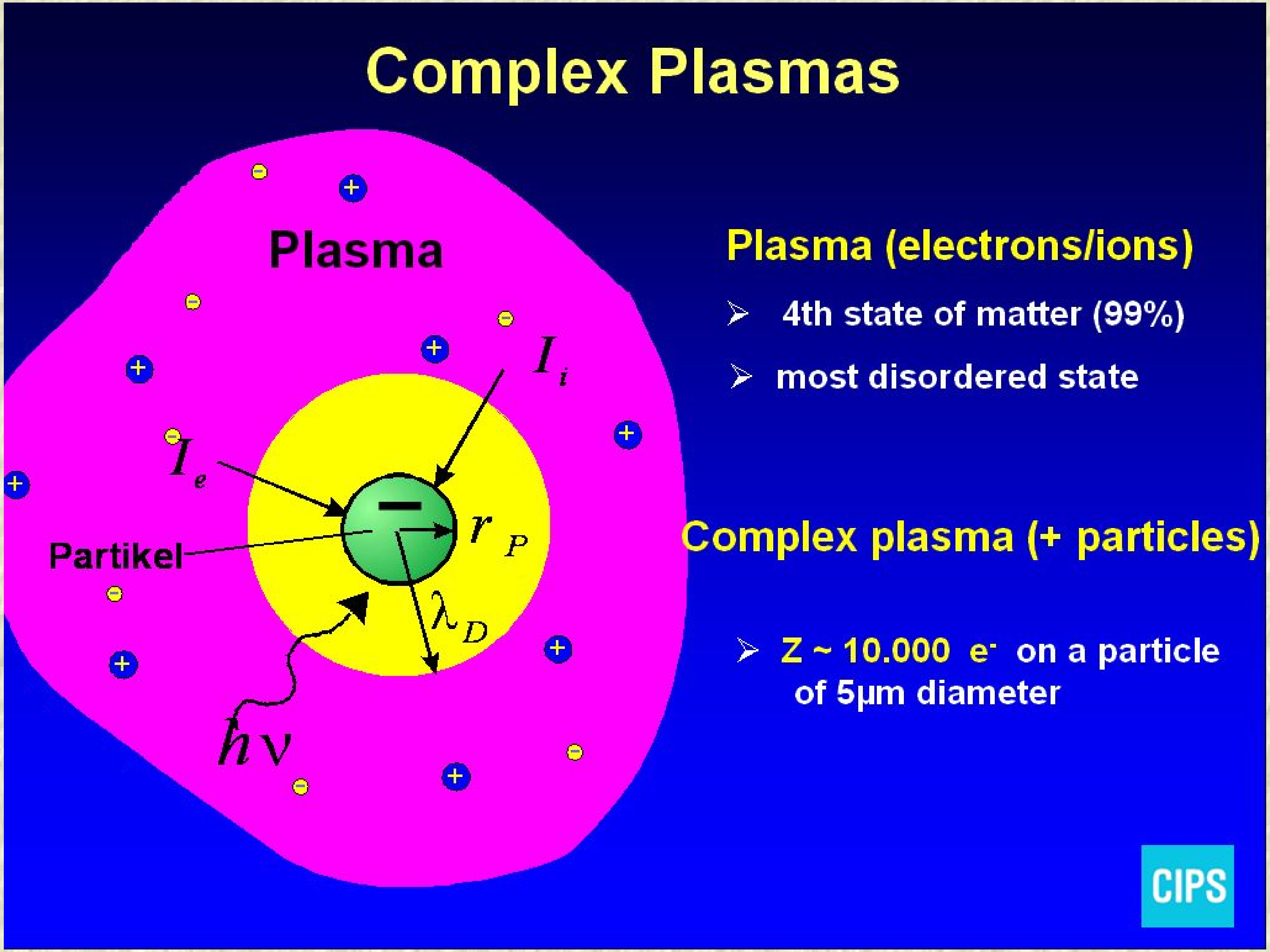
Winter PPCF 1998

- But so far an impact of dust on the performance of current fusion devices is not clear

CHARGING MECHANISMS

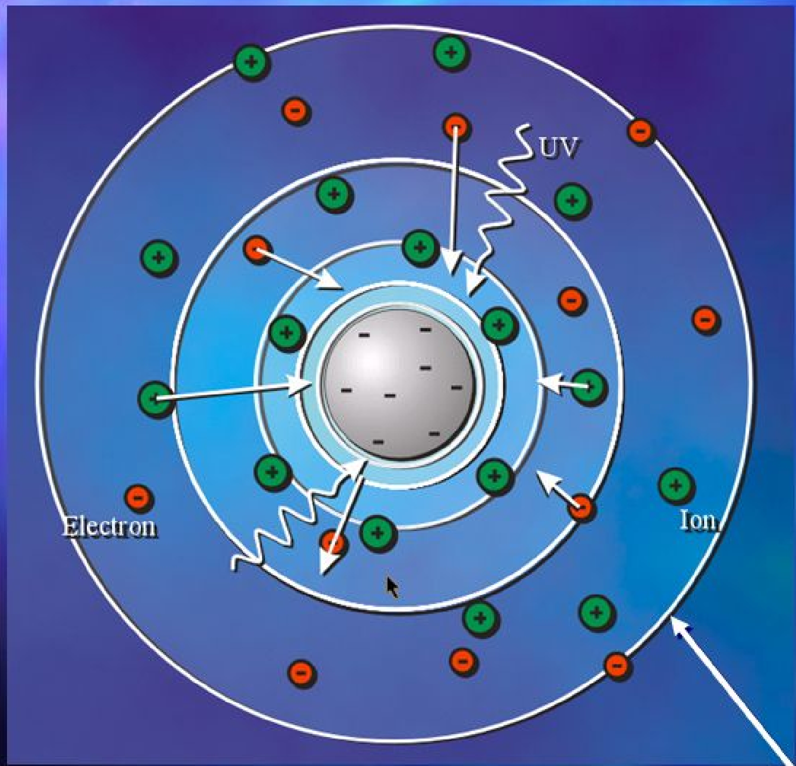


CHARGING MECHANISMS (continued)



CHARGING MECHANISMS (continued)

Charging of a single particle in a plasma



Collection of charges

particle is negatively charged due to higher mobility of electrons

positive charge cloud around particle ⇨ Debye screening

Temporal charge variation

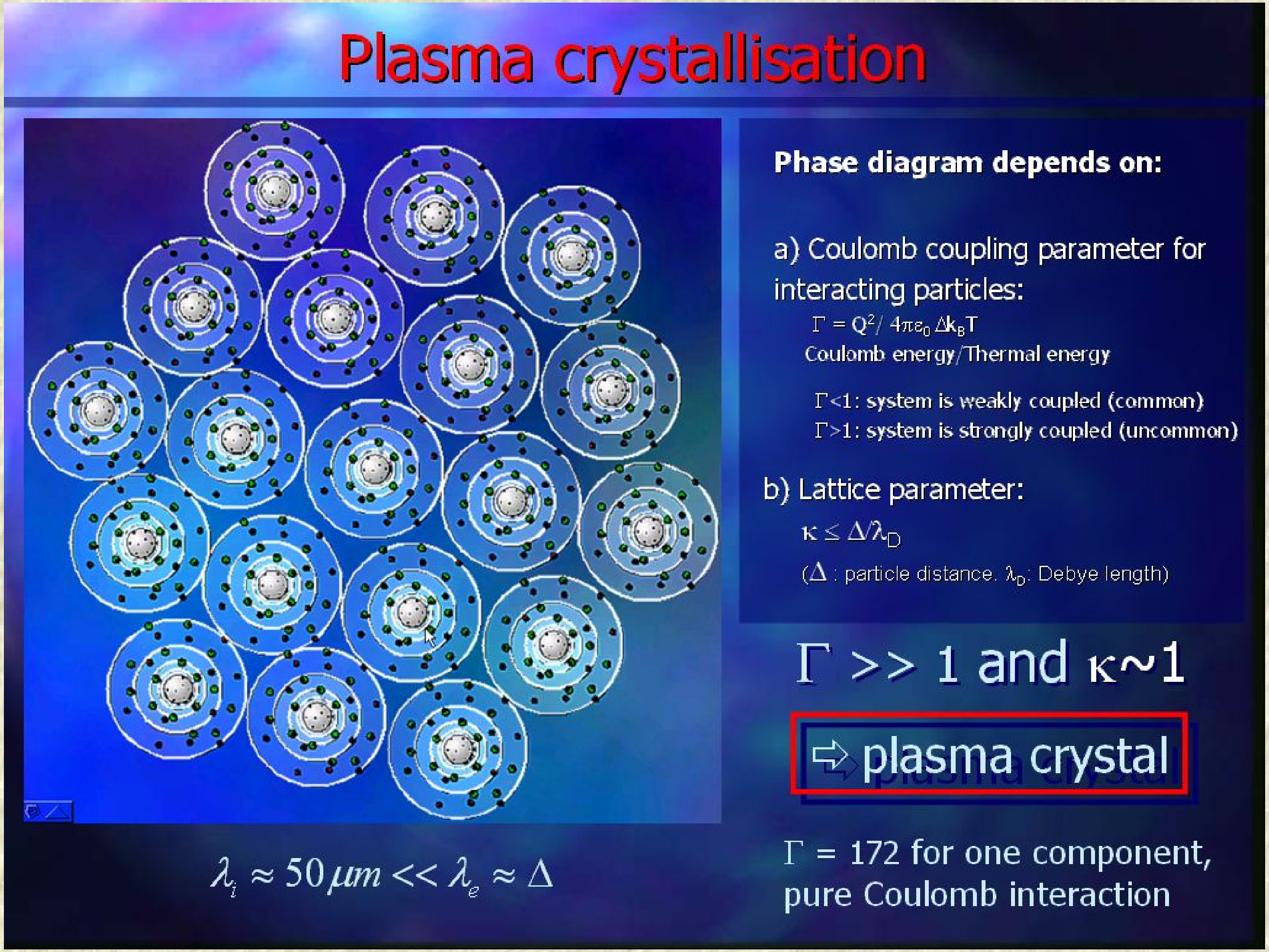
$$\frac{dQ}{dt} = I_{electrons} + I_{ions} + I_{...}$$

Steady state: $\frac{dQ}{dt} = 0$

For a particle of 1μm diameter: $Q = -1500e$

Debye length: $\lambda_D = \sqrt{\frac{kT}{4\pi e^2 n}}$

Potential contour lines



First prediction by H. Ikezi, Phys. Fluids (1986); Observations: Wu & Lin I, PRL (1994), Thomas et al, PRL (1994).

