The BRITISH UNIVERSITY IN EGYPT

The Abdus Salam International Centre for Theoretical Physics

EGY Plasma

Dusty Plasma

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Port Said University

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Aim of the Lect.

- **Why Dusty Plasma Is an Unusual State of Matter?**
- **Why Dusty Plasmas Have Many Applications?**
- **Dusty Plasma Terminology**

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 (Dense) plasma**

  Electrons / positrons / holes / +ve ions

Occurance of dusty plasma

Natural

- Solar nebula
- Planetary rings
- Interstellar medium
- Comet tails
- Noctilucent clouds
- Lightning

Man-made

- Microelectronic processing
- Rocket exhaust
- Fusion devices

Occurance of dusty plasma

Rosette Nebula

Eagle Nebula

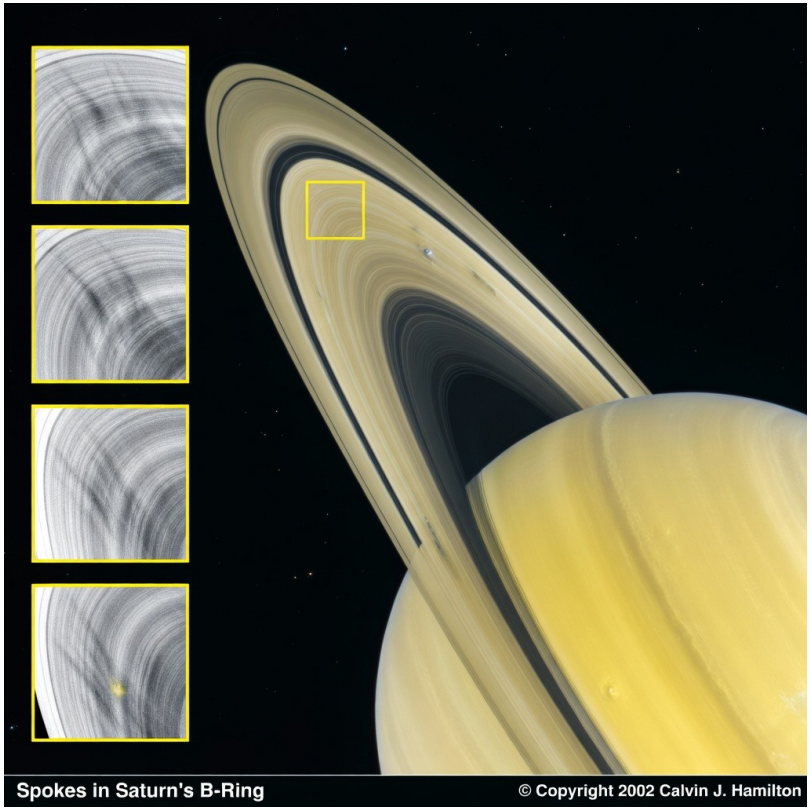
Our solar system accumulated out of a dense cloud of gas and dust, forming everything that is now part of our world.

