Dusty Plasma

Waleed Moslem
Professor of Theoretical Plasma Physics

Outline

- Types of plasma
- Occurance of dusty plasma
- Properties of dusty plasma
- Two milestones in dusty plasma
- Mach cones
- Wakefield

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Types of plasma

- **(I) Classical plasma (electron-ion plasma)**

  +ve ions / electrons / -ve ions / positrons

- **(II) Dusty (complex) plasma**

  +ve dust / -ve dust / +ve ions / electrons / -ve ions

- **(III) Quantum plasma**

  Electrons / positrons / holes / +ve ions

Types of plasma, cont.

Irving Langmuir
1927

Padma Kant Shukla
1990

Giovanni Manfredi
2000

Types of plasma, cont.

Classical plasma

- Mainly $\rightarrow$ +ve ions & electrons
- Sometimes $\rightarrow$ -ve ions & positrons
- 1927 $\rightarrow$ now
- Applications / observations / Experiment $\rightarrow$ laboratory, space plasma, astrophyical plasma

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Occurance of dusty plasma

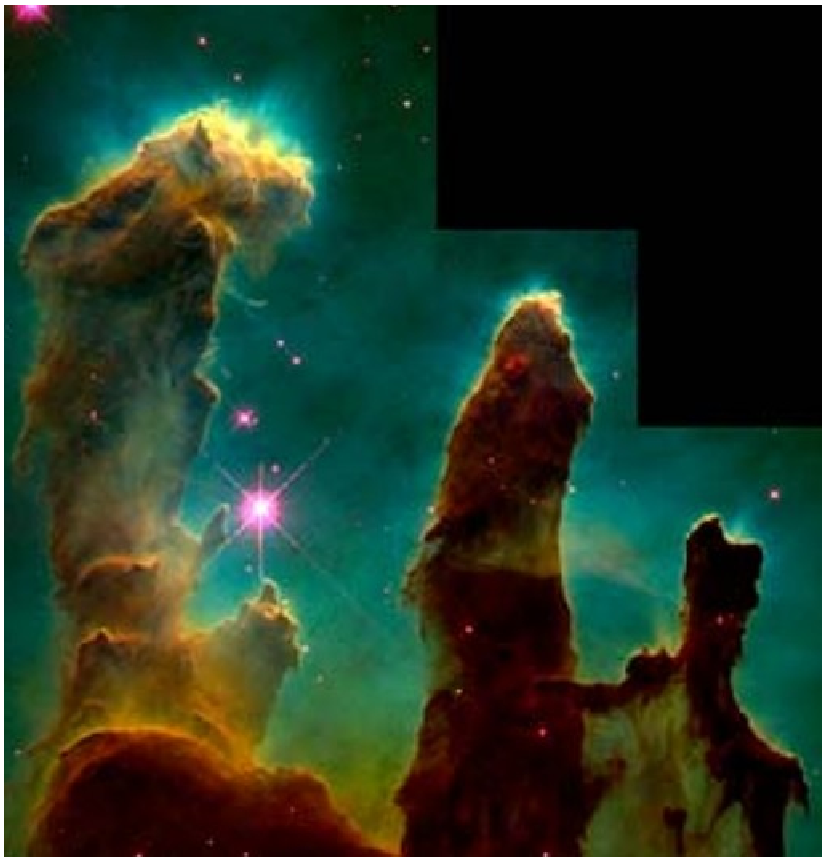
- What is dusty plasma? A four component system, consisting of electrons, ions, neutral atoms and micron size solid dust grains
- A few nanometers to tens of micrometers
- A four component system, consisting of electrons, ions, neutral atoms and micron size solid dust grains
- Observations → Comet tails, Planetary rings, Solar and planetary nebulae, Lower ionosphere (mesosphere), Atmospheric lightning, Industrial plasma processing devices, Magnetic fusion devices ,...etc.

Occurance of dusty plasma

Hyakutake

Hale-Bopp

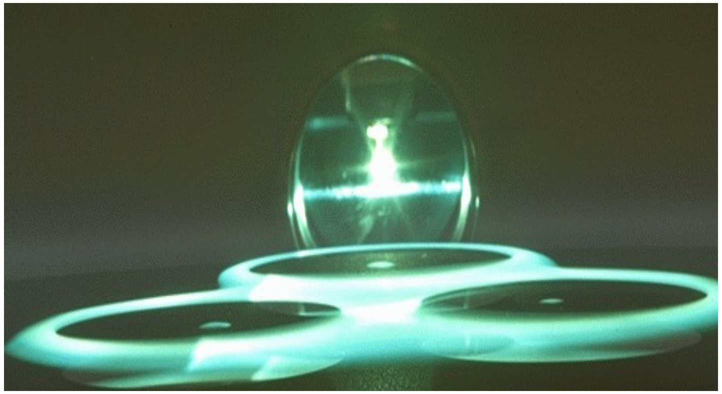
Occurance of dusty plasma



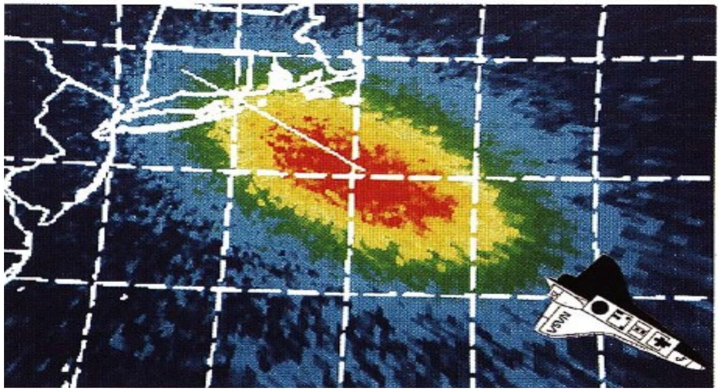
Eagle Nebula

Saturn Rings

Occurance of dusty plasma

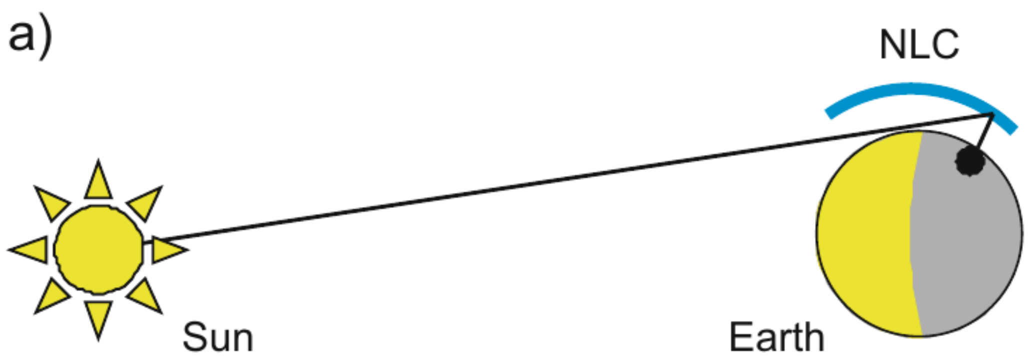


Charged dust clouds around silicon wafers, formed in a plasma processing device; a serious contamination issue



Dusty plasma of charged ice caused by the Space Shuttle engine exhaust

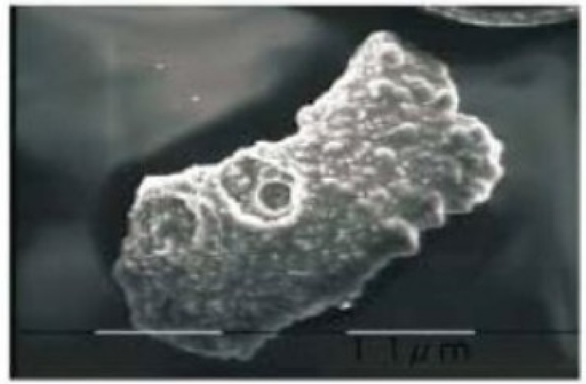
Occurance of dusty plasma



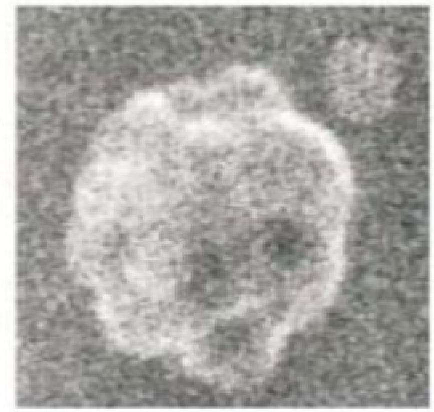
Noctilucent clouds formed in the summer mesosphere at 75-80 km altitude range; 100 nm water ice, charged

Occurance of dusty plasma

0.1 mm

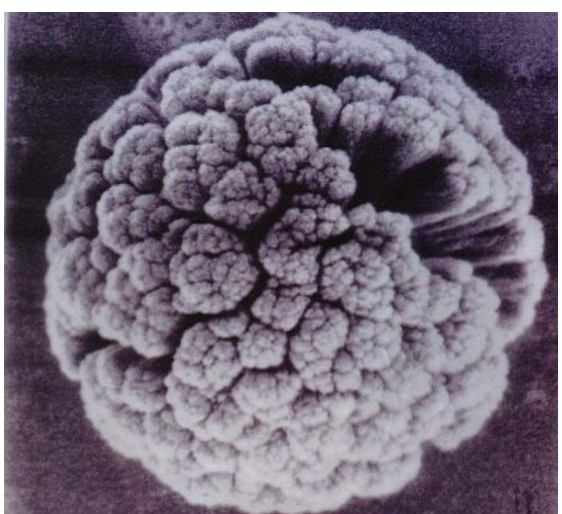


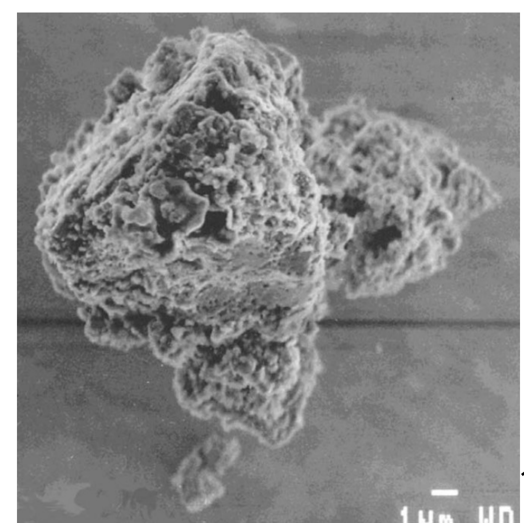
1μm



200 nm

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





Occurance of dusty plasma

- The “dust” is a result of the strong interaction between the material walls and energetic plasma, which causes flaking, blistering, arching and erosion of the carbon limiters or beryllium surfaces.

- Studies indicate that dust can be transported deep into the plasma, causing a serious contamination problem.

- Movies 1 & 2 & 3 & 4

Occurance of dusty plasma

- Flaking of redeposited material,

تقشر المواد المعاد ترسيبها

- Agglomeration from supersaturated vapour,

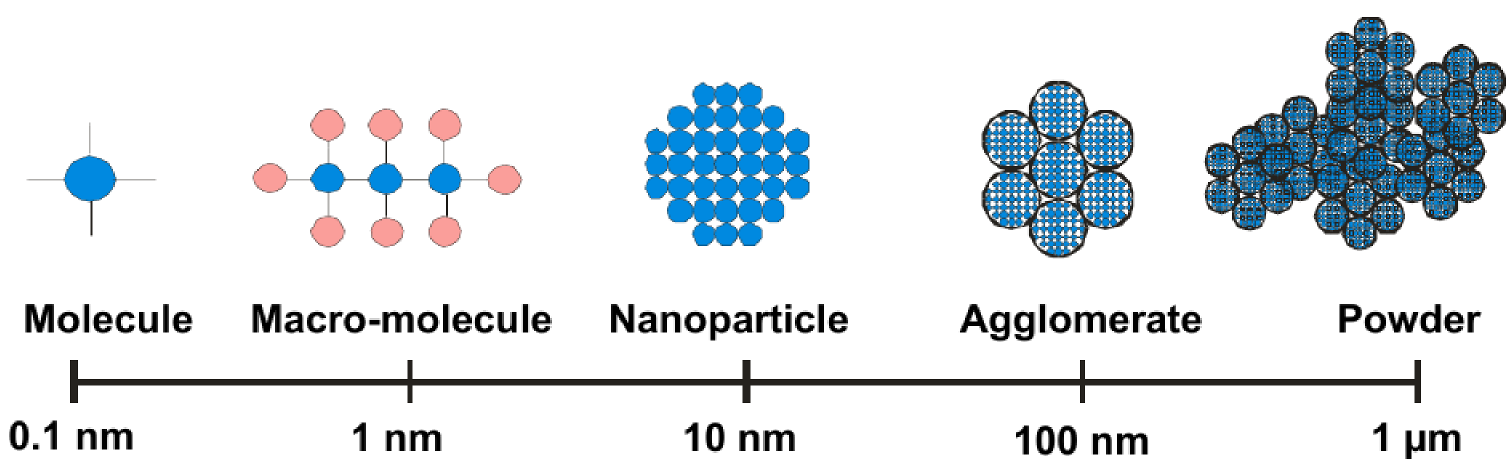
تكتل من بخار مفرط التشبع

- Particulate ejection due to thermal transients,

طرد الجسيمات بسبب العبور الحراري

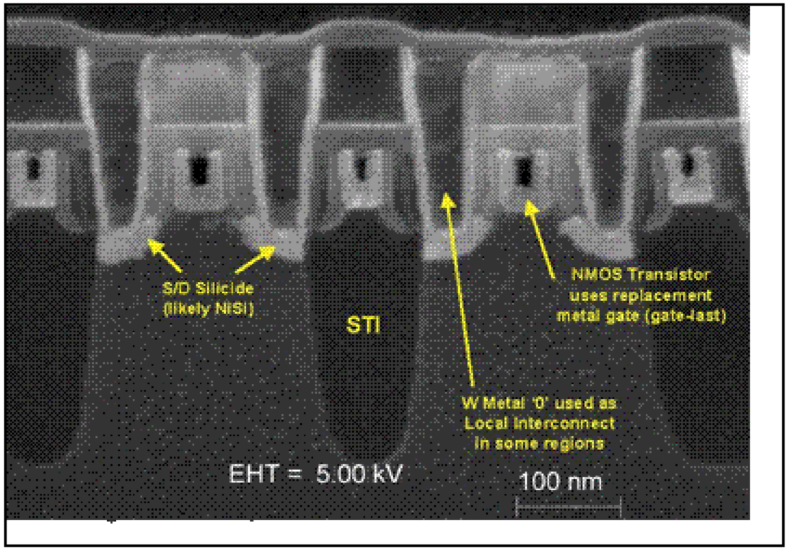
- Growth from hydrocarbon.