Phase diagram

Coulomb coupling parameter for interacting particles:

- Γ = (shielded) Coulomb energy / Thermal energy
- $\Rightarrow \Gamma<1$: system is weakly coupled (common)
- $\Rightarrow \Gamma>1$: system is strongly coupled (uncommon)

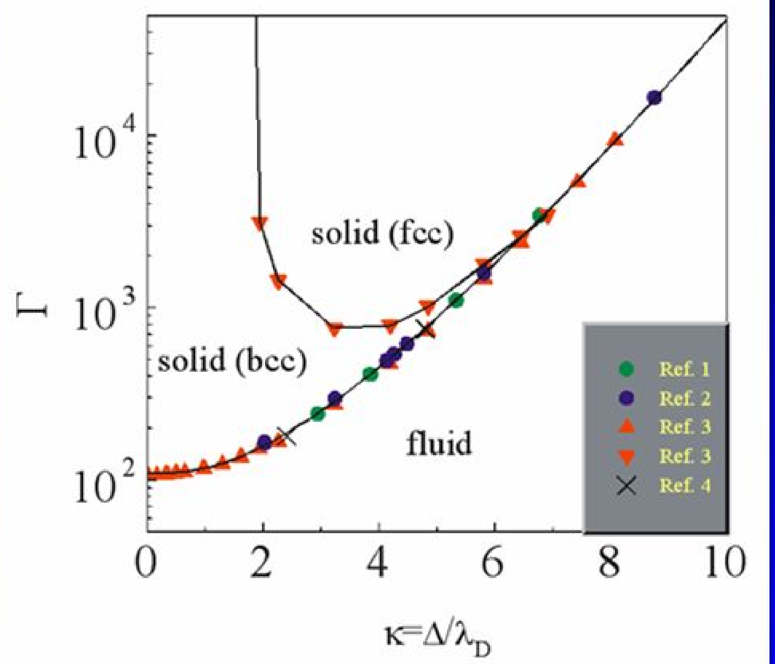
Lattice parameter:

$\kappa \leq \Delta/\lambda_D$

(Δ : particle distance. λ_D: Debye length)

For complex plasmas:

$\kappa \sim 1, \Gamma \geq \Gamma_C$ ⇨ Plasma Crystals



References:

[1] E.J. Meijer and D. Frenkel, J. Chem. Phys94, 2269 (1991)

[2] M.J. Stevens and M.O. Robbins,ibid . 98, 2319 (1993)

[3] S. Hamaguchiet al., Phys. Rev. E 56, 4671 (1997)

[4] O. Vaulina and S. Khrapak, JETP92, 228 (2001)

CIPS

PROPERTIES OF DUSTY PLASMAS

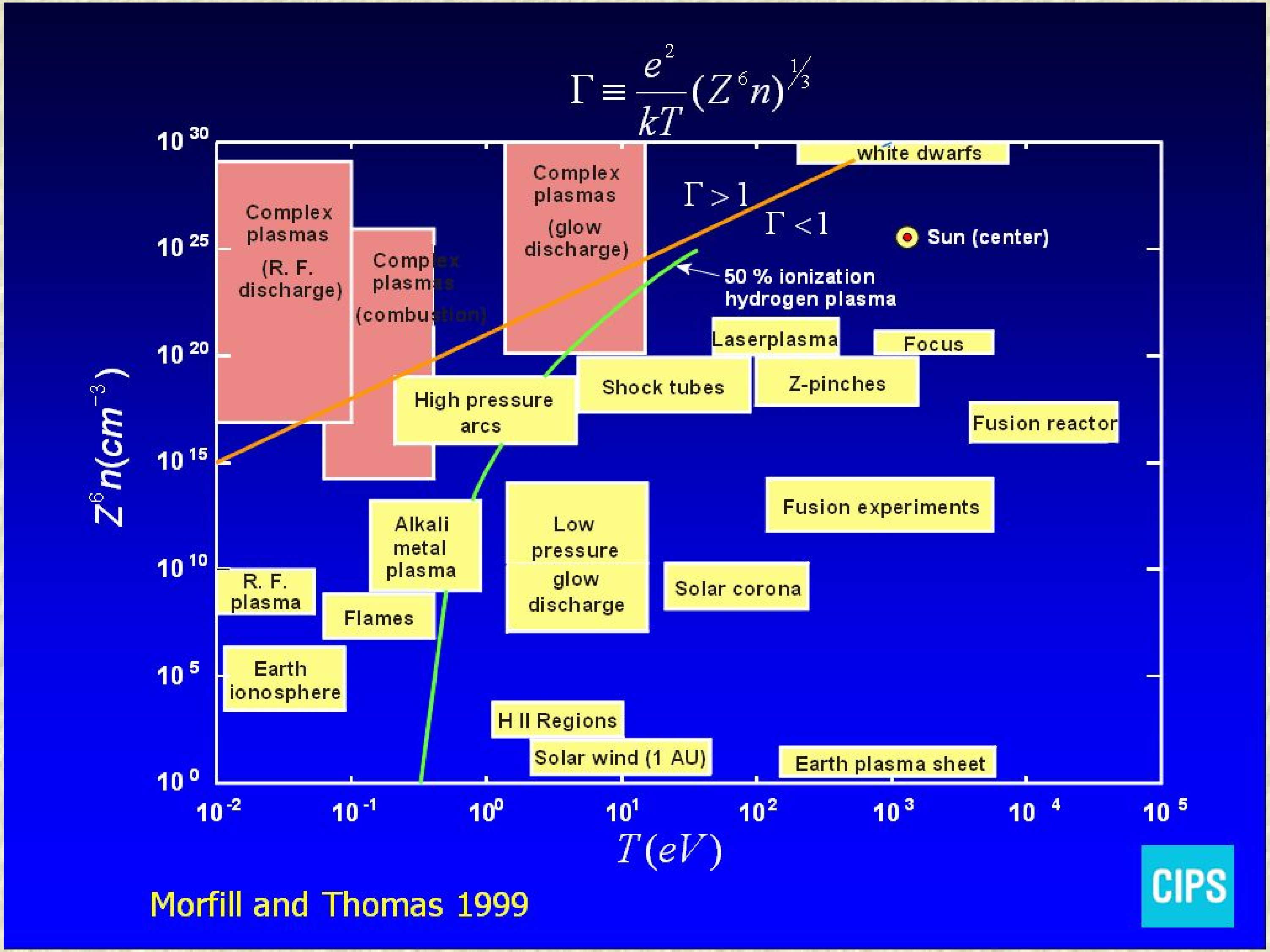
Electron–ion plasma	**Dusty plasma**
$n_{e0} = \sum_i Z_i n_{i0}$	$Q_d n_{d0} + e n_{e0} = e \sum_i Z_i n_{i0}$
$Q_i = Z_i e$	$Q_d = Z_d e \gg Q_i$
$Z_i =$const.	$dQ_d/dt = I_e + I_i + I_s + \ldots$
m_i	$m_d \sim 10^{12} m_i$
λ_{De}	$\lambda_D \sim \lambda_{Di}$
Uniform particle sizes	Size distributions
Particle $\mathbf{E} \times \mathbf{B}_0$ motion at low B_0	Dust $\mathbf{E} \times \mathbf{B}_0$ motion requires high (Tesla) B_0
IAW, EIC, f ~1 kHz	DAW, DLW, SW, f ~10 Hz,

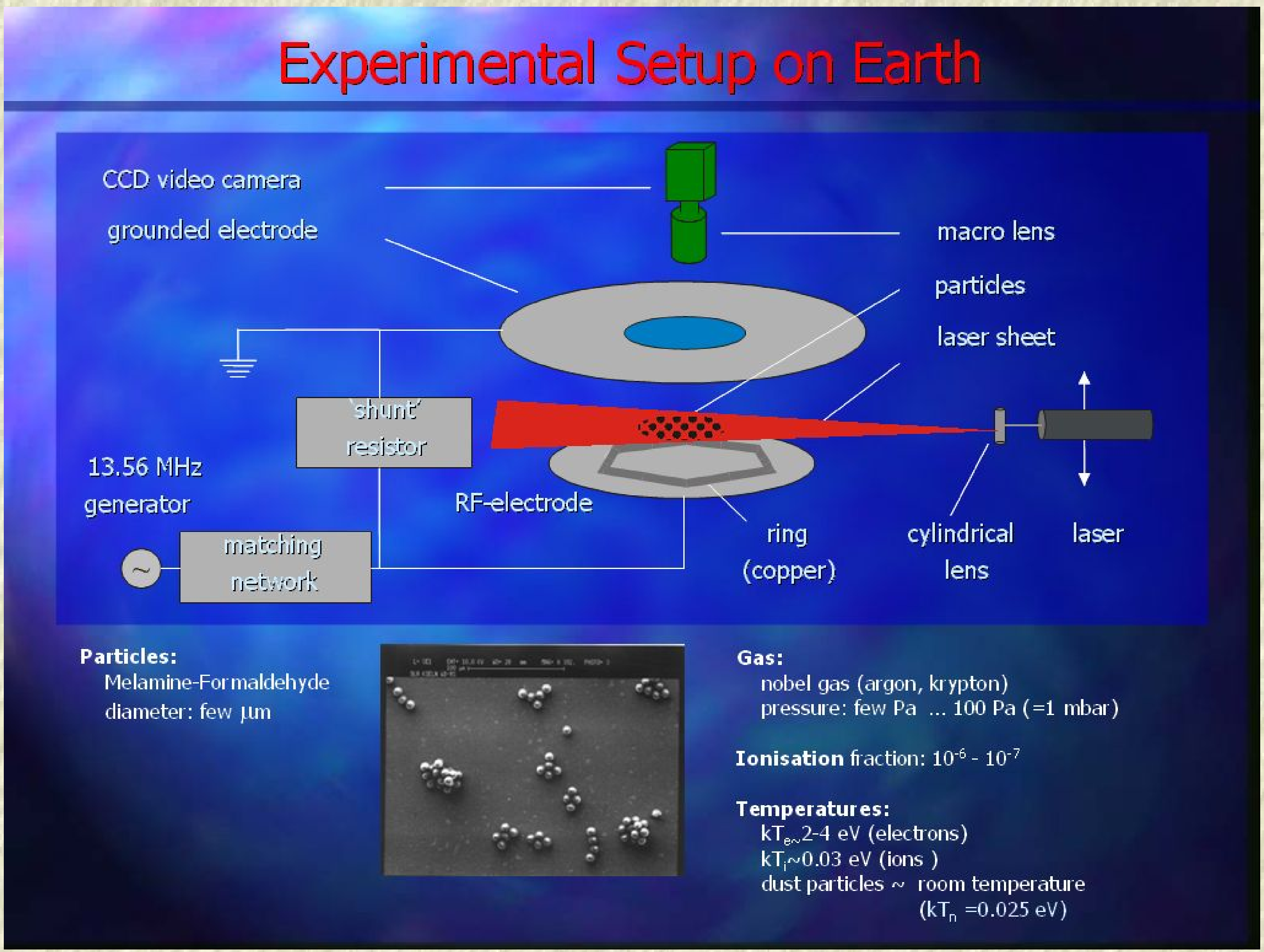
PROPERTIES OF DUSTY PLASMAS

Electron–ion plasma	**Dusty plasma**
IA Solitons Compression/Rarefaction	DAW Shock Waves/Holes Mach Cones
Debye–Hückel Interactions	Attractive Forces, Ion Drag
El. & Ion Crystalization Wigner Crystals	Dust Crystals Cryogenic Plasmas
Phase Transition	Phase Transition