Occurance of dusty plasma

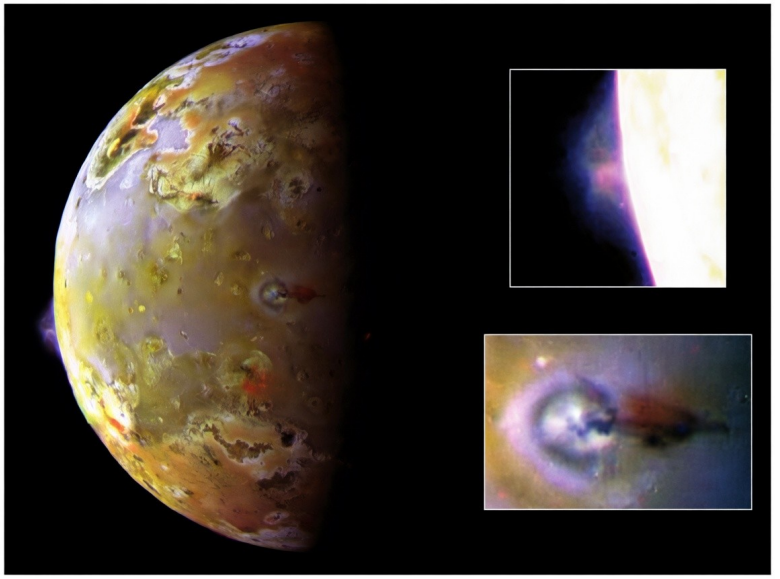
Hyakutake

Hale-Bopp

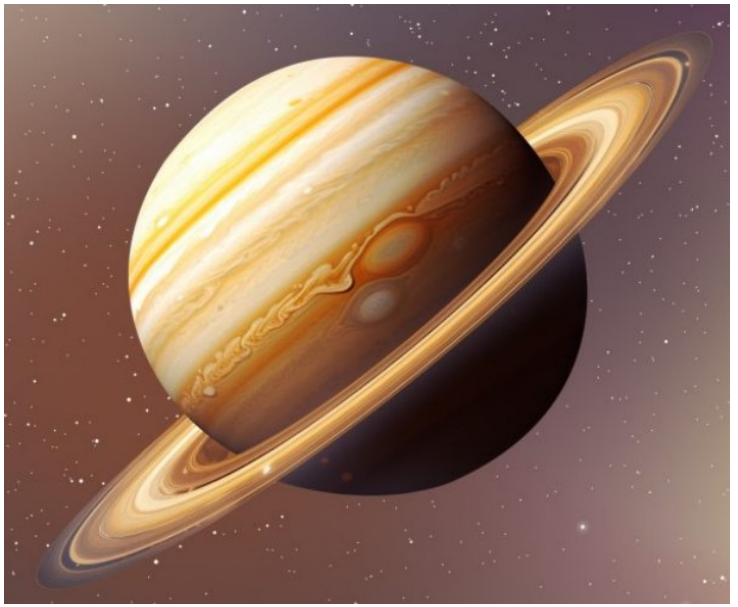
Occurance of dusty plasma



Saturn

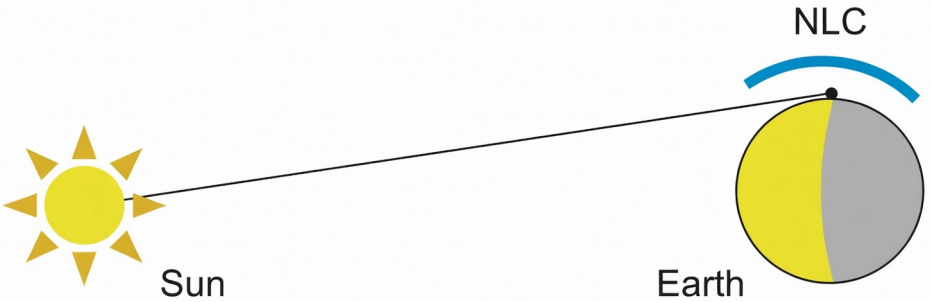


Io moon



Jupiter

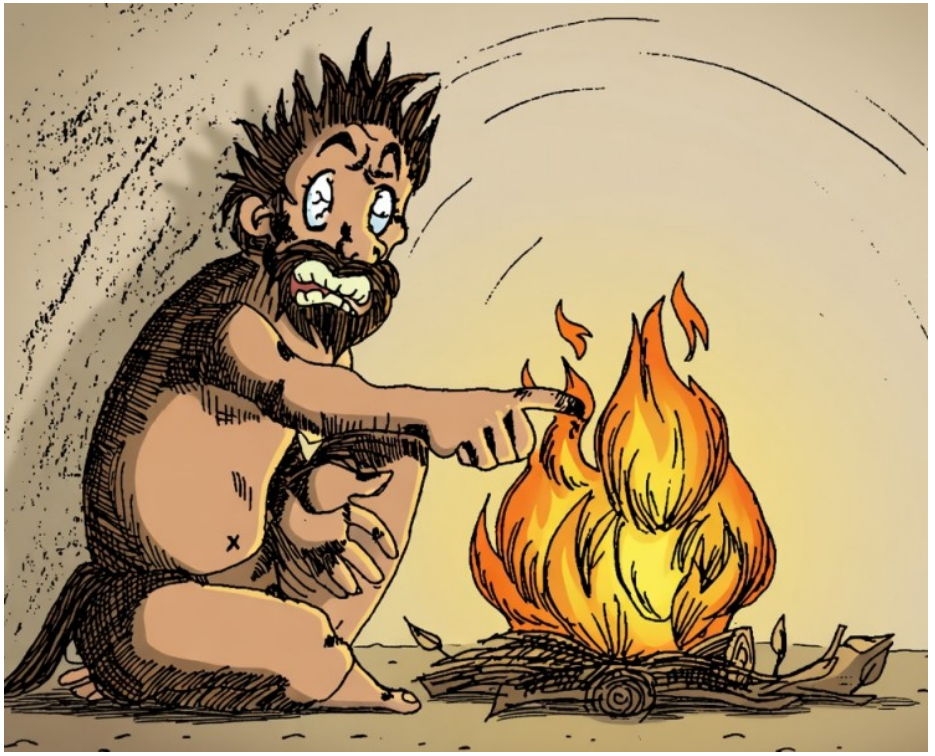
Occurance of dusty plasma



- Noctilucent clouds (NLCs) are the highest clouds in Earth's atmosphere.
- They form at altitudes of 75–80 km.
- NLCs appear mostly during summer.
- They are made of tiny water ice particles, about 100 nanometers in size.
- These ice particles are often electrically charged.