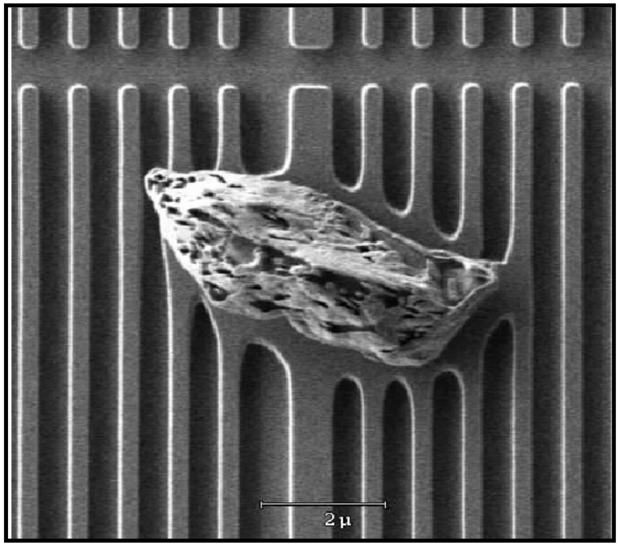
النمو من مركبات الهيدروكربونات



Occurance of dusty plasma

- Semiconductor industry
- Plasma chemistry and nanotechnology → coagulation of macroparticles





Outline

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- **Properties of dusty plasma**
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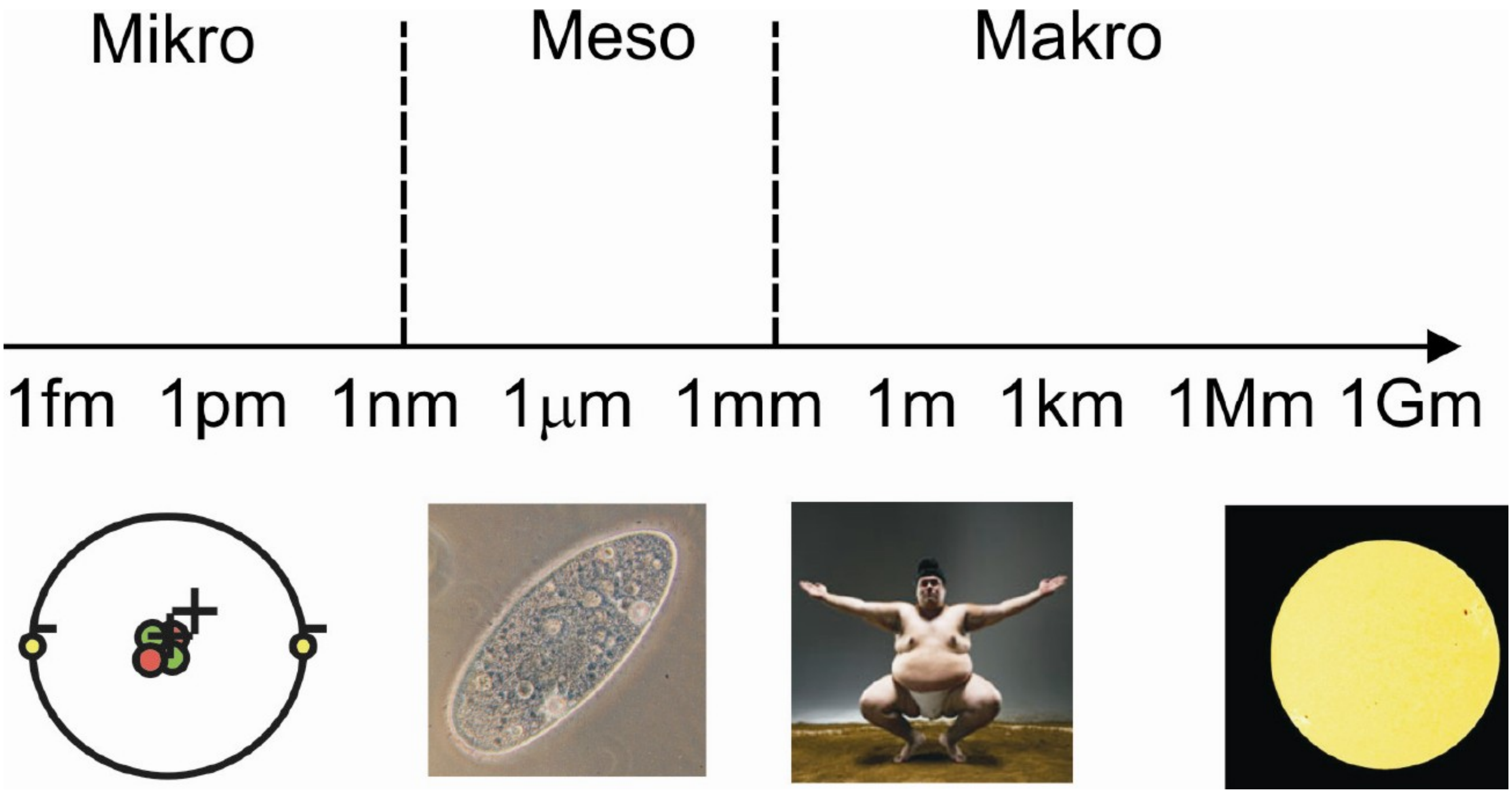
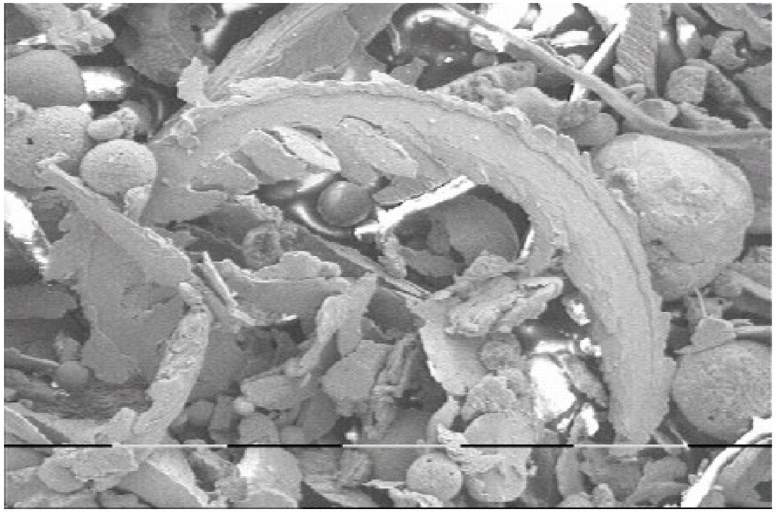
Properties of dusty plasma

- Dusty plasmas are multi-component plasmas
- They contain electrons, ions, neutral atoms/molecules, and micro-particles/charged dust grains

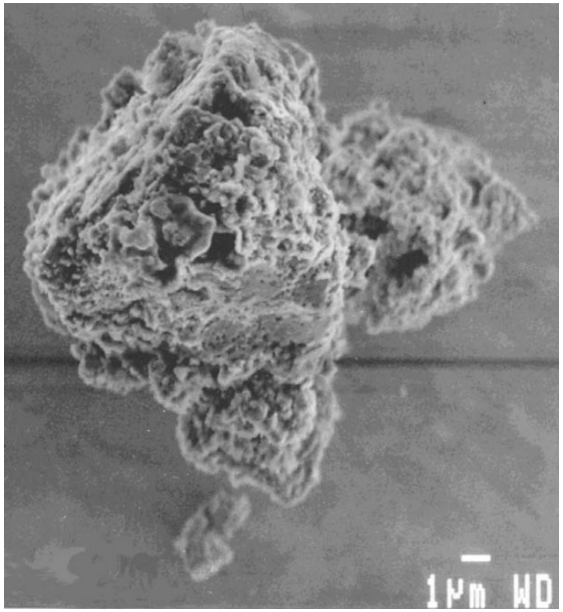


Properties of dusty plasma

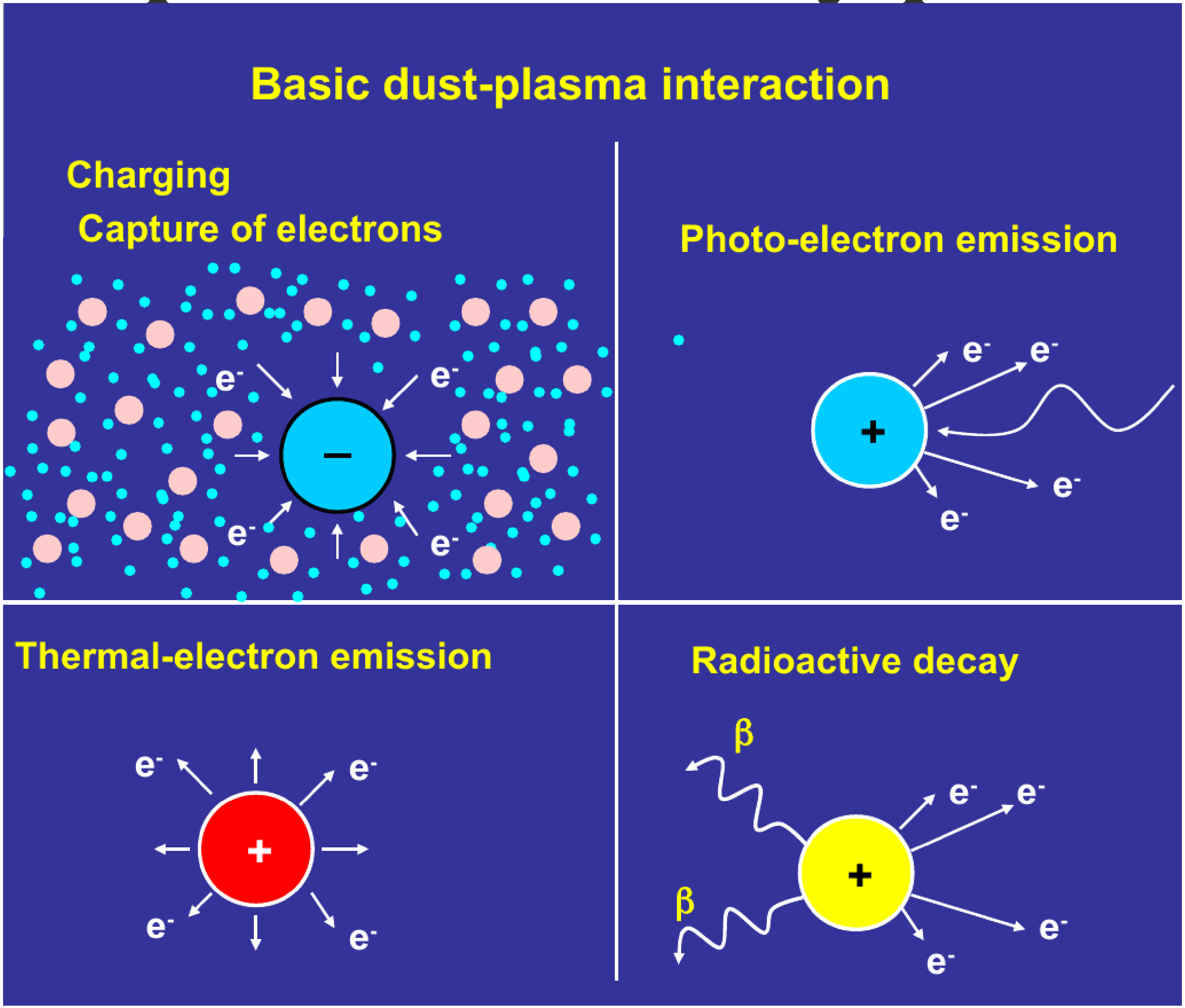
- They are significantly different from the usual electron-ion plasmas: dust size distributions
- New time scales associated with dust particle motion
- Dust charging as a dynamical variable