Solid State Crystals	**Dust Crystals**
$Z_i > 1$	$Z_d \sim 10^3$–10^5
$\mathcal{E}_{\text{interaction}}$ a few eV	$\mathcal{E}_{\text{interaction}} \geq 900$ eV
Lattice Spacing $L \sim 0.1$ nm	$L \sim 1$ mm

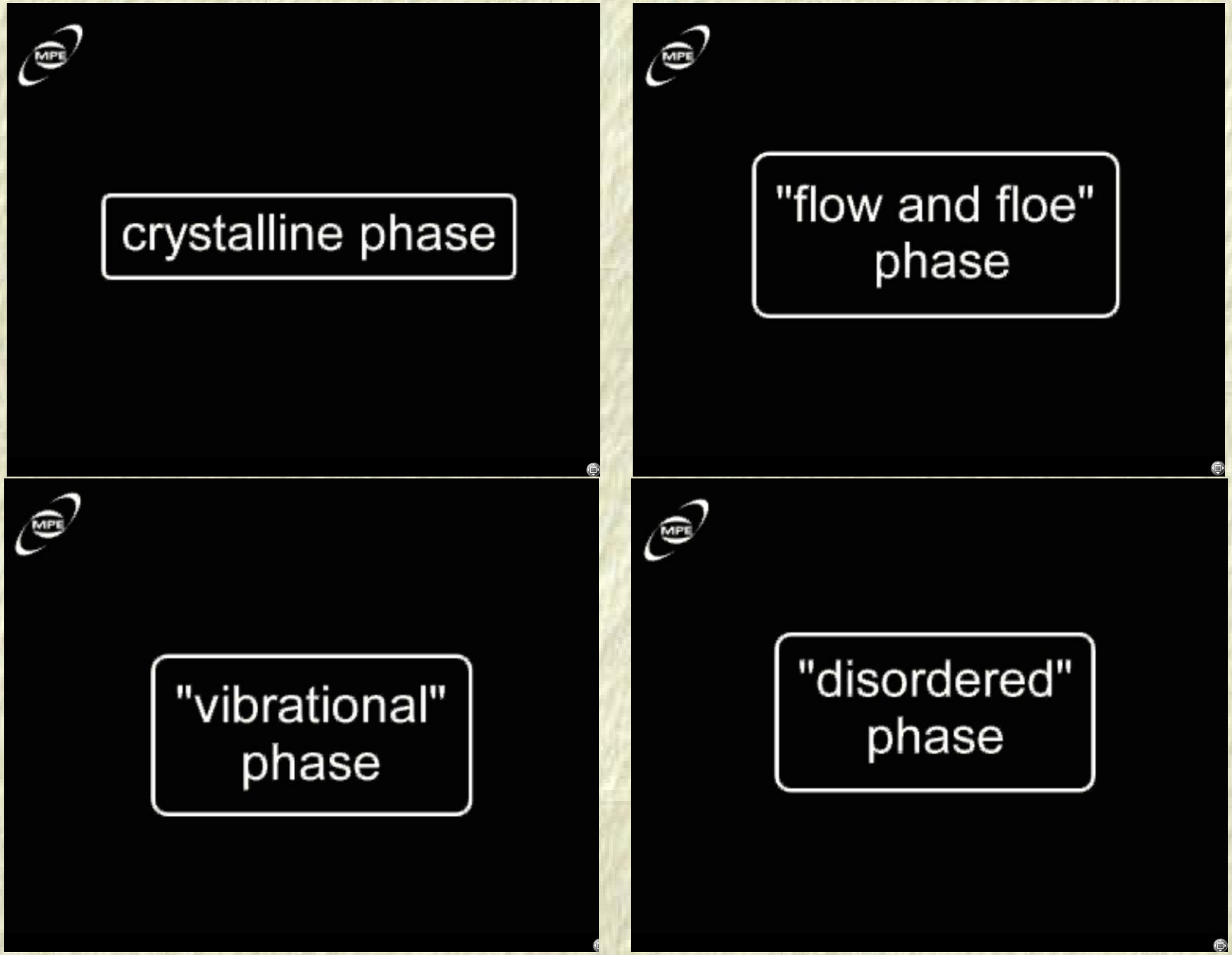
EXISTENCE DIAGRAM





Thomas et al., PRL (1994).

DIFFERENT PHASES

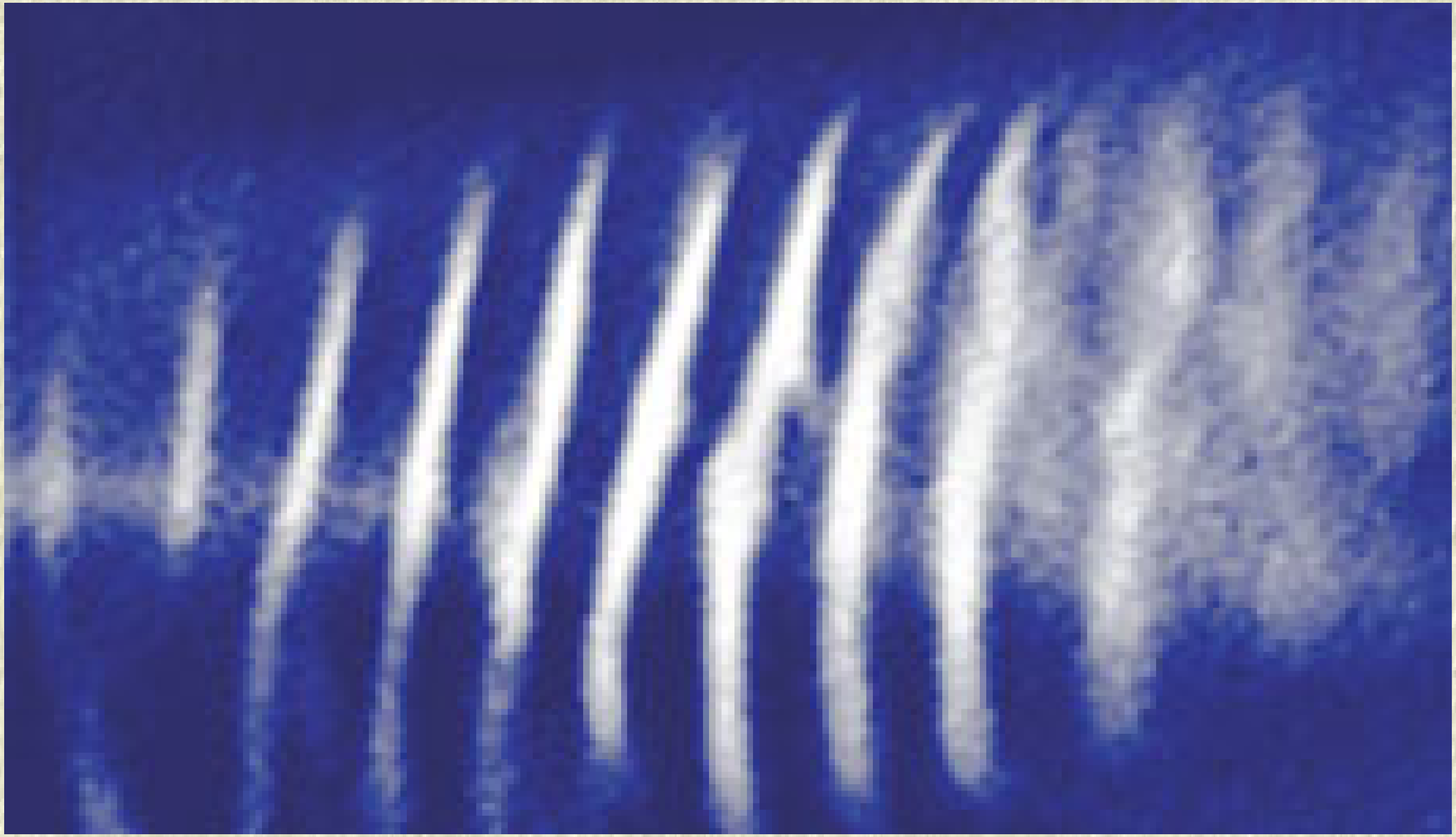


Morfill & Thomas, Nature, 1996.

COLLECTIVE PROCESSES: PHYSICS OF WAVES

	Restoring Forces	Inertia	Phase Speed
SW	Neutral Gas Pressure	Mass of Neutral Atoms	$(T_n/m_n)^{1/2}$
IAW	Electron Pressure	Ion Mass	$C_s = (T_e/m_i)^{1/2}$
DIAW	Electron Pressure	Ion Mass	$(n_{i0}/n_{e0})^{1/2} C_s$
DAW	Ion Pressure Electron Pressure	Dust Mass Dust Mass	$Z_d(n_{d0}T_i/n_{i0}m_d)^{1/2}$ $Z_d(n_{d0}T_e/n_{e0}m_d)^{1/2}$
AW	Magnetic Tension	Ion Mass	$(B_0^2/8\pi n_{i0} m_i)^{1/2}$
DALW	Magnetic Tension	Dust Mass	$(B_0^2/8\pi n_{i0} m_d)^{1/2}$

DUST ACOUSTIC WAVES



Observation: A. Barkan, R. L. Merlino, and N. D'Angelo, 1995, Phys. Plasmas **2** 3563; Prediction: P. K. Shukla, 1st Dusty Plasma Workshop Proc., July 1989.

RSY Linear & Nonlinear DAW Theory and Observation

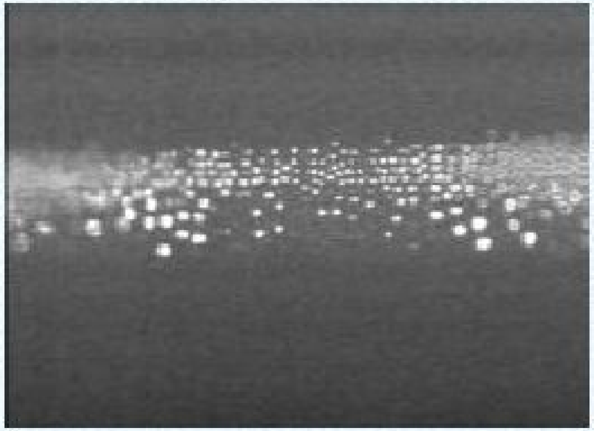
- N. N. Rao, P. K. Shukla, and M. Y. Yu, 1990, Planet. Space. Sci **38**, 543.
- A. Barkan, R. L. Merlino, and N. D'Angelo, 1995, Phys. Plasmas **2** 3563.