Occurance of dusty plasma

A flame is a very weakly ionized plasma
that contains soot particles



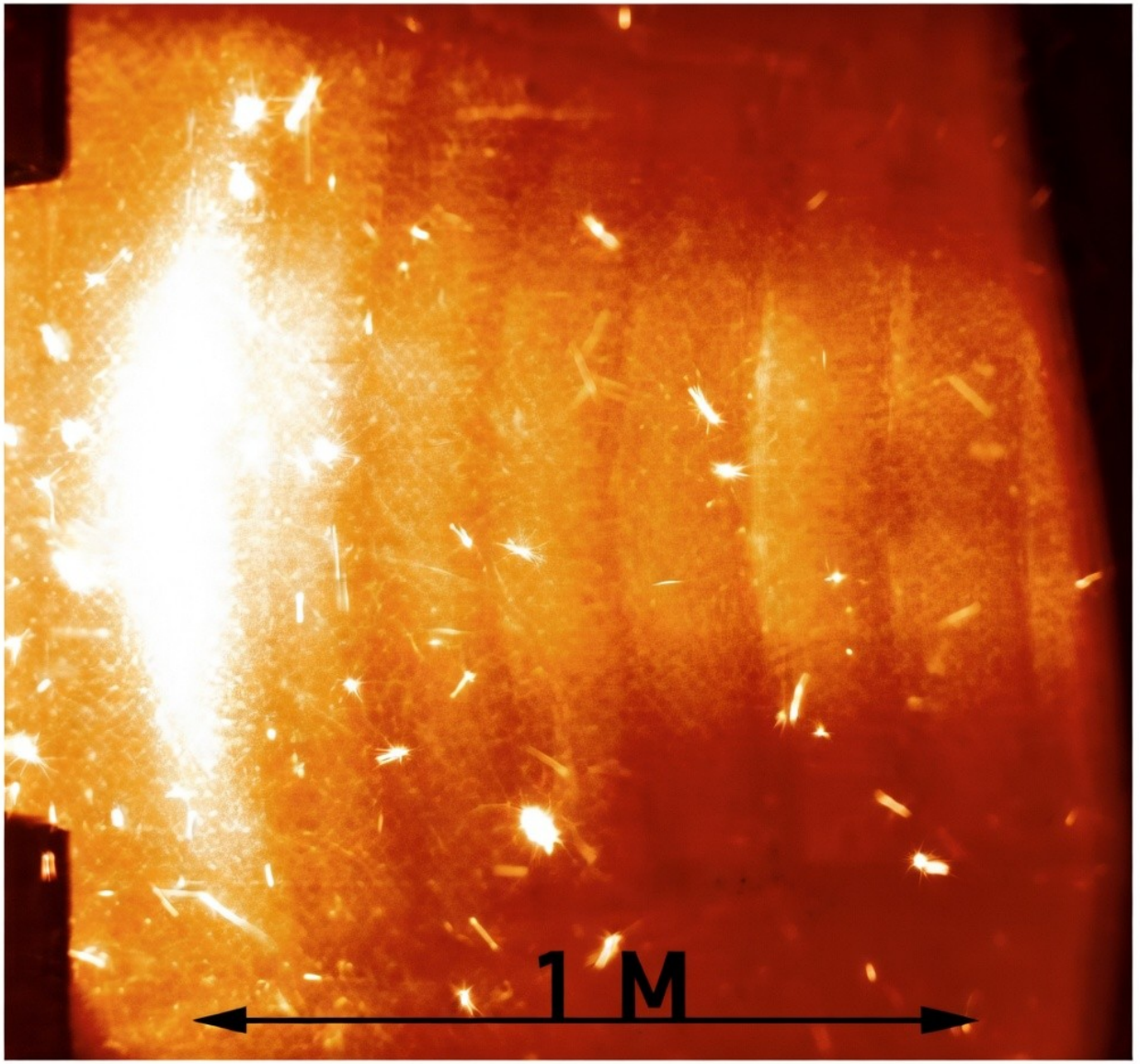
An early temperature measurement in a dusty plasma

Occurance of dusty plasma

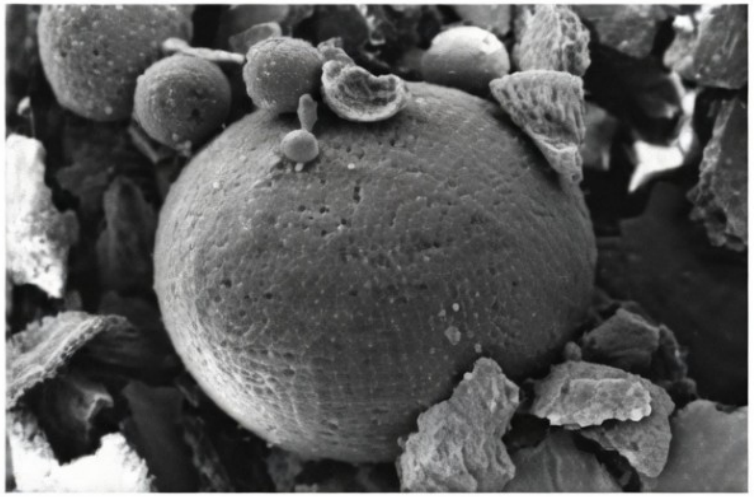
- Space Shuttle exhaust releases water vapor into the upper mesosphere.
- This water vapor freezes into tiny ice particles at high altitudes (~80 km).
- The ice particles become electrically charged, forming a dusty plasma.
- This process can enhance Noctilucent Cloud formation.
- Observations show a temporary increase in NLCs after Shuttle launches.

Occurance of dusty plasma