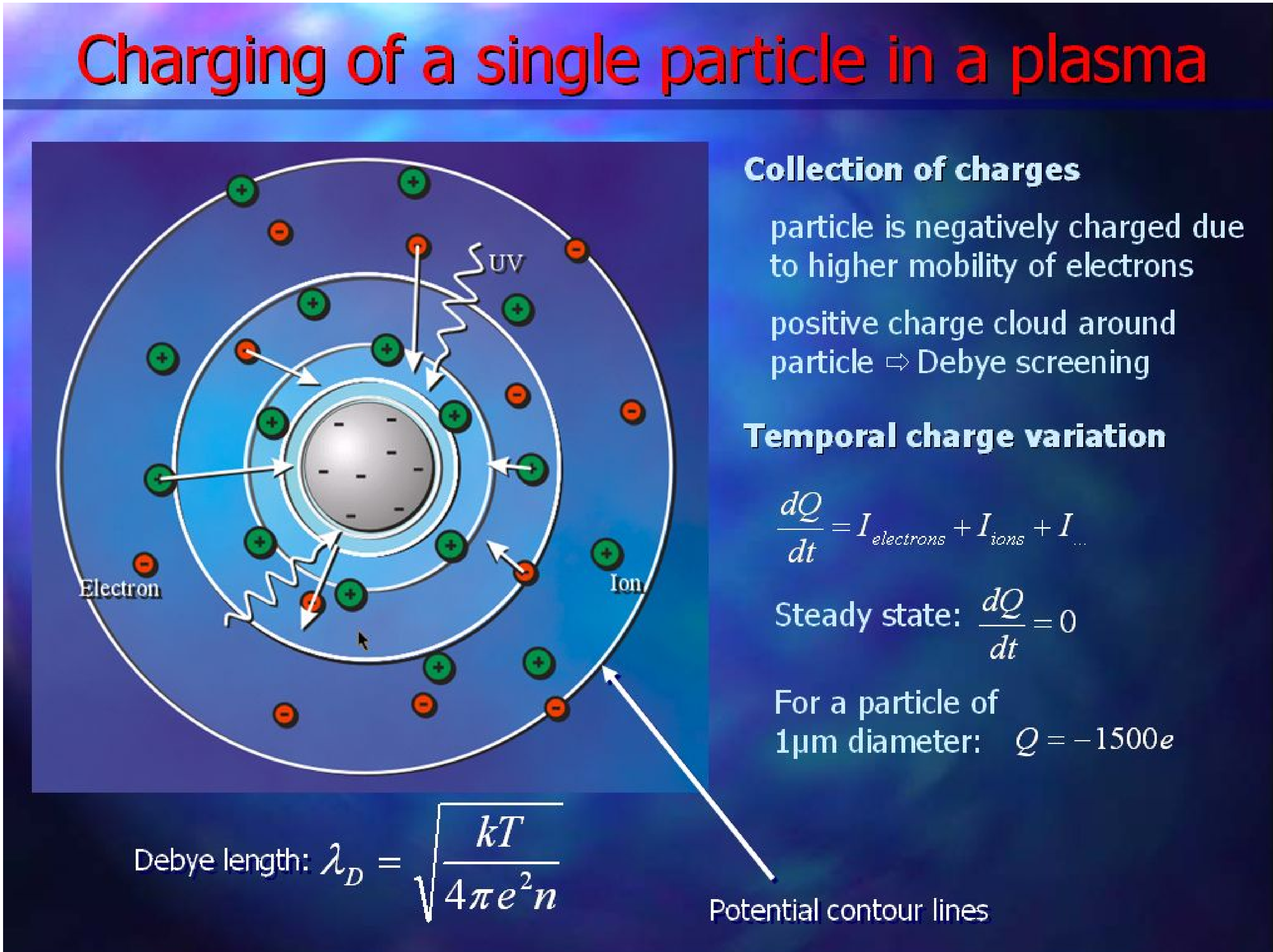
------- 0.1 mm



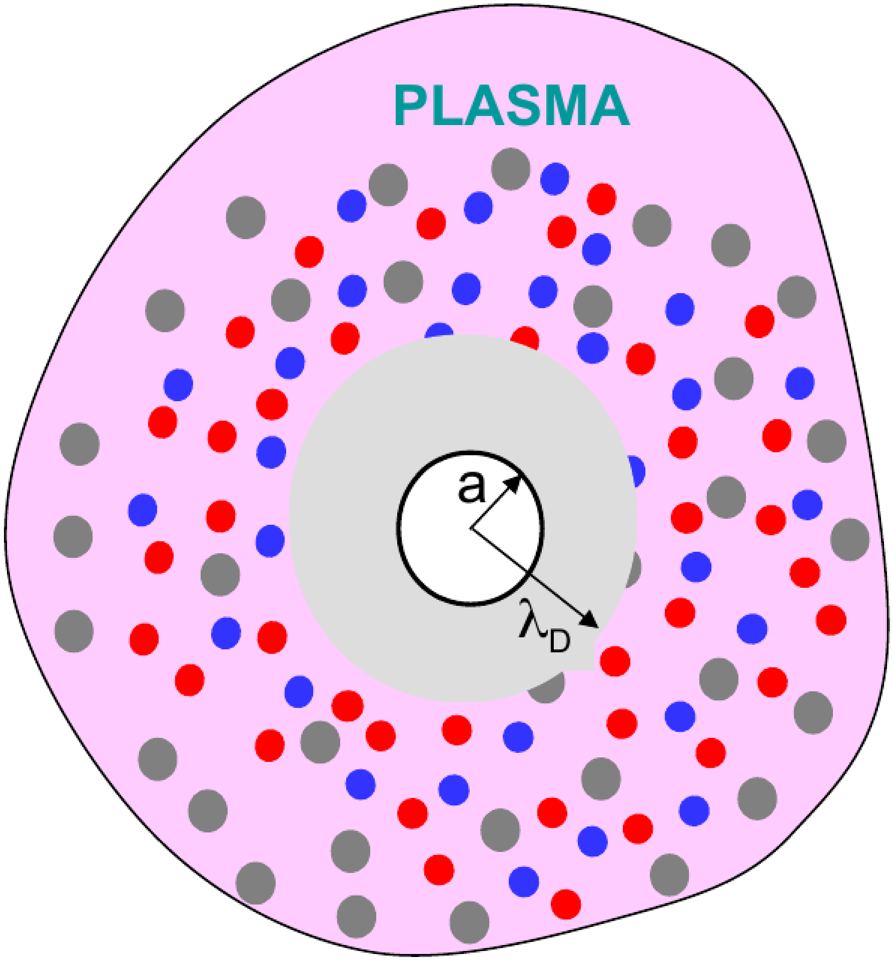
Properties of dusty plasma



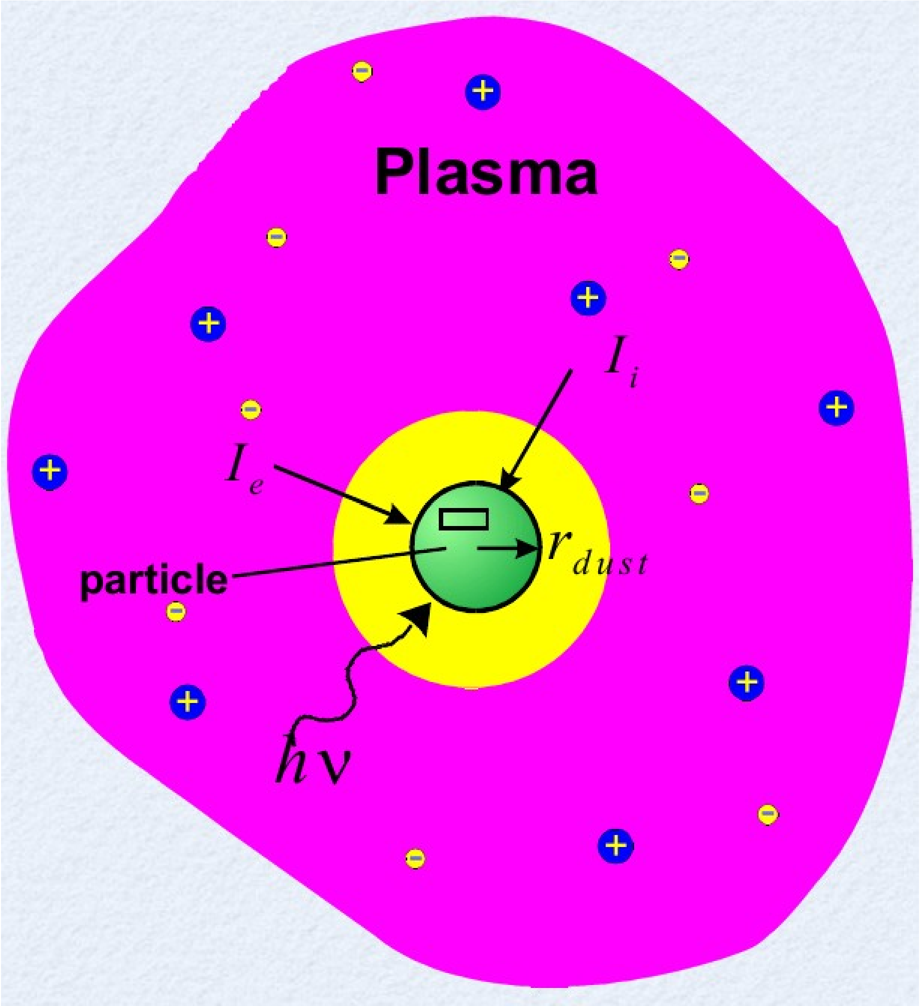
Properties of dusty plasma

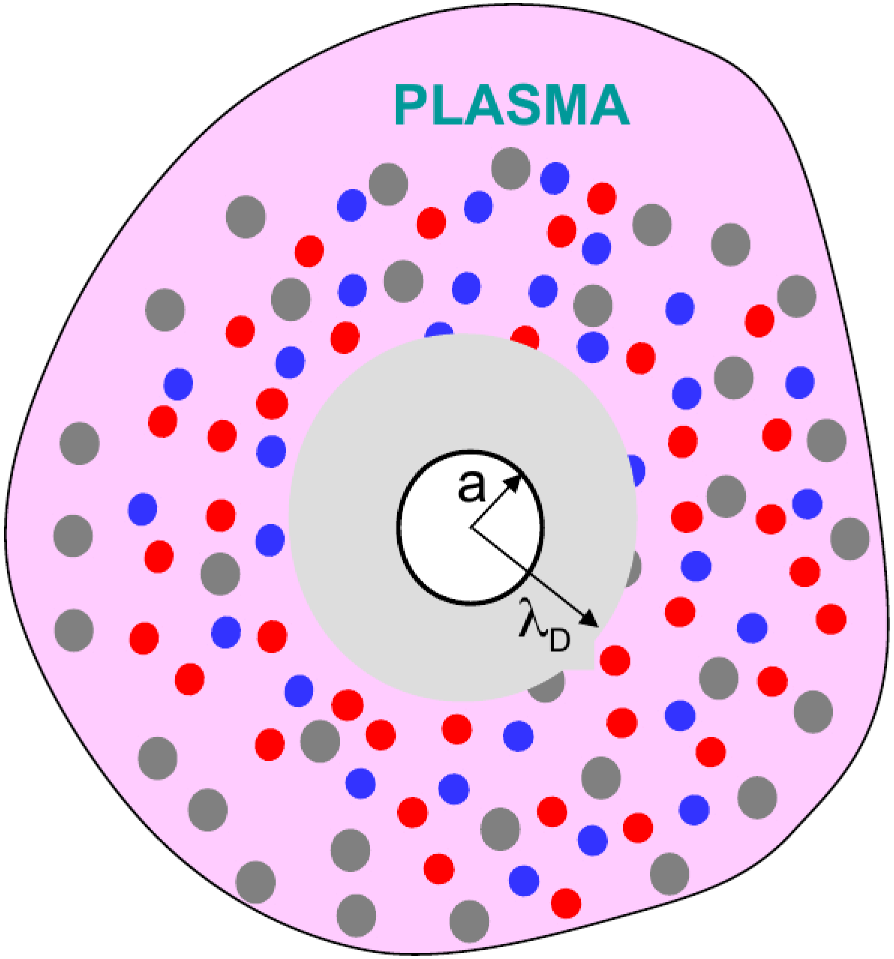


Properties of dusty plasma



Properties of dusty plasma





Properties of dusty plasma

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.	$dQ_d/dt = I_e + I_i + I_s + \dots$
m_i	$m_d \sim 10^{12} m_i$
λ_{De}	$\lambda_D \sim \lambda_{Di}$
Uniform particle sizes	Size distributions
IAW, EIC, f ~1 kHz	DAW, DLW, f ~10 Hz,

Properties of dusty plasma

- Debye shielding

$$\lambda_D = \frac{\lambda_{De}\lambda_{Di}}{\sqrt{\lambda_{De}^2 + \lambda_{Di}^2}}$$

$$\lambda_{De} = (k_B T_e / 4\pi n_{e0} e^2)^{1/2} \text{ and } \lambda_{Di} = (k_B T_i / 4\pi n_{i0} e^2)^{1/2}$$

- -ve dust → what happen?
- +ve dust → what happen?