($n_d/n_i \sim 5 \times 10^{-4}$, $Z_d \sim 2 \times 10^3$, $m_d \sim 10^{-12}$ g, $T_i \sim 0.2$ eV, $T_e \sim 3$ eV)

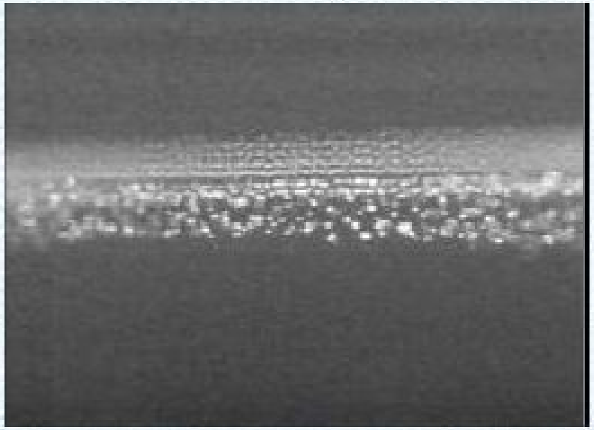
Theory	Observation
$v_{ph} = Z_d \left(\frac{T_i n_d}{m_d n_i} \right) = 9$ cm/s ($\lambda = 0.6$ cm, $\nu = 15$ Hz)	$v_{ph} = 10$ cm/s

DUST ACOUSTIC-LIKE WAVES

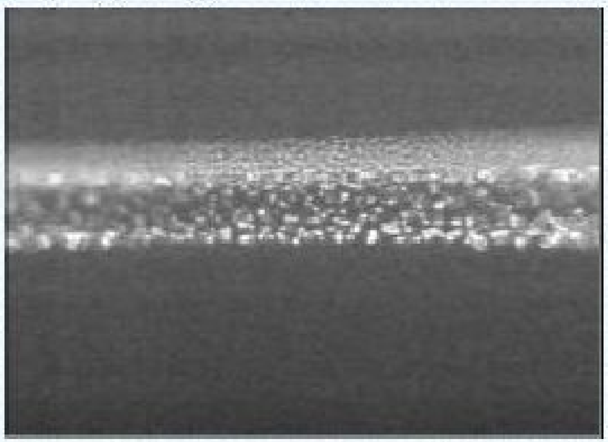
Stable crystal: $P=0.198$ Torr



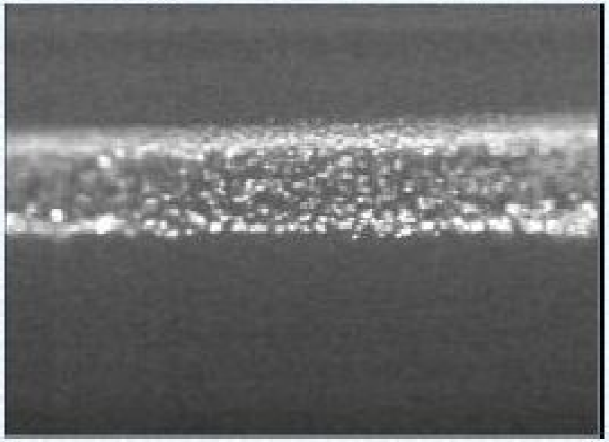
Onset of the instability: $P=0.185$ Torr



Propagating waves: $P=0.175$ Torr



Propagating waves: $P=0.165$ Torr



Ticos, Smith & Shukla, Plasma Phys. Contr. Fusion, 2004.

TWO-STREAM ION-DUST INSTABILITY

Dispersion relation (Shukla & Mamun, *Introduction to Dusty Plasma Physics*, IOP, 2002)

$$1 + \frac{1}{k^2\lambda_D^2} - \frac{\omega_{pi}^2}{(\omega - ku)(\omega - ku + i\nu_i)} - \frac{\omega_{pd}^2}{\omega(\omega + i\nu_d)} = 0$$

Definitions:

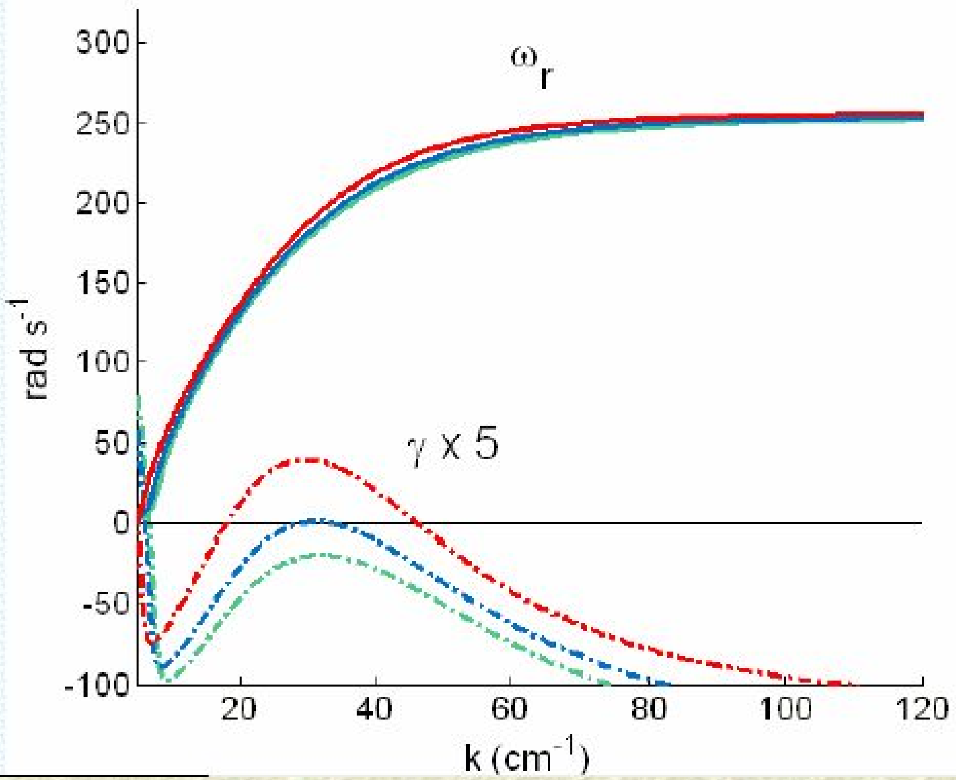
$$\nu_i = \sigma_i \left(\frac{P_n}{T_n}\right) u_B$$

$$\nu_d = \frac{4}{3}\pi r_d^2 \left(\frac{P_n}{T_n}\right) V_{Tn} \frac{m_n}{m_d}$$

SOLUTION OF THE DISPERSION RELATION

$u = u_B = 2.9 \cdot 10^3 \, \mathrm{ms}^{-1}, \quad n_d = 2 \cdot 10^{11} \, \mathrm{m}^{-3}, \quad Z_d = -2 \cdot 10^3 e,$

$T_e = 3.5 \, \mathrm{eV}, \quad T_i = 0.03 \, \mathrm{eV}, \quad n_e = n_i = 2 \cdot 10^{15} \mathrm{m}^{-3}, \omega_{pi} = 9.3 \cdot 10^6 \, \mathrm{s}^{-1}$



$\gamma < 0, \quad P = 0.3$ Torr (green)

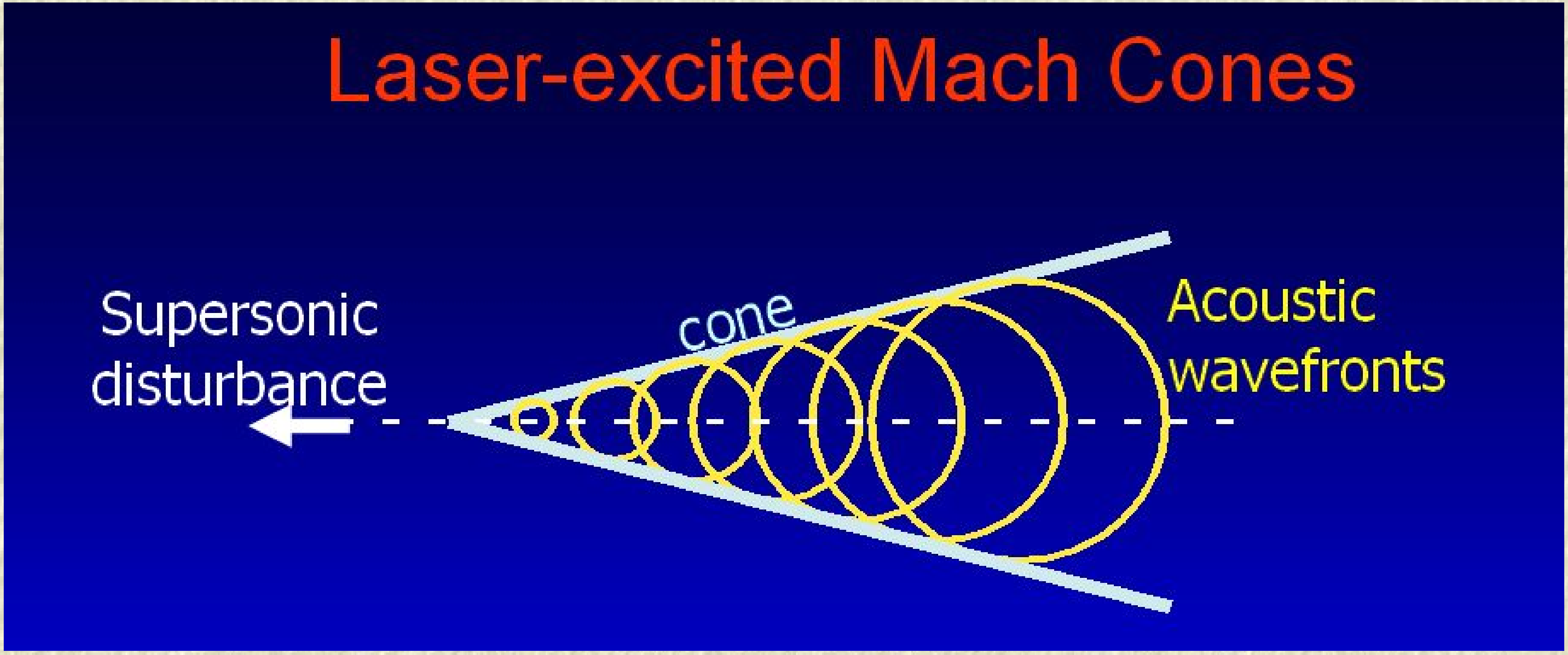
$\gamma = 0, \quad P_C \approx 0.275$ Torr (blue)

$\gamma > 0, \quad P = 0.23$ Torr (red)

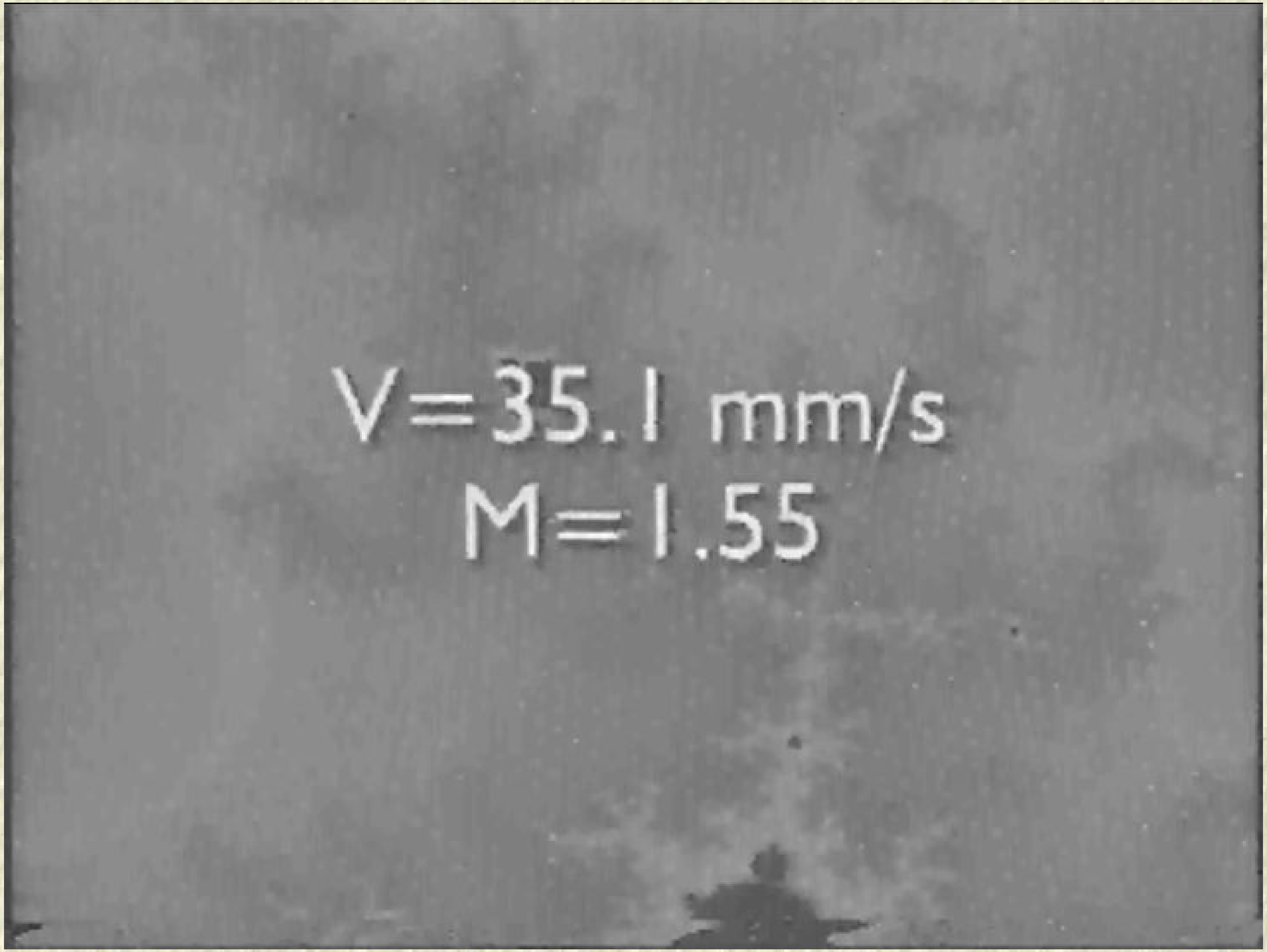
- ω_r strongly depends on Z_d .
- Z_d= $-2 \cdot 10^3$ e chosen such that ω_r agrees with the experiment.