- Dust plasma frequency

$$\omega_{pd} = (4\pi n_{d0} Z_d^2 e^2 / m_d)^{1/2}$$

Properties of dusty plasma

- **Dust-in-plasma & Dusty plasma → G.W.**
- **Intergrain distance & Debye length**
- **Intergrain distance > Debye length → ??**
- **Intergrain distance < Debye length → ??**

Properties of dusty plasma

- Dust-in-plasma & Dusty plasma → G.W.
- Intergrain distance & Debye length
- Intergrain distance > Debye length → Dust-in-plasma
- Intergrain distance < Debye length → Dusty plasma

Properties of dusty plasma

$$Z_d \approx 10^3,\, m_d \approx 2\times 10^{-12}\ \mathrm{g},\, n_{d0} \approx 10^{-9}\mathrm{cm}^{-3}$$

$$T_e \approx 5 - 22\ \mathrm{eV},\ T_i \approx 60 - 120\ \mathrm{eV},\ n_{e0} \approx 1 - 23 \times 10^3\mathrm{cm}^{-3}$$

Calculate

- Debye length
- Dust frequency
- Intergrain distance
- Type of plasma (dust-in-plasma or dusty plasma)

Outline

- Types of plasma
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- Properties of dusty plasma
- **Two milestones in dusty plasma**
- Mach cones
- Wakefield

Two milestones in dusty plasma

- **Dust Coulomb crystal (IKEZI 1986)**

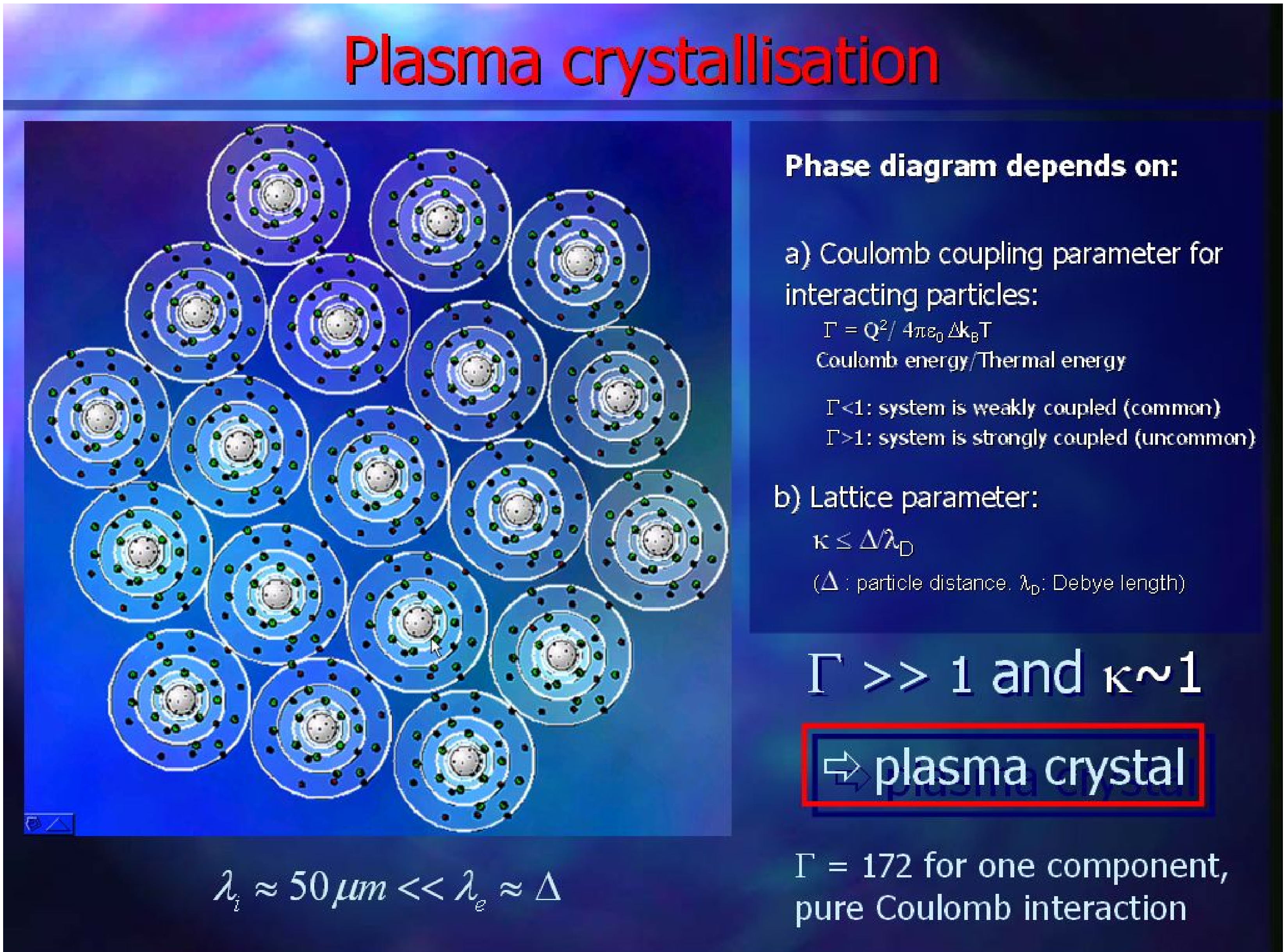
  First prediction by H. Ikezi, Phys. Fluids 29, 1764 (1986); Observations: Chu & Lin I, PRL 72, 4009 (1994); Physica A, 205, 183 (1994); Thomas et al, PRL 73, 653 (1994).

- **Dust-acoustic waves (SHUKLA 1989; RAO, SHUKLA & YU 1990)**

  First prediction: P. K. Shukla, Proc. 1st Capri Workshop on Dusty Plasmas, pp. 38–39, 28 May – 2 June 1989. N. N. Rao, P. K. Shukla, and M. Y. Yu, Planet. Space. Sci 38, 543 (1990). Observation: J. Chu, J.-B. Du, Lin I, J. Phys. A: Appl. Phys. 27, 296 (1994); A. Barkan, R. L. Merlino, and N. D'Angelo, Phys. Plasmas 2 3563 (1995).

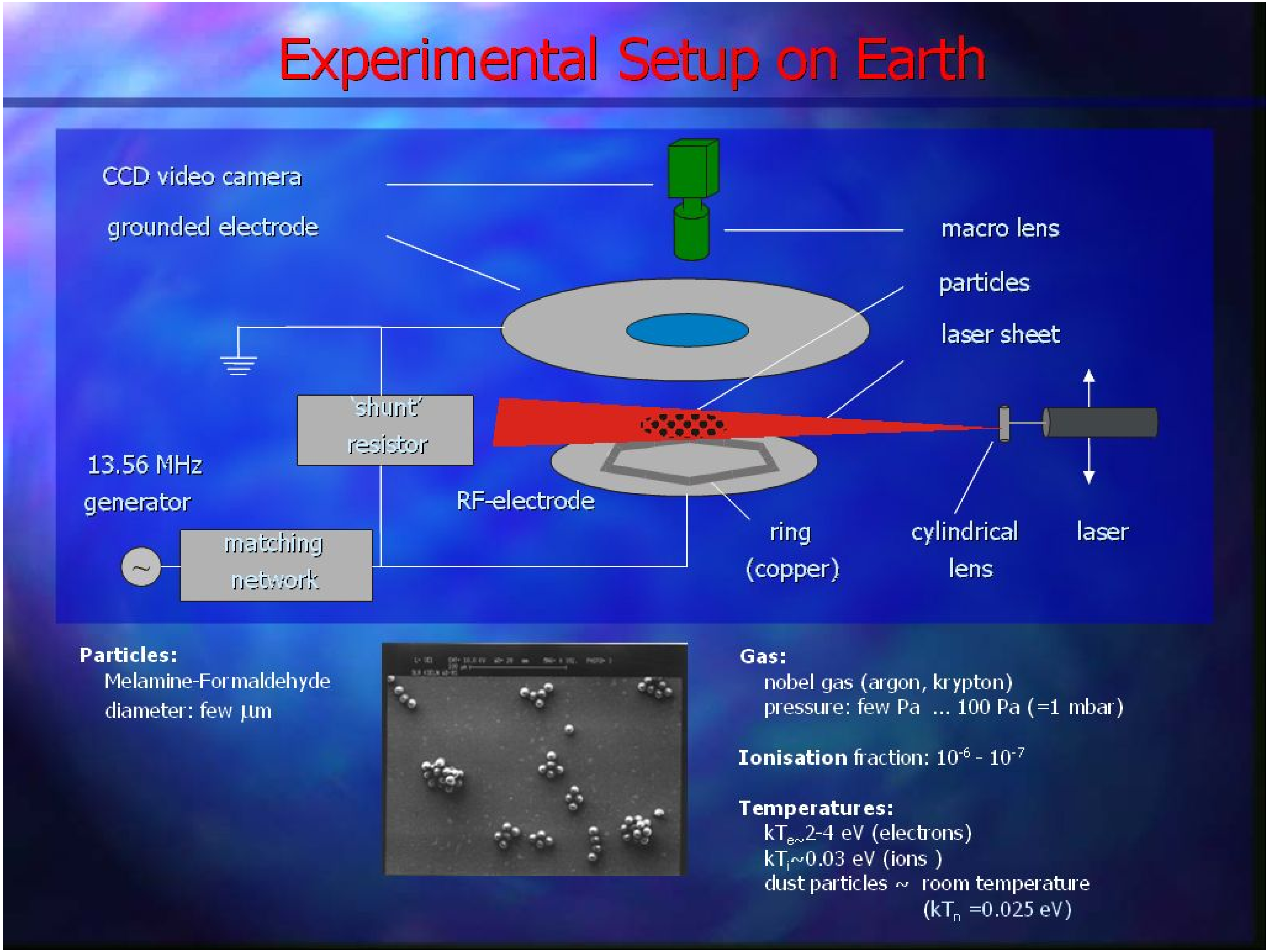
Two milestones in dusty plasma

Dust Coulomb crystal



Two milestones in dusty plasma

Dust Coulomb crystal



Two milestones in dusty plasma

Dust Coulomb crystal

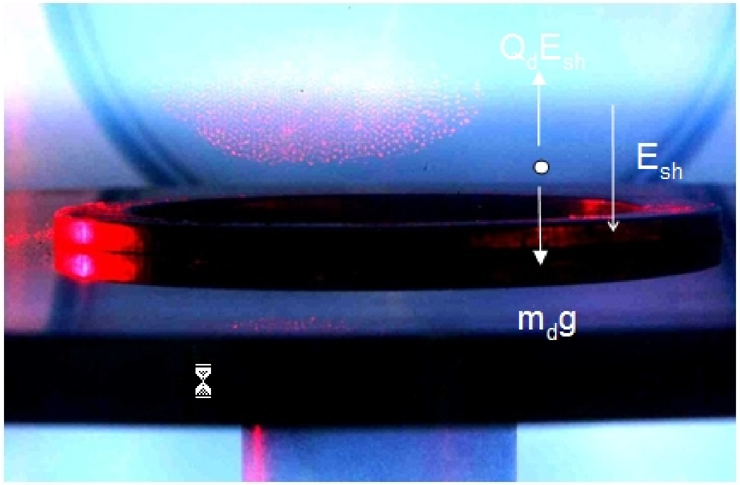
Crystals in RF plasma sheath

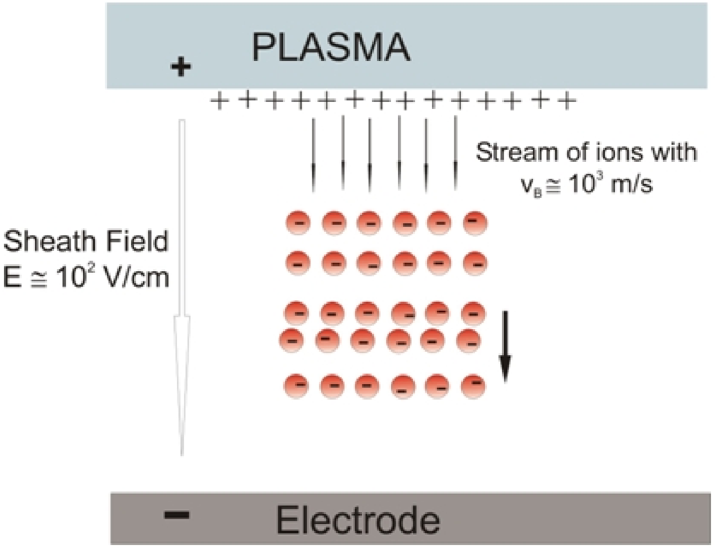
- RF frequency f=13.56 Mhz

(self-bias≈ -10…-100 V) (p-p ~50-200 V)

$$V_{electrode} = V_{dc} + V_{rf} \sin(2\pi f\, t)$$

- Dust has inertia → in equilibrium $Q_d E_{sh} = m_d g$ (E_{sh} is time averaged sheath field)