Mach Cone: Movie

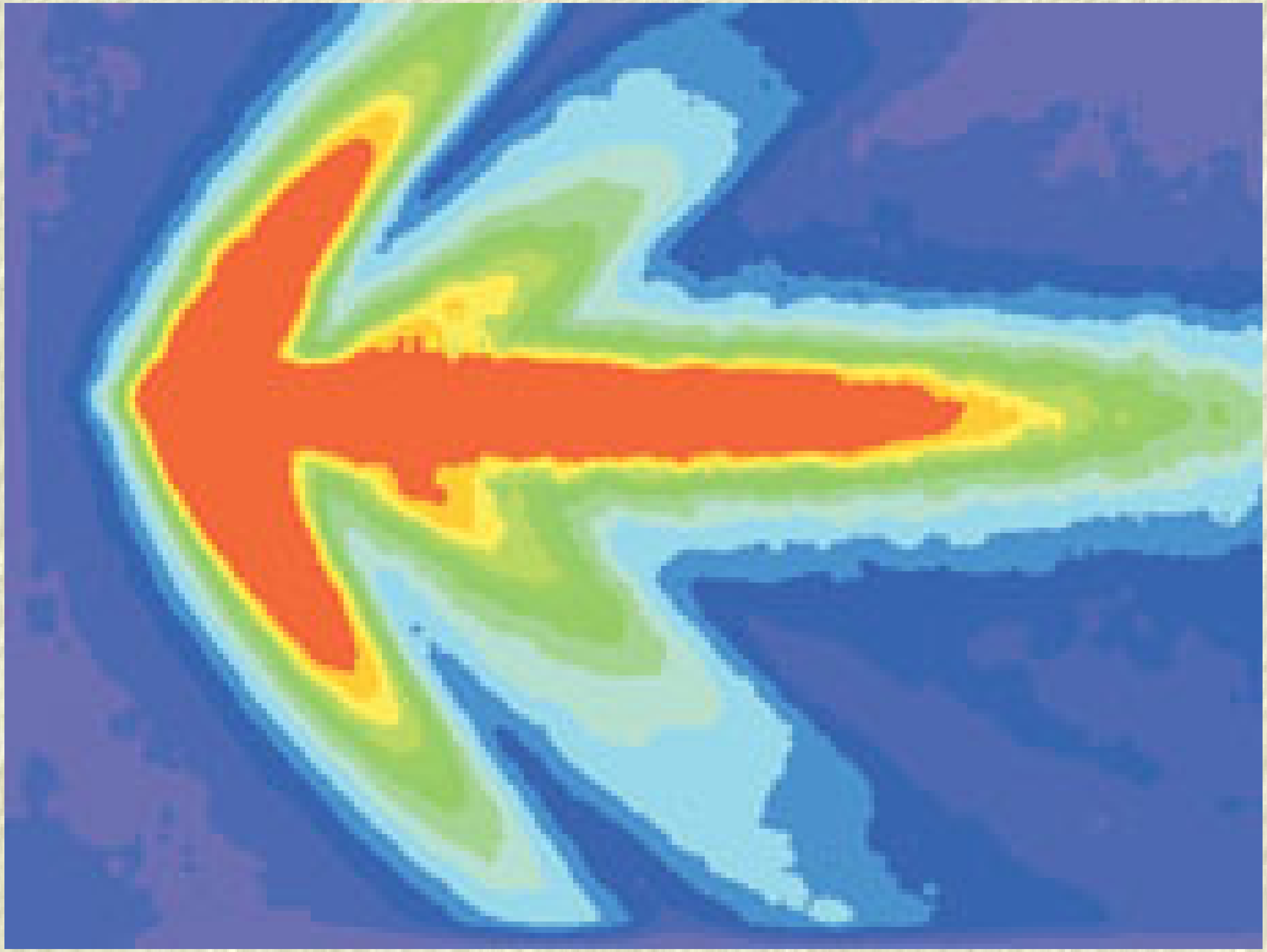
PHYSICS OF MACH CONES



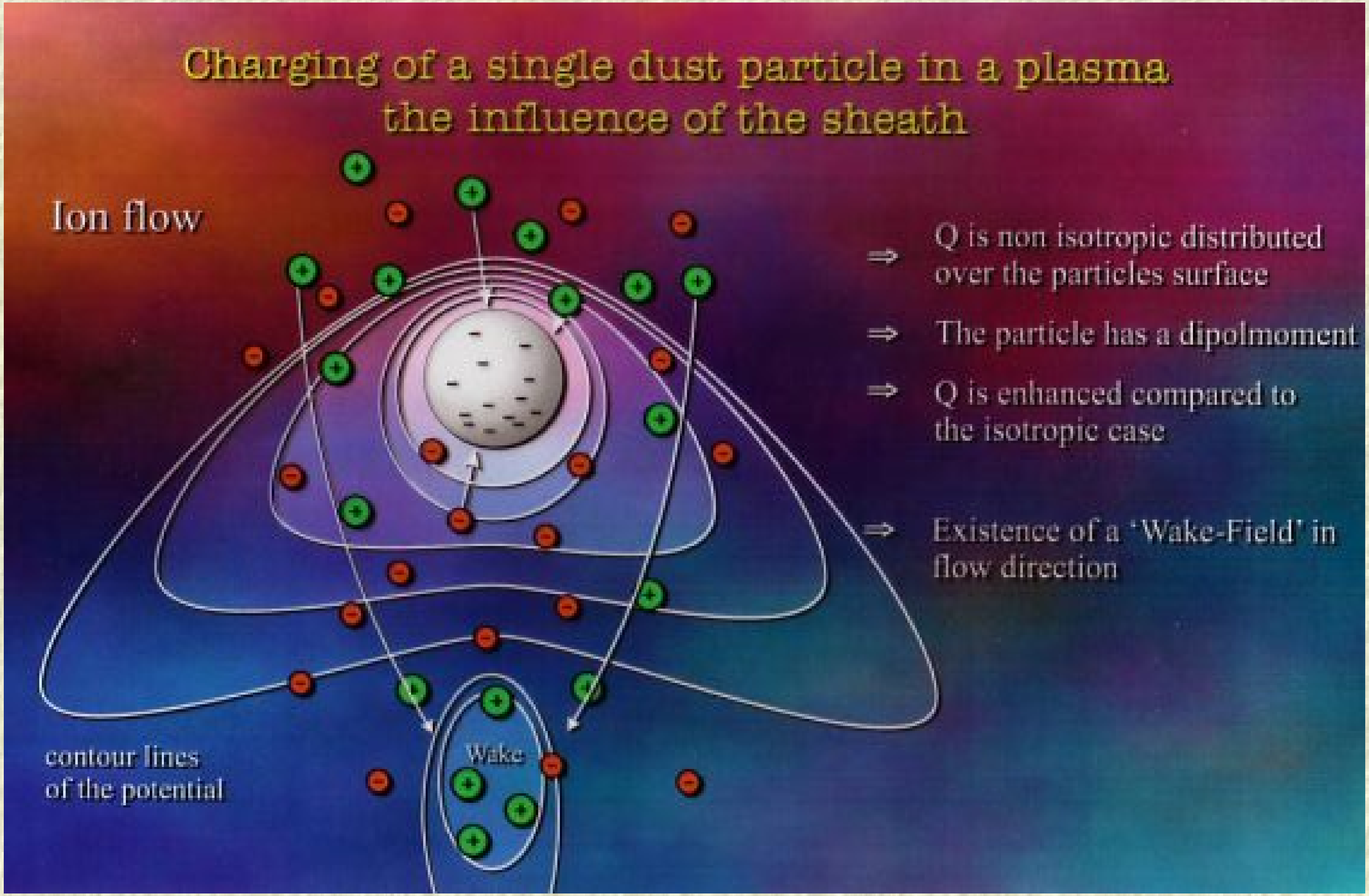
MACH CONES IN DUST CRYSTALS



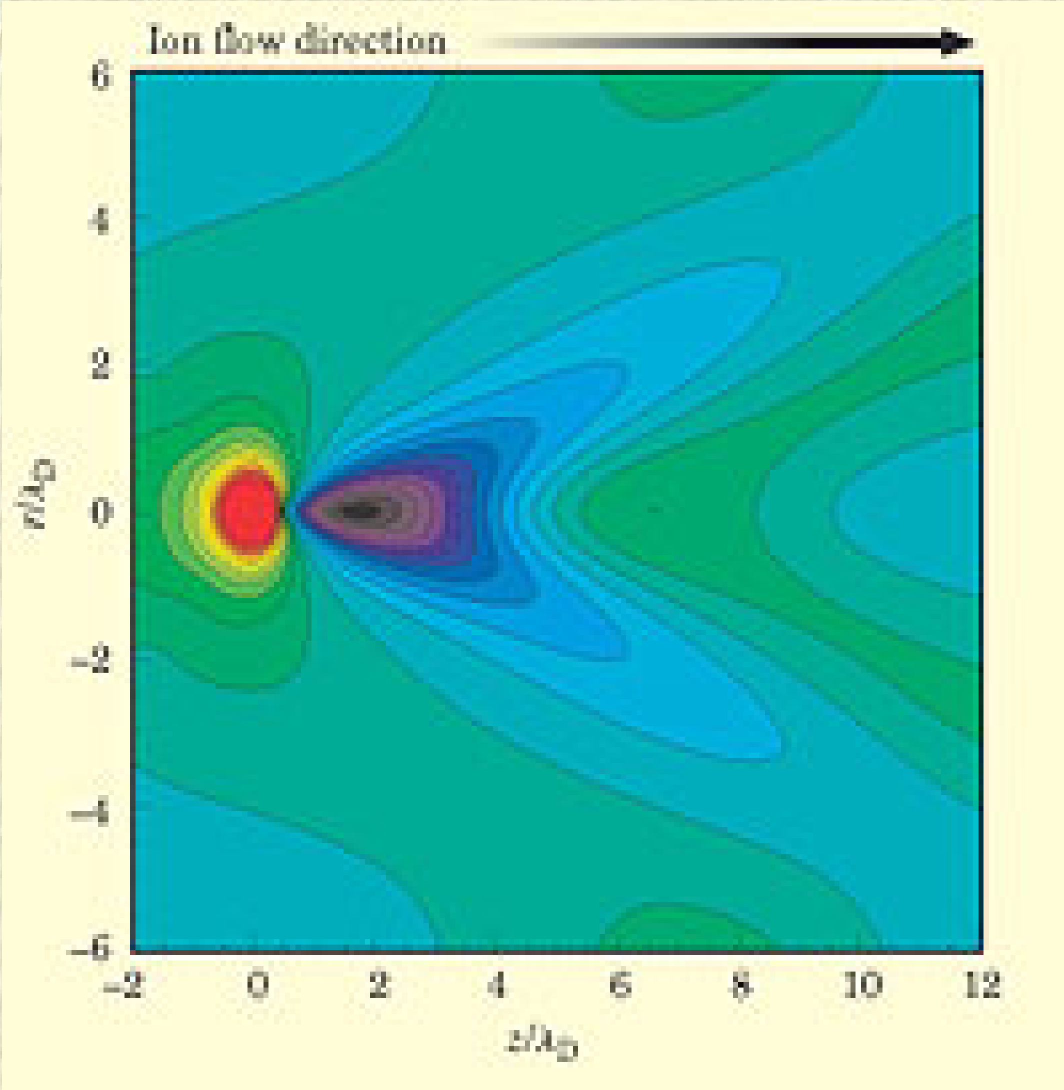
DOUBLE MACH CONES



WAKE FIELD

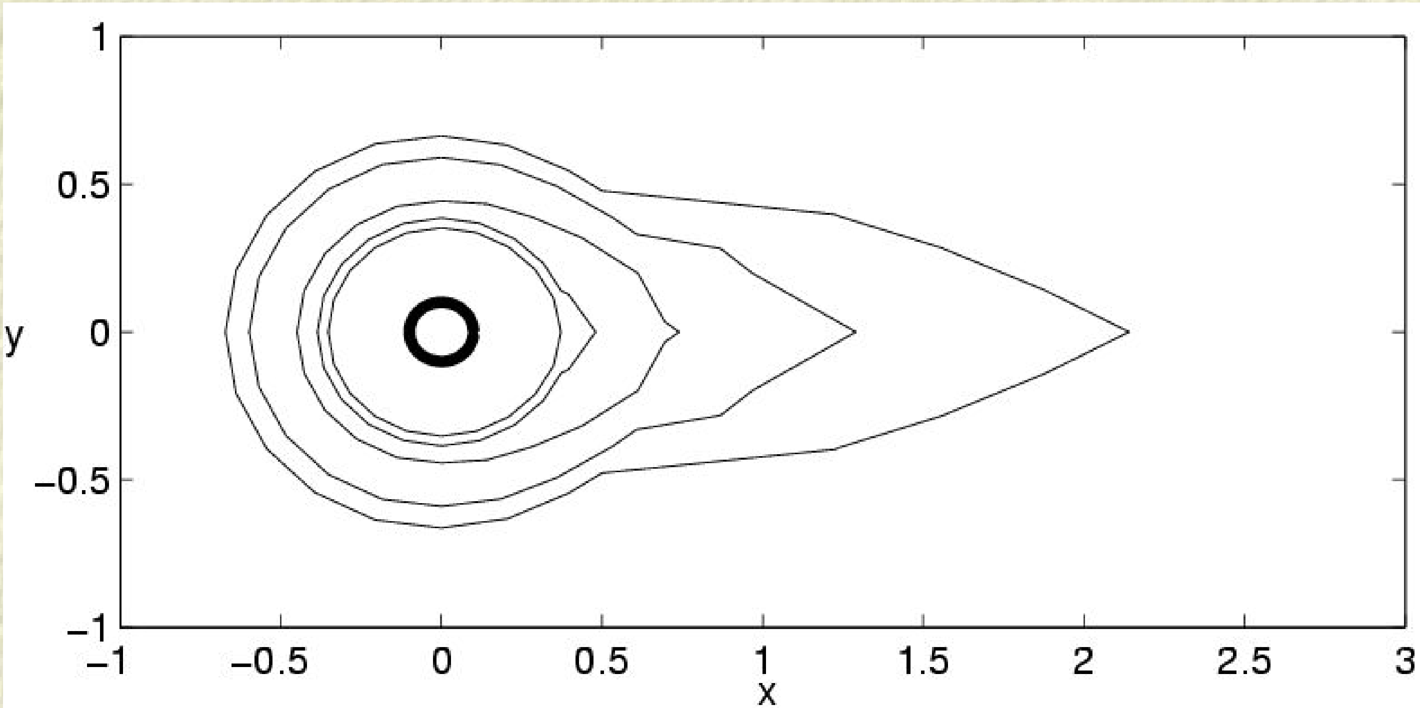

Charging of a single dust particle in a plasma
the influence of the sheath
Ion flow
⇒ Q is non isotropic distributed over the particles surface
⇒ The particle has a dipolmoment
⇒ Q is enhanced compared to the isotropic case
⇒ Existence of a 'Wake-Field' in flow direction
Wake
contour lines
of the potential

ION WAKE



ION WAKE, KINETIC DESCRIPTION

D. D. Tskhakaya, P. K. Shukla, and B. Eliasson, Phys. Lett. A 331,404 2004.



THEORY OF DIA SHOCK WAVES

DISSIPATION + DISPERSION

$$\omega \approx kC_s \left(1 - \frac{k^2}{2k_0^2}\right) - i\nu k^2 \lambda^2$$

WAVES IN A DISSIPATIVE MEDIUM

$$\frac{\partial u}{\partial t} + C_s \frac{\partial u}{\partial x} + \frac{C_s}{2k_0} \frac{\partial^3 u}{\partial x^3} = \nu \lambda^2 \frac{\partial^2 u}{\partial x^2}$$

THEORY OF DIA SHOCK WAVES

K-dV-BURGERS EQUATION

$$\frac{\partial u}{\partial t} + \alpha u \frac{\partial u}{\partial x} + \frac{C_s}{2k_0^2}\frac{\partial^3 u}{\partial x^3} = \nu\lambda^2 \frac{\partial^2 u}{\partial x^2}$$