Two milestones in dusty plasma

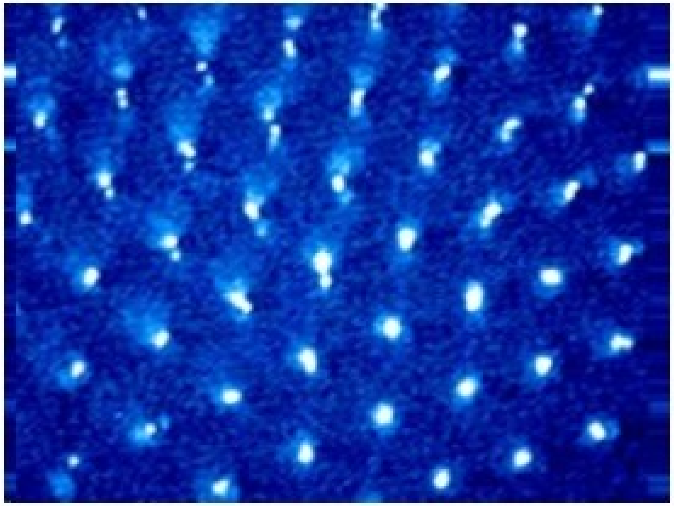
Dust Coulomb crystal

微粒電漿晶格

微粒的大量負電荷造成強大靜電交互作用力

自動排列成晶格或液體結構，懸浮於背景電漿中

1993
春季



首度實驗室觀測/ 博士班學生朱仁宏的研究成果

J.H.Chu and Lin I, PRL(1994) Lin I et al, Science (1996)

數百微米微粒間距，提供一可以透過數位光學顯微技術直接觀測與追蹤粒子軌跡的平台

Two milestones in dusty plasma

Dust Coulomb crystal

- Two particles
- Three particles
- Disorder phase
- Flow phase
- Crystalline phase

Two milestones in dusty plasma

Dust Coulomb crystal

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

Two milestones in dusty plasma

Dust acoustic waves

- Padma K. Shukla and his collaborators predicted the existence of dust acoustic waves, dust ion acoustic waves and shocks....etc.
- His interest:

(1) Physics of low- and high-temperature plasma
(2) Nonlinear quantum plasma physics
(3) Nonlinear space and astroplasmas
(4) Nonlinear processes in geophysical flows
(5) Collective interactions in dusty plasmas
(6) Laser-plasma interactions
(7) Plasma high-energy charged particle accel.
(8) Nonlinear photonics/optics

Padma Kant Shukla
1950 – 2013 (India-Germany)
Member of The Royal Swedish Academy of Science

Two milestones in dusty plasma

Dust acoustic 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	$(B_0^2/8\pi n_{i0}m_d)^{1/2}$

Two milestones in dusty plasma

Dust acoustic waves

Planet. Space Sci., Vol. 38, No. 4, pp. 543–546, 1990
Printed in Great Britain.

DUST-ACOUSTIC WAVES IN DUSTY PLASMAS

N. N. RAO,* P. K. SHUKLA and M. Y. YU

Physica Scripta. Vol. 45, 508, 1992.

Dust Ion-Acoustic Wave

P. K. Shukla* and V. P. Silin†

Two milestones in dusty plasma

Dust acoustic waves

- Xu et al. 1992 → modifay the Q-machine to allow the dispersal of dust grains over a portion of the cylindrical plasma column

- Chu et al. 1994 → for the first time a dusty plasma has been confined in a cylindrical symmetric rf plasma system

J. Phys. D: Appl. Phys. **27** (1994) 296–300. Printed in the UK

Coulomb solids and low-frequency fluctuations in RF dusty plasmas

J H Chu, Ji-Bin Du and Lin I

Department of Physics, National Central University, Chungli, Taiwan 32054, Republic of China

Received 23 April 1993, in final form 4 August 1993

Phys. Plasmas **2** (10), October 1995

Laboratory observation of the dust-acoustic wave mode

A. Barkan, R. L. Merlino, and N. D'Angelo

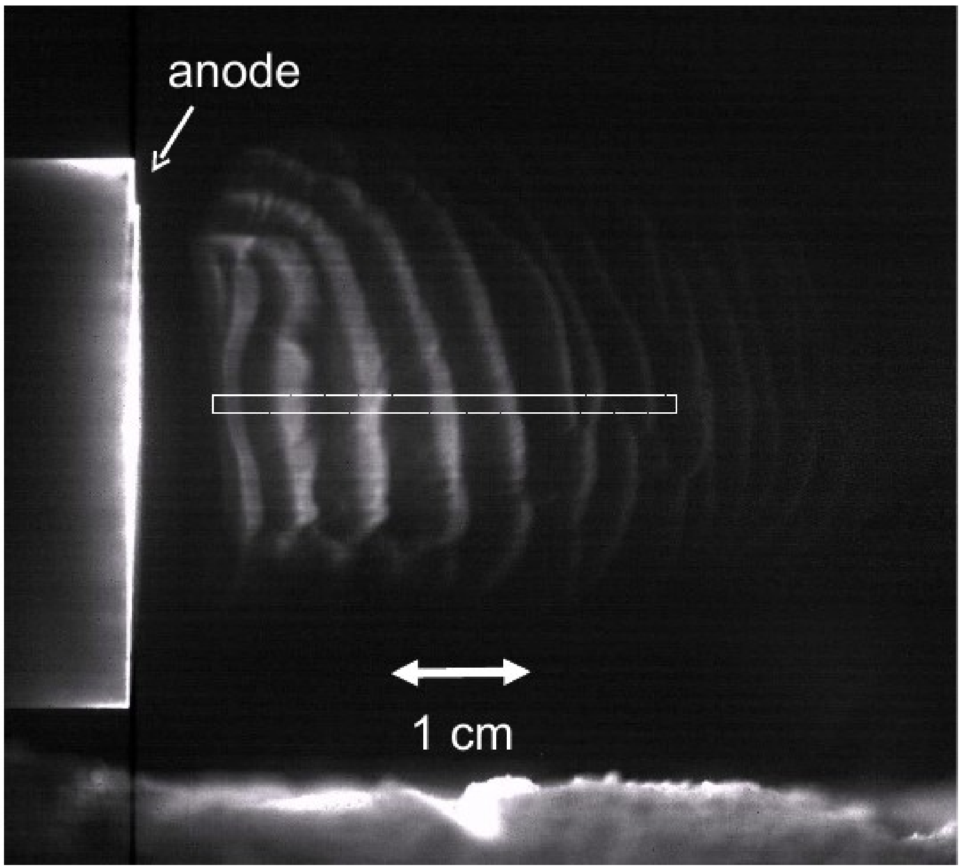
Planet. Space Sci., Vol. 44, No. 3, pp. 239–242, 1996

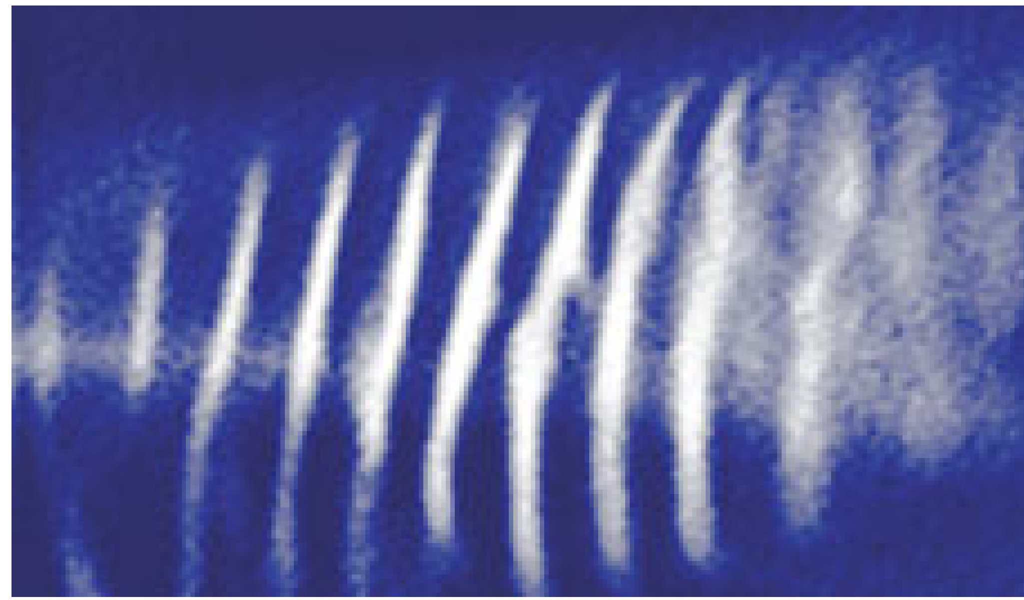
Experiments on ion-acoustic waves in dusty plasmas

A. Barkan, N. D'Angelo and R. L. Merlino

Two milestones in dusty plasma

Dust acoustic waves





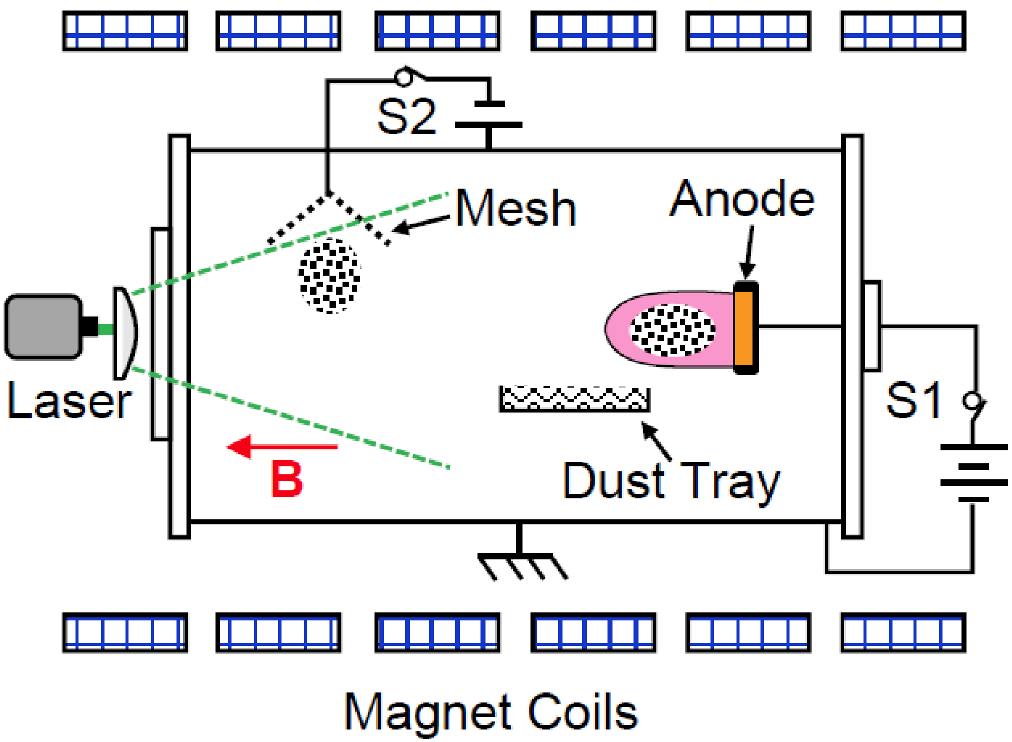
Movies 1 & 2 & 3

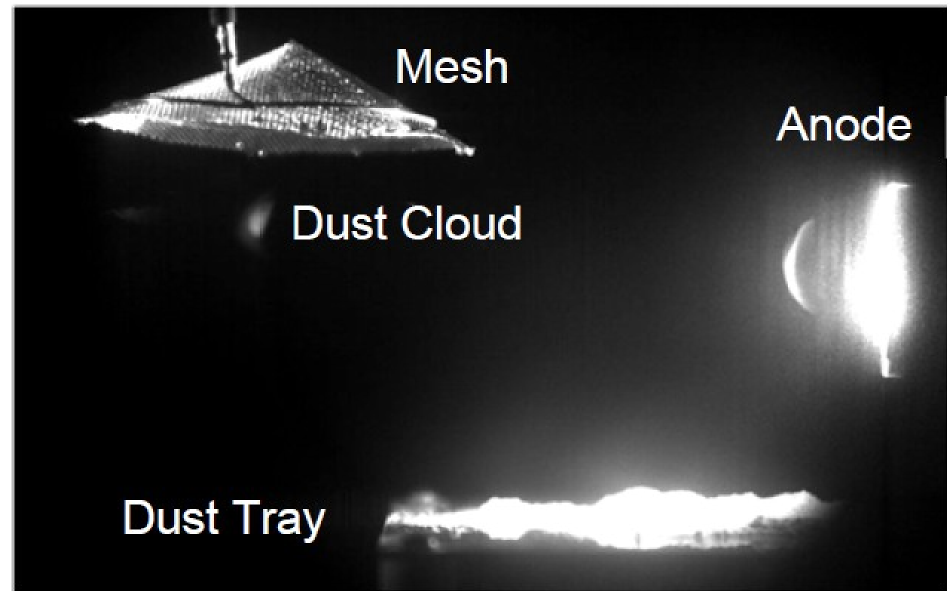
Two milestones in dusty plasma

Dust acoustic waves

Theory	Observation
$v_{ph} = Z_d \left(\frac{T_i n_d}{m_d n_i} \right)^{1/2} = 8$ cm/s ($\lambda = 0.5$ cm, $f = 15$ Hz)	$v_{ph} = 9$ cm/s ($\lambda = 0.6$ cm, $f = 15$ Hz)