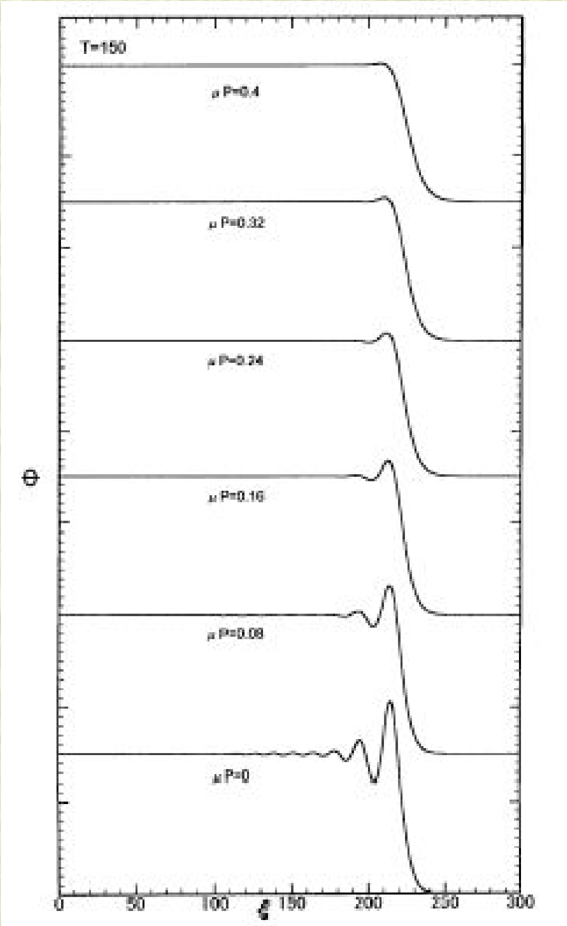
WITHOUT DISPERSION

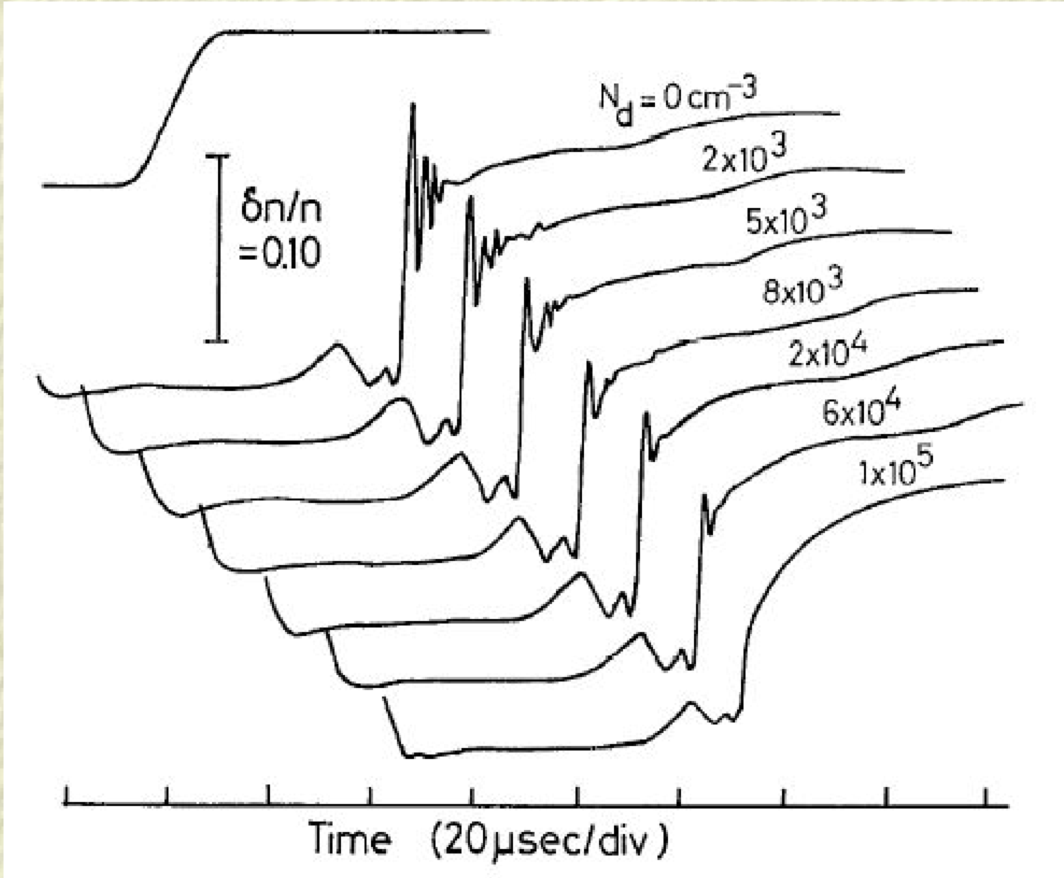
$$u = V(1 - \tanh\theta)$$

WITH

$$\theta = \frac{V(x - Vt)}{\delta_s}, \quad \delta_s = 2\nu\lambda^2, \quad \alpha = 1$$

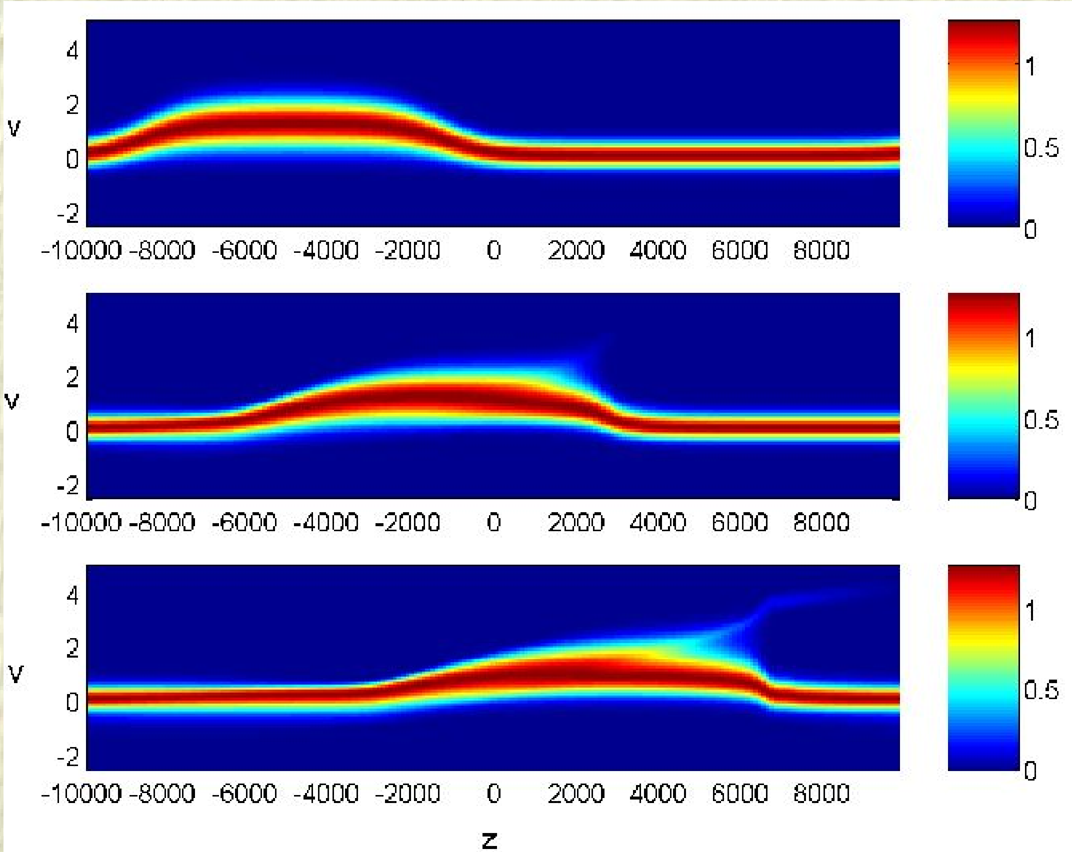
DIA SHOCK WAVE: SIMULATIONS & OBSERVATIONS





Nakamura, Bailung & Shukla, Phys. Rev. Lett. 1999

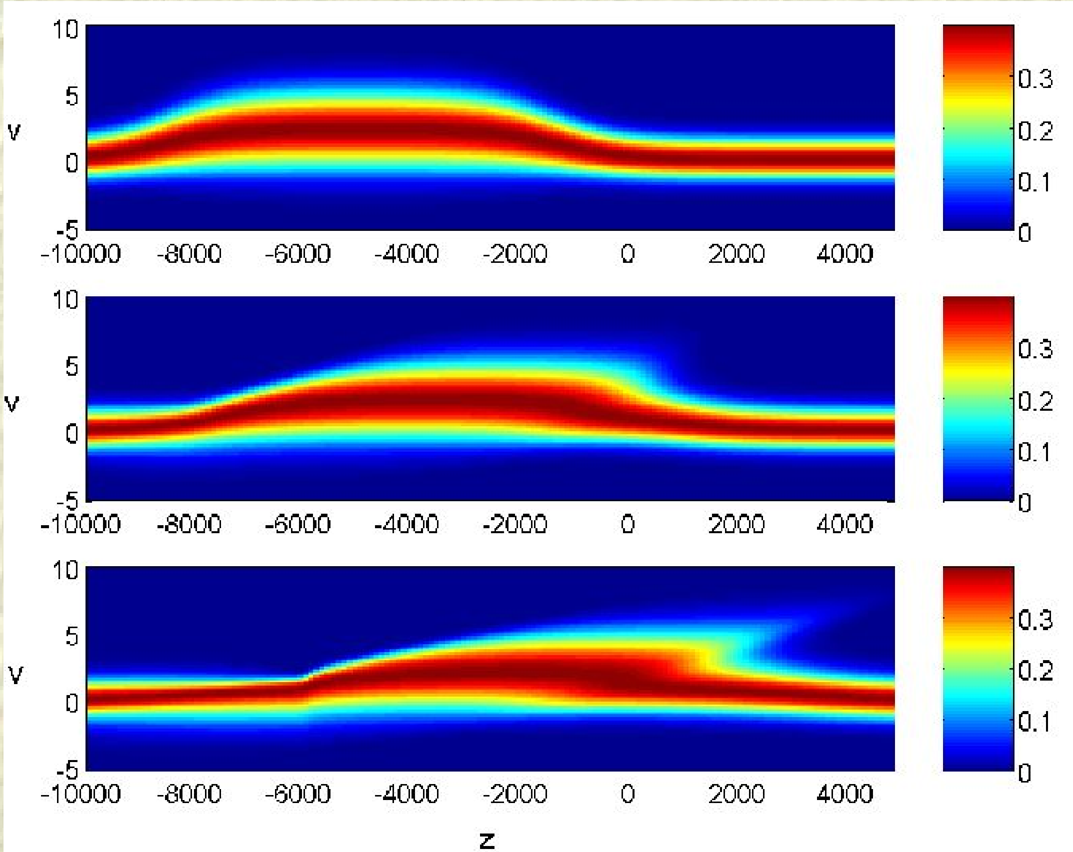
DIA SHOCK WAVE: VLASOV SIMULATION



$$T_i/T_e = 0.1, \quad n_{e0}/n_{i0} = 0.25$$

Eliasson & Shukla, Phys. Plasmas, 2004.