Two milestones in dusty plasma





- DC glow discharge in argon at p ~ 0.1 – 0.2 Torr
- 1 micron diameter spherical silica particles
- Conical mesh used to trap a secondary dust cloud

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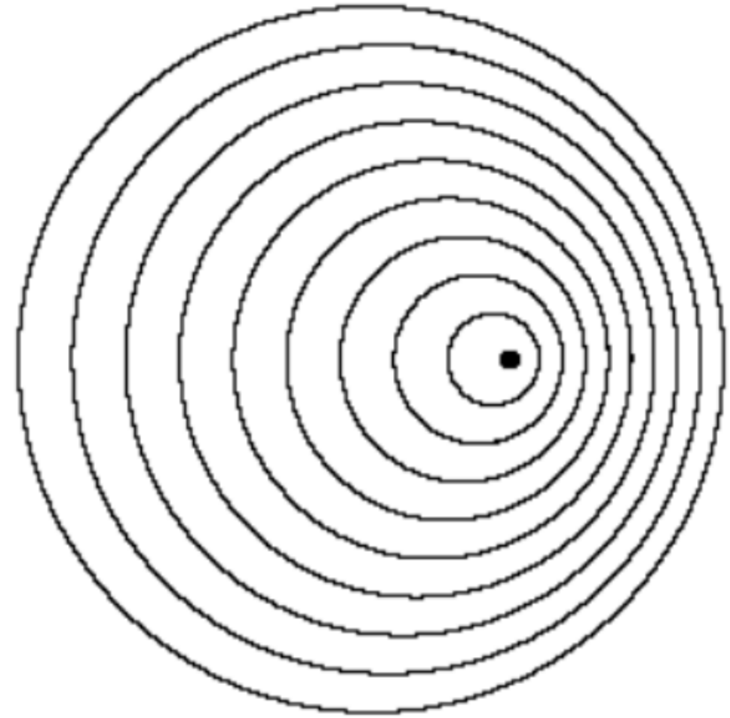
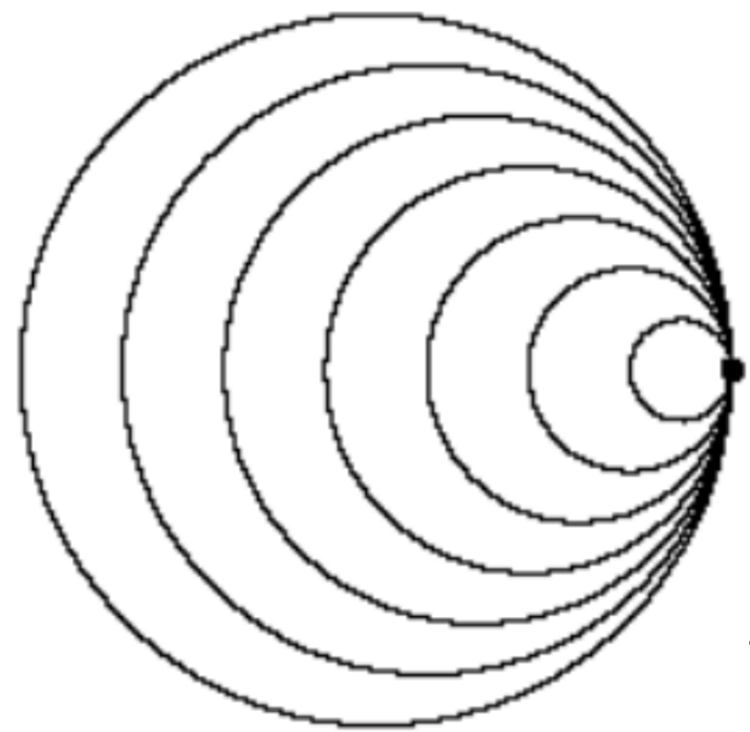
- Wakefield

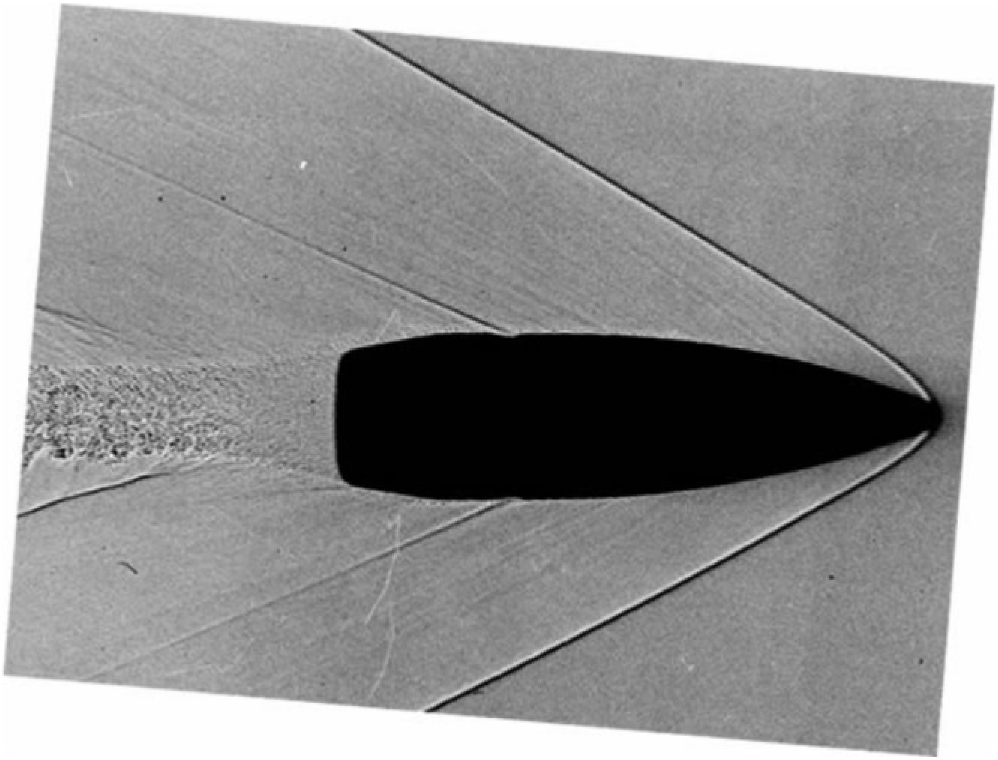
Mach Cones

- When an object moves through the air it pushes the air in front of it away, creating a pressure wave.
- This pressure wave travels away from the object at the speed of sound.
- If the object itself is travelling at the speed of sound then these pressure waves build up on top of each other to create a shock wave





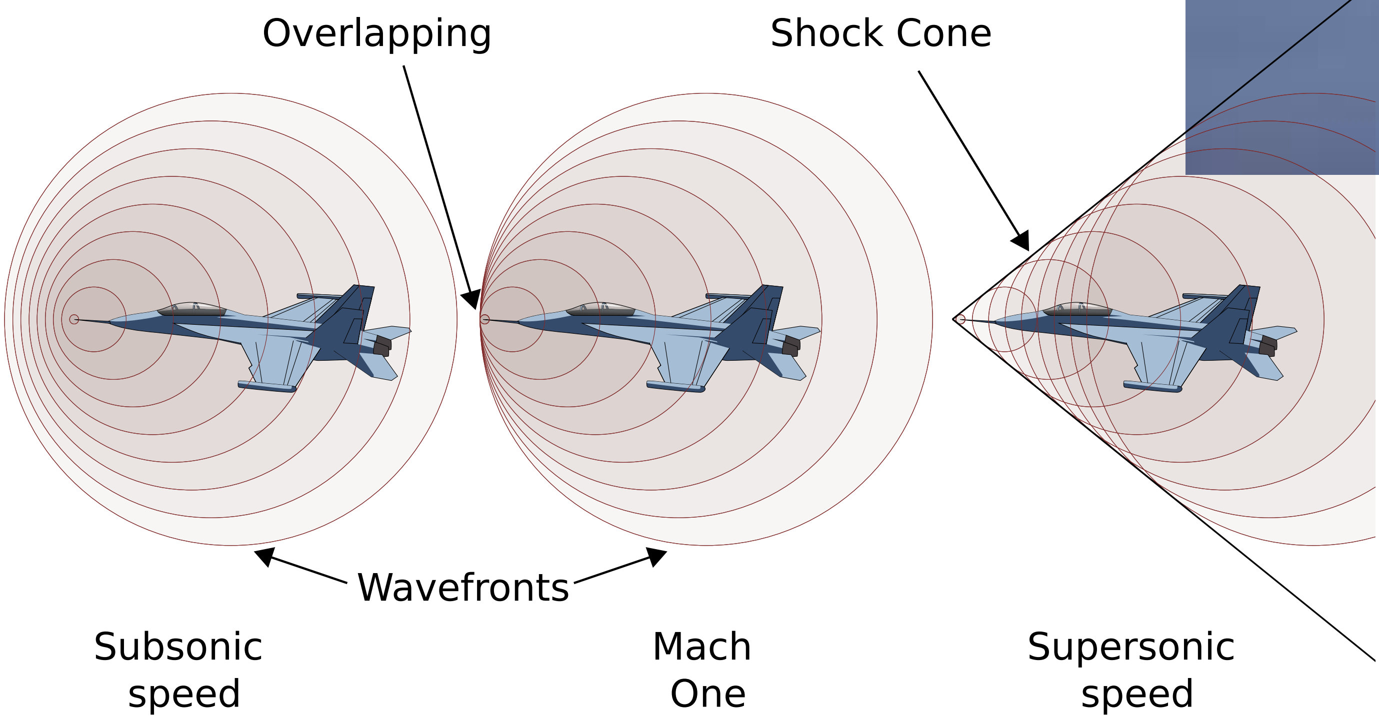
Mach Cones, cont.



In the photograph above the Mach cone angle is 28° and therefore the bullet must have been travelling at Mach 2.1 or 720 metres per second (assuming the speed of sound is 340 m/s).

Mach Cones, cont.

Movie 1



Mach Cones, cont.

- Havnes et al (1995, 1996) theoretically predicted the existence of super DA Mach cones in dusty plasmas that are relevant to planetary rings and interstellar space.

Mach Cones, cont.

VOLUME 83, NUMBER 18 PHYSICAL REVIEW LETTERS 1 NOVEMBER 1999

Mach Cones in a Coulomb Lattice and a Dusty Plasma

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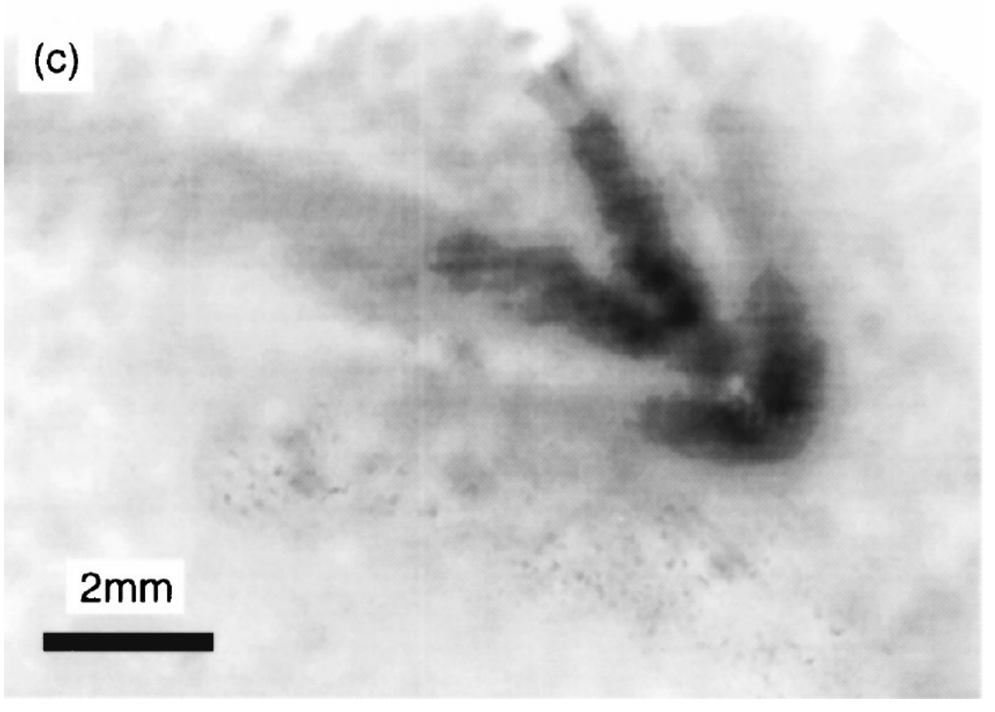
Department of Physics and Astronomy, The University of Iowa, Iowa City, Iowa 52242

H. M. Thomas and G. E. Morfill
Max Planck Institut für extraterrestrische Physik, 85740 Garching, Germany



Mach Cones, cont.

PHYSICAL REVIEW E VOLUME 61, NUMBER 5 MAY 2000

Mach cone shocks in a two-dimensional Yukawa solid using a complex plasma

D. Samsonov* and J. Goree[†]
Department of Physics and Astronomy, The University of Iowa, Iowa City, Iowa 52242

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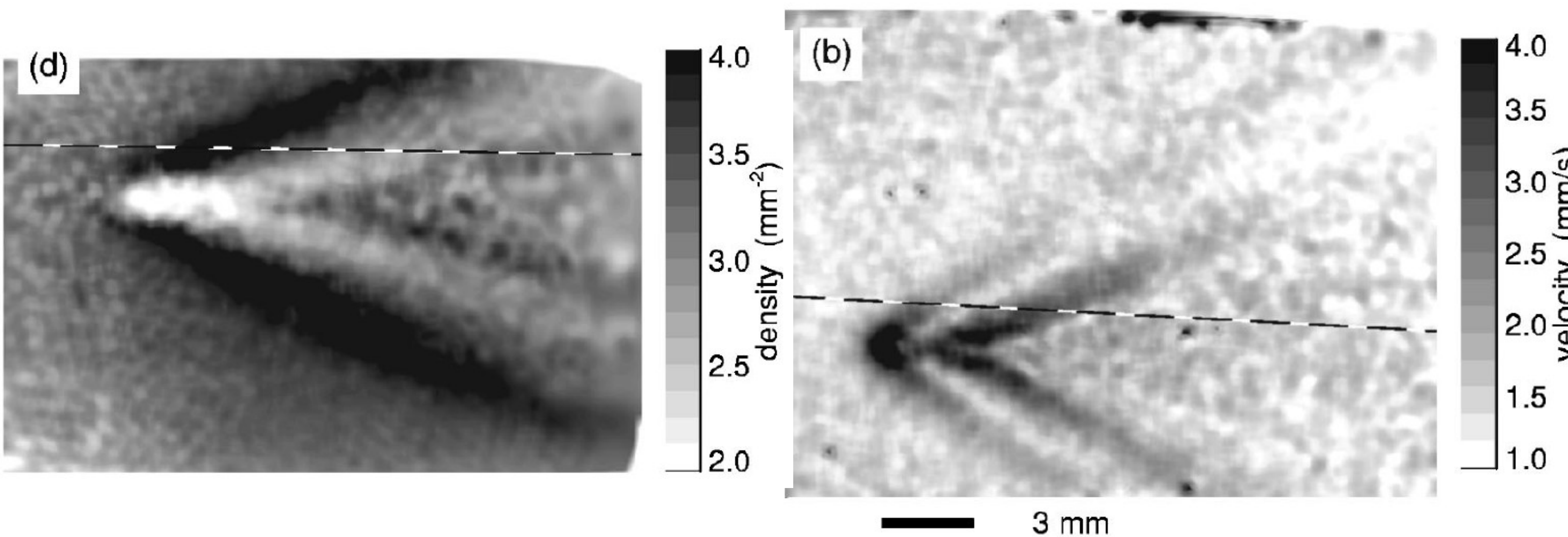
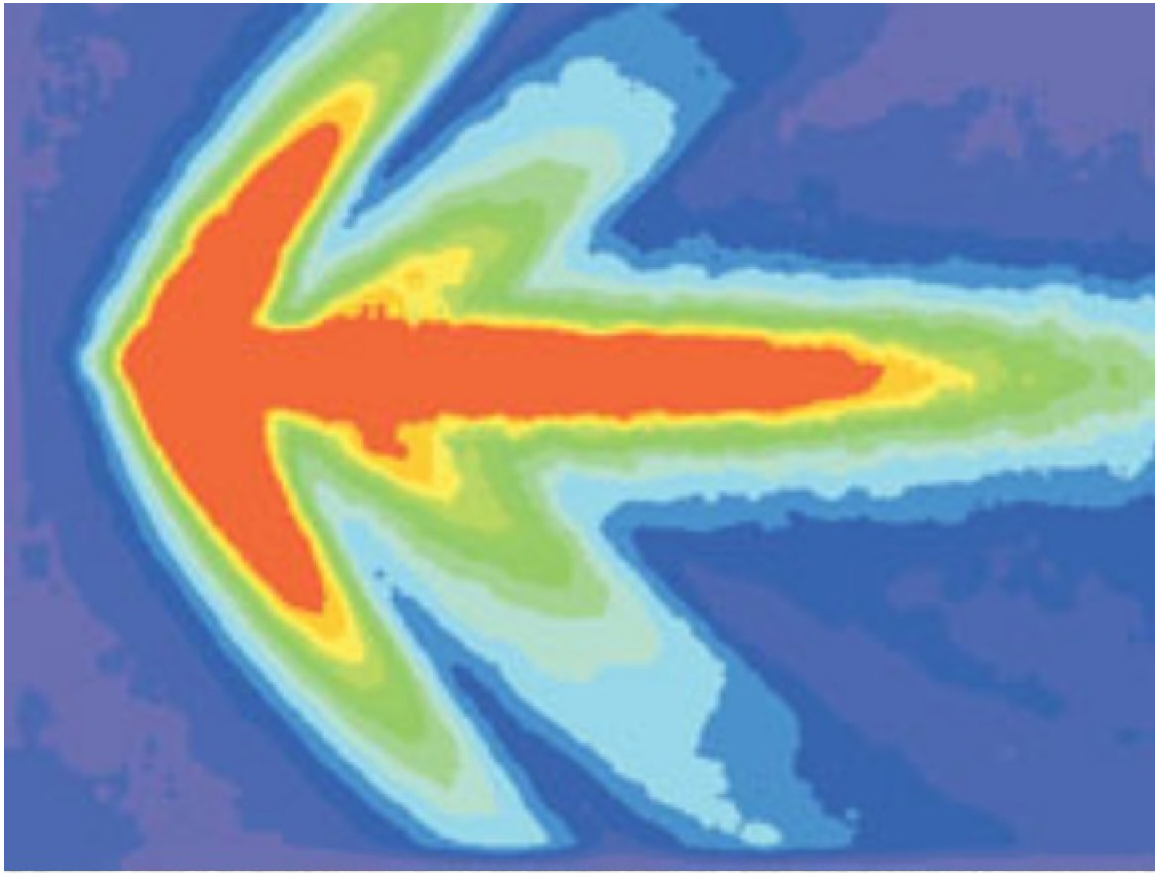
Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstrasse, 85740 Garching, Germany



Mach Cones, cont.

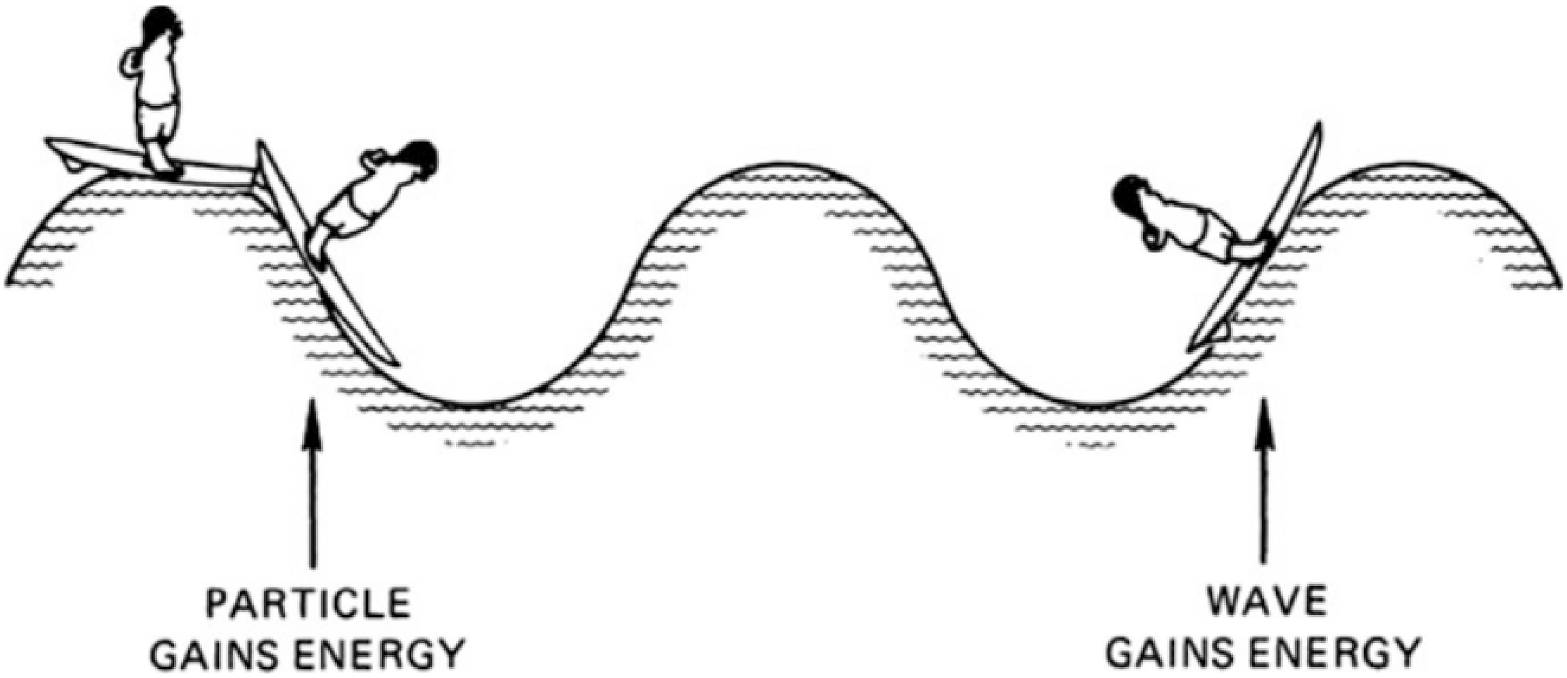
- Mach cones in dusty crystal
- Movie 1



Outline

Wakefield

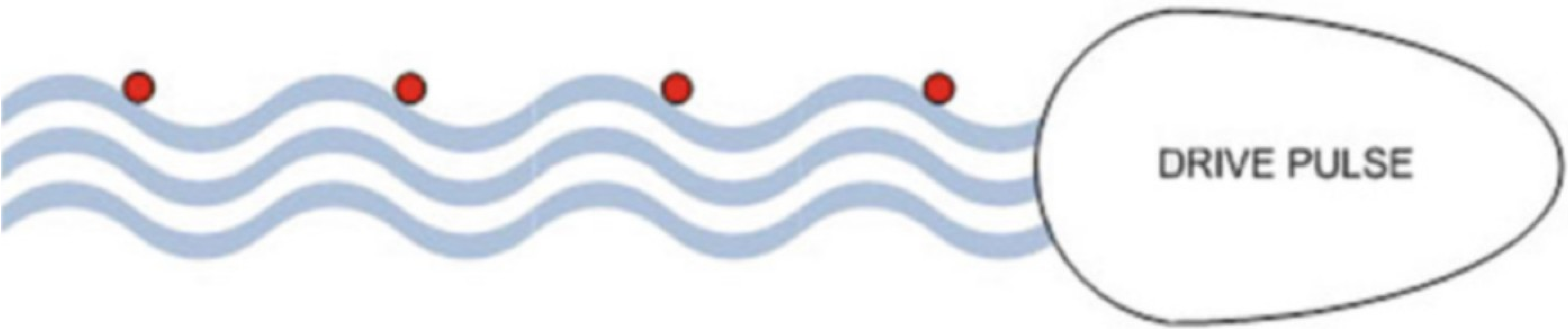
- In 1979 John Dawson, in a paper with T. Tajima, proposed that Landau damping effect could be used to accelerate particles
- In plasma, there are electrons both faster and slower than the wave.



Wakefield, cont.

Wakefield, cont.

- There were two early ideas on plasma accelerators: *beatwave* and *wakefield*.