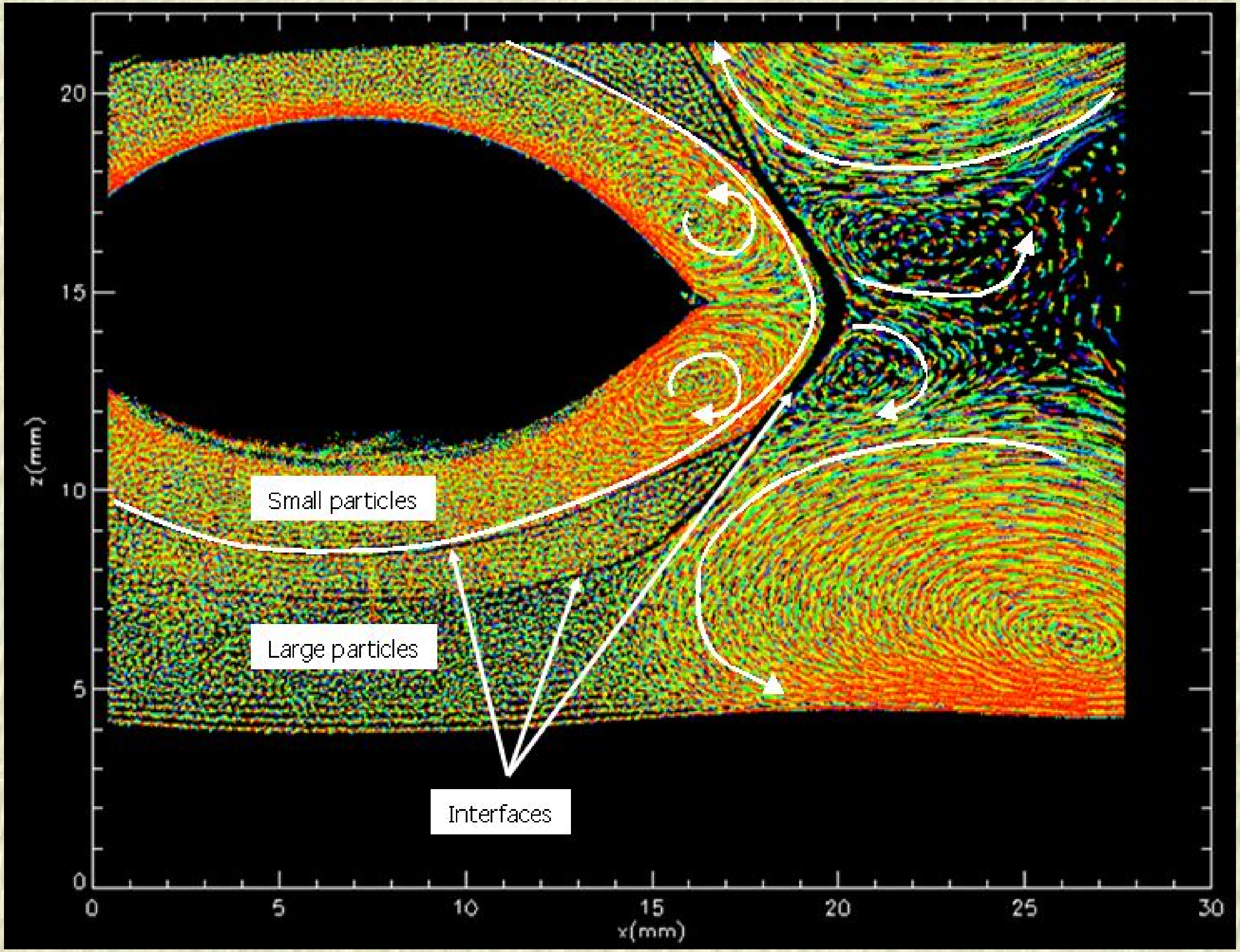
DIA SHOCK WAVE: VLASOV SIMULATION



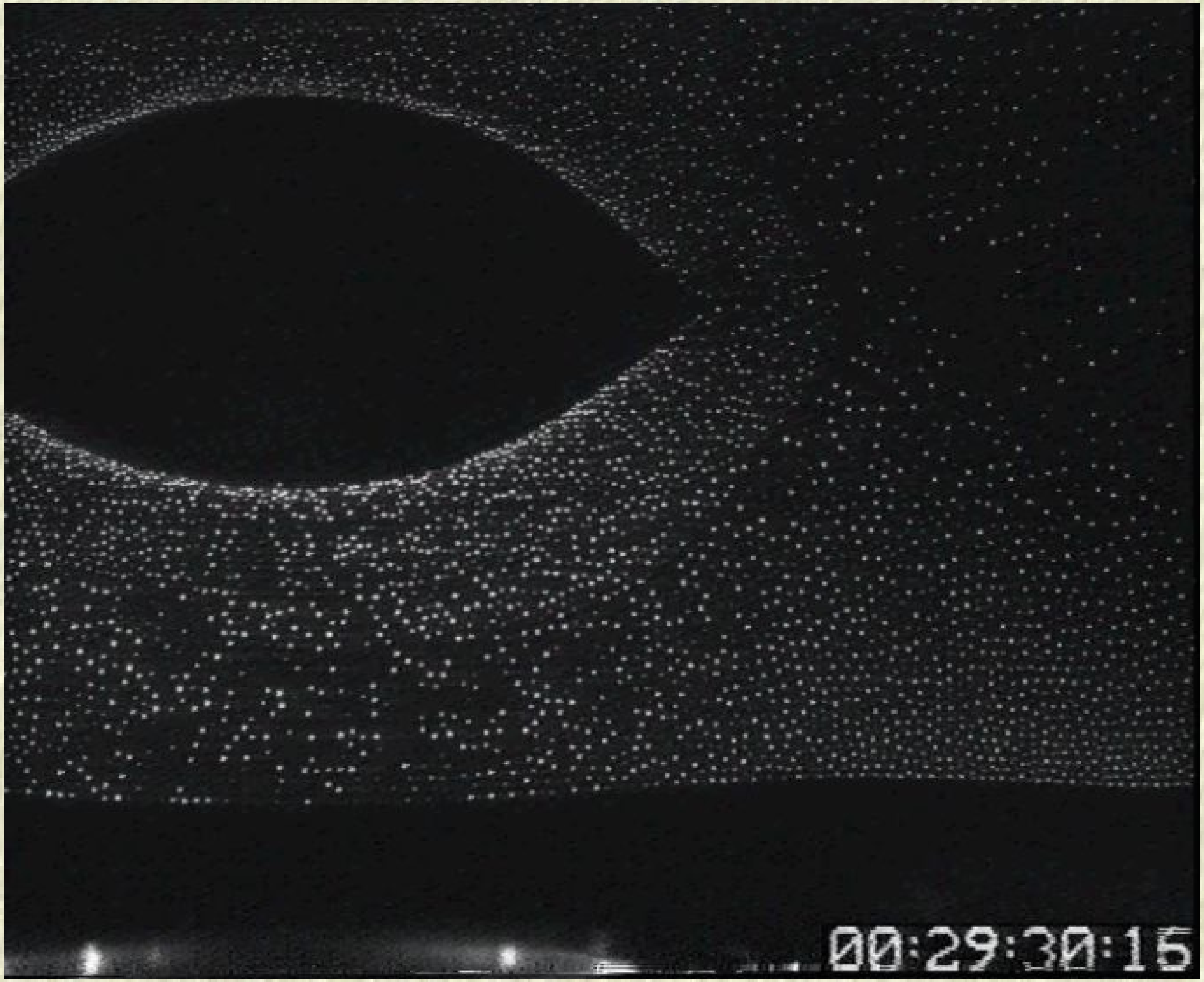
$$T_i/T_e = 1, \quad n_{e0}/n_{i0} = 0.05$$

Eliasson & Shukla, Phys. Plasmas, 2004.

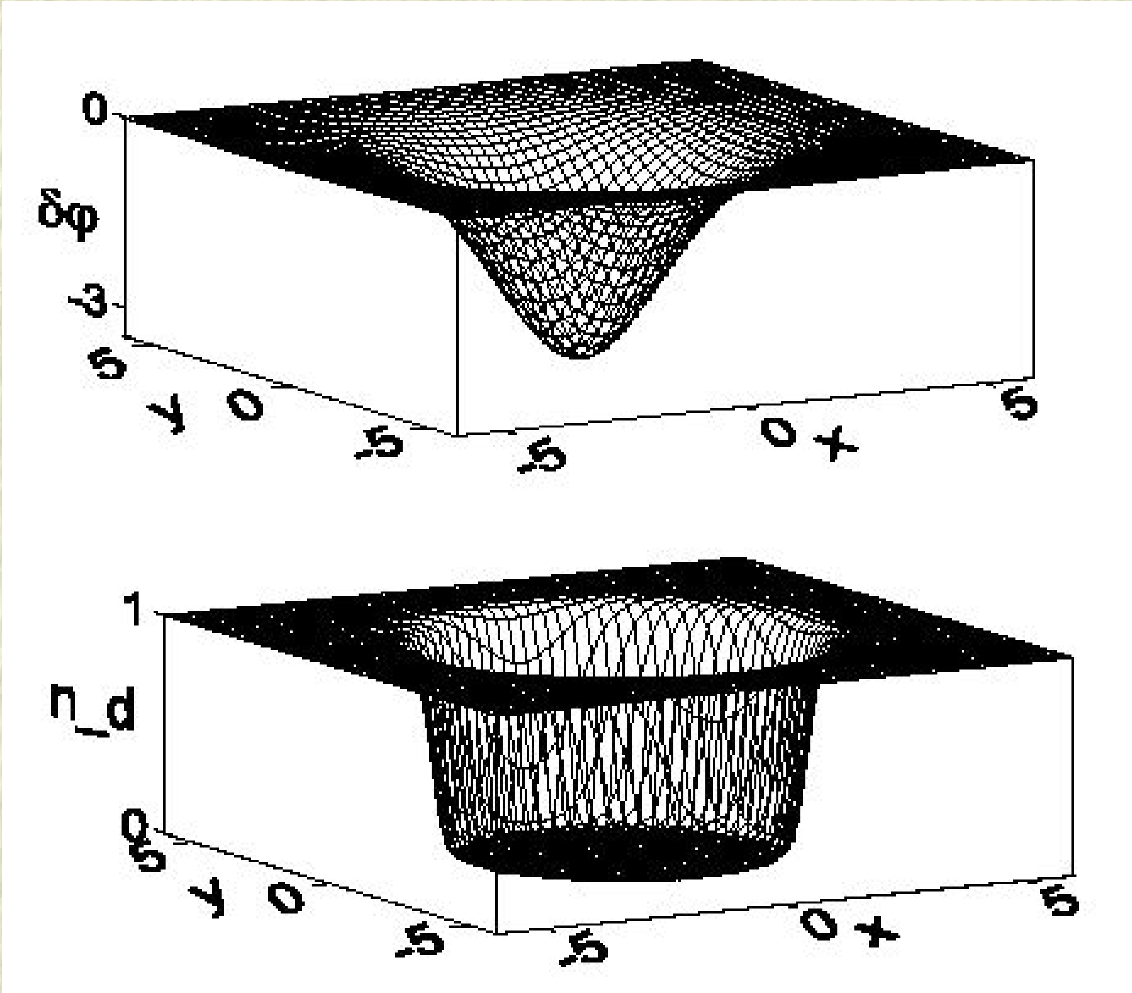
MOVIE OF VORTICES AROUND DUST VOID



MOVIE OF DUST VOID CLOSURE



DUST VOID IN MAGNETIZED PLASMAS



Jovanović & Shukla, Phys. Lett A, 2004.

SUMMARY & CONCLUSIONS

- A. WE HAVE DISCUSSED PROPERTIES OF DUSTY PLASMAS
- B. DUST CHARGING
- C. OCCURRENCE OF DUSTY PLASMAS IN SATURN RINGS, COMET TAILS, SPACE NEBULAS AND IN NOCTILUCENT CLOUDS IN POLAR MESOSPHERE
- D. DUST IN COMMERCIAL PLASMA ETCHING REACTORS AND IN TOKAMAKS
- E. NEW FORCES: WAKE FIELDS
- F. NONLINEAR STRUCTURES: MACH CONES, DIA SHOCKS, VOIDS, VORTICES