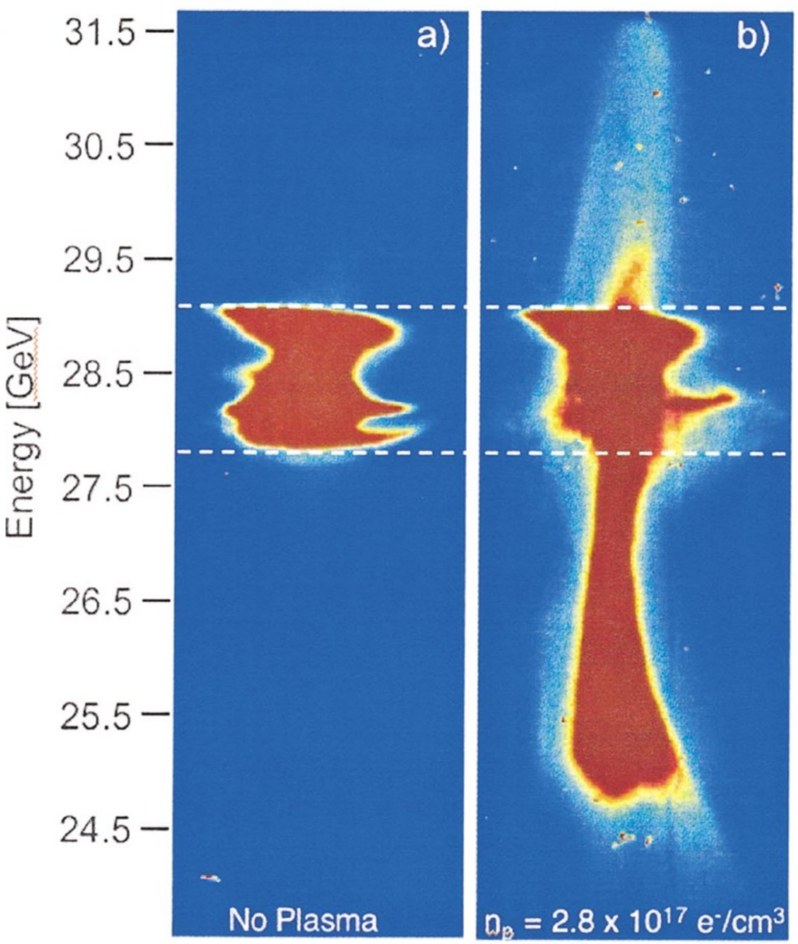


Wakefield, cont.

PRL **95,** 054802 (2005) PHYSICAL REVIEW LETTERS week ending 29 JULY 2005

Multi-GeV Energy Gain in a Plasma-Wakefield Accelerator

J. Decker,[1] S. Deng,[3] P. Emma,[1] C. Huang,[2] R. H. Iverson,[1] D. K. Johnson,[2]
Lu,[2] K. A. Marsh,[2] W. B. Mori,[2] P. Muggli,[3] C. L. O'Connell,[1] E. Oz,[3]
R. H. Siemann,[1] and D. Walz[1]



a) No Plasma → Only electron beam with 1 GeV energy.

b) 10 cm long lithium plasma → the core of the electron bunch has lost energy driving the plasma wake while particles in the back of the bunch have been accelerated to 2.7 GeV

Wakefield, cont.

Wakefield, cont.

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Attractive potential between resonant electrons

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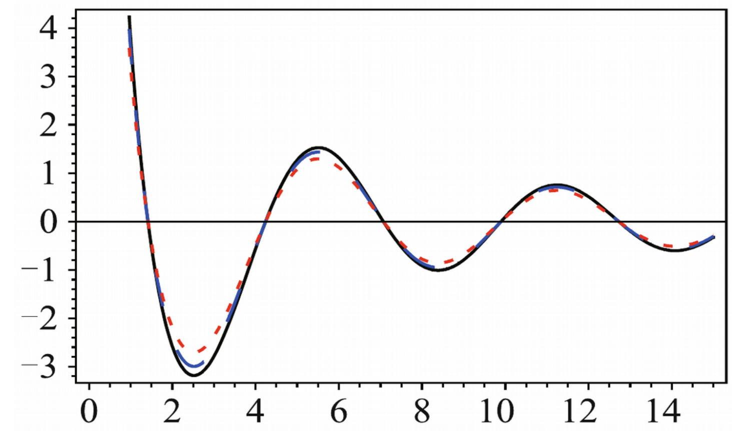
Physics Letters A 203 (1995) 40–42

Attractive forces between charged particulates in plasmas

Mitsuhiro Nambu, Sergey V. Vladimirov [1], Padma K. Shukla [2]

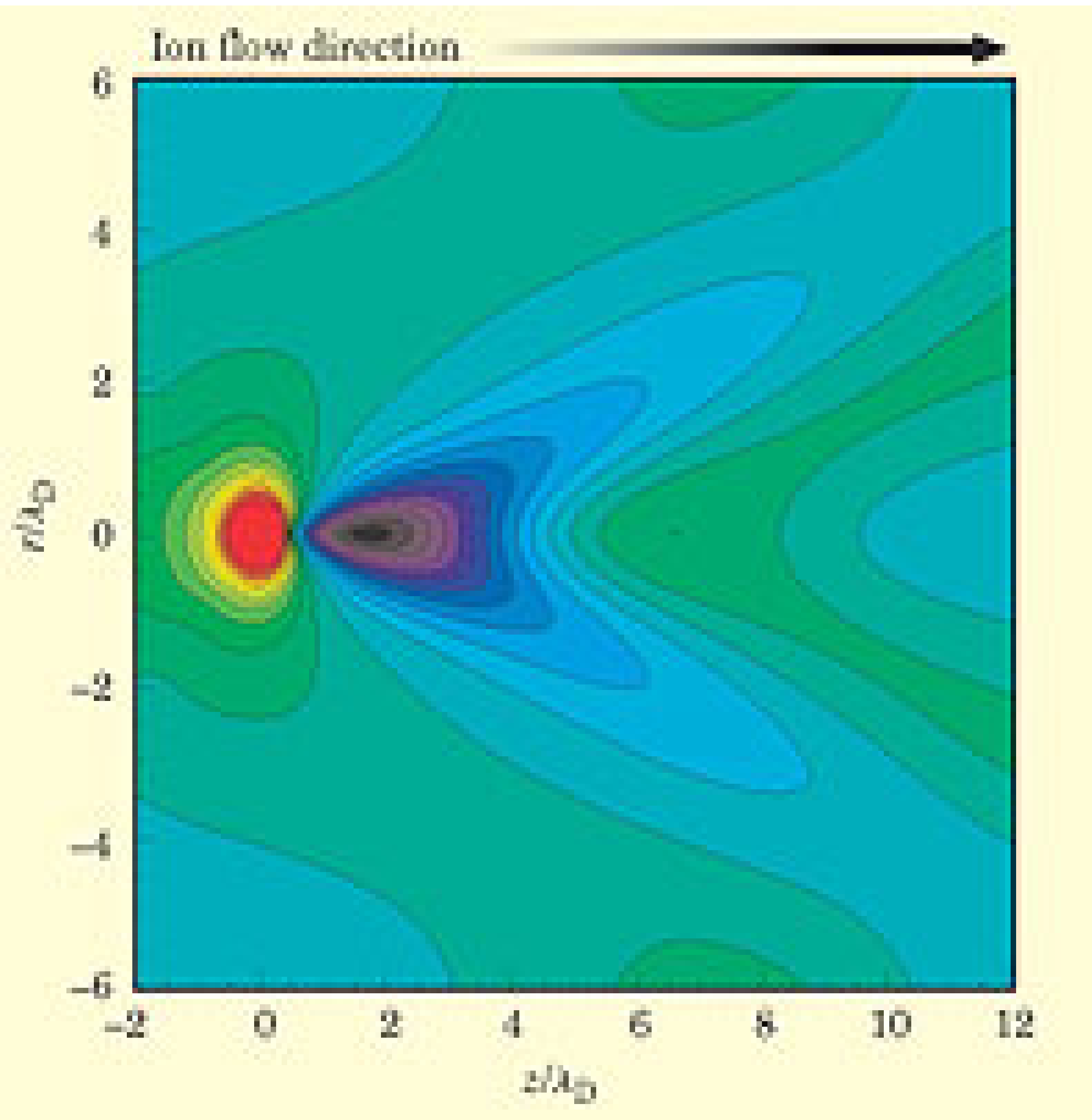
The charged particles having the same polarity can attract each other...!!

Wakefield, cont.

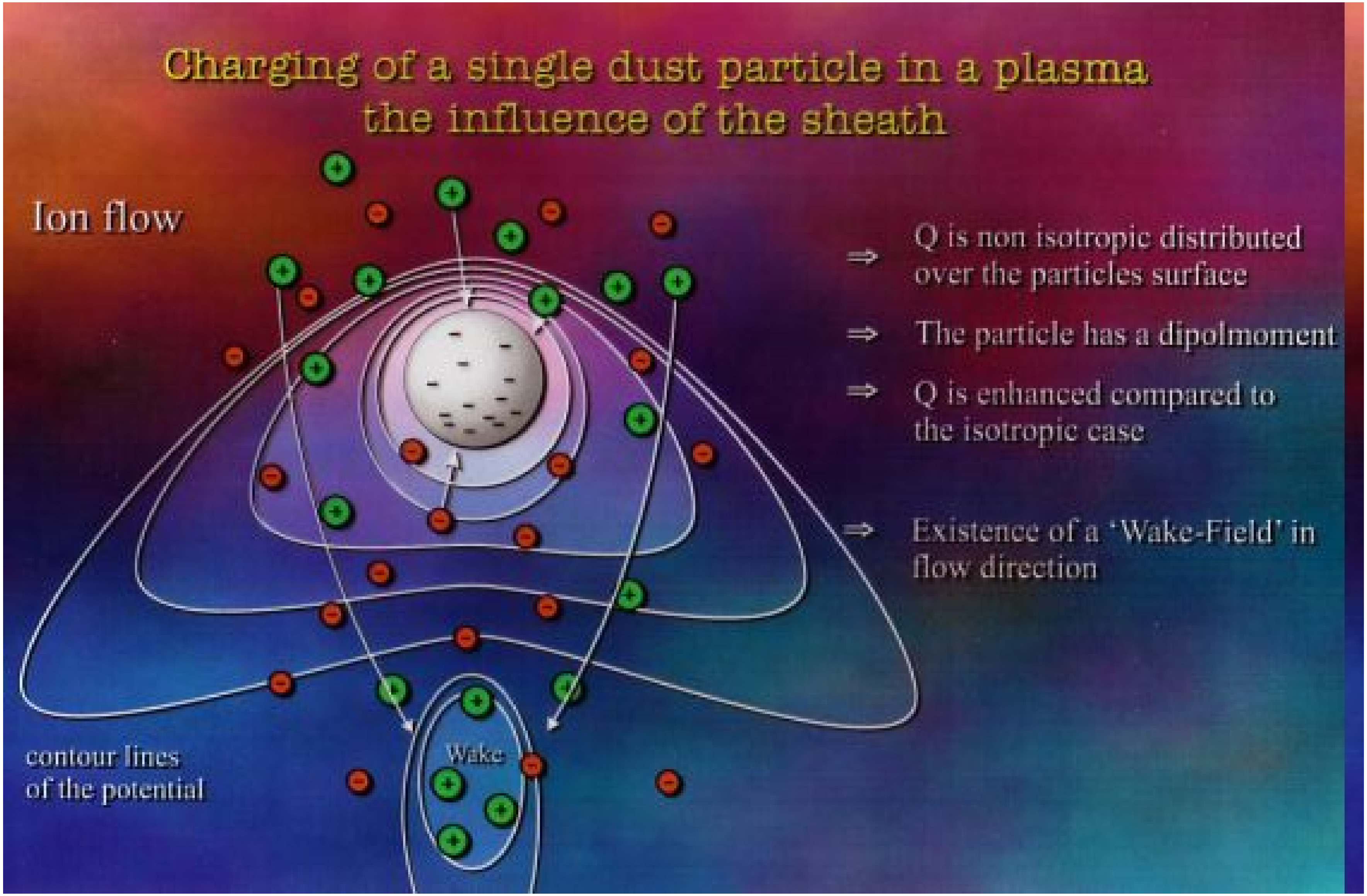


- **Vph ~ Cs**
- Appearing long-range **oscillatory wakefield**
- The background **positive ions are trapped/focused** in the negative part of the oscillatory wake potential.
- The **negative charges are attracted** to each other as they are **glued by positive ions** in a linear chain
- Dust crystals

Wakefield, cont.



Wakefield, cont.



سؤال هام

طائر يبلغ طوله سبعة عشر سنتيمترا ,ويتميز بشكله المستدير, وجناحيه الطويلين مما يجعله قادرا علي الطيران لمسافات طويلة وهو مكون من لونين الأبيض ,والبني.......

طائر يبلغ طوله سبعة عشر سنتيمترا ,ويتميز بشكله المستدير, وجناحيه الطويلين مما يجعله قادرا علي الطيران لمسافات طويلة وهو مكون من لونين الأبيض ,والبني...... نامسلا

Finally ....!!!!!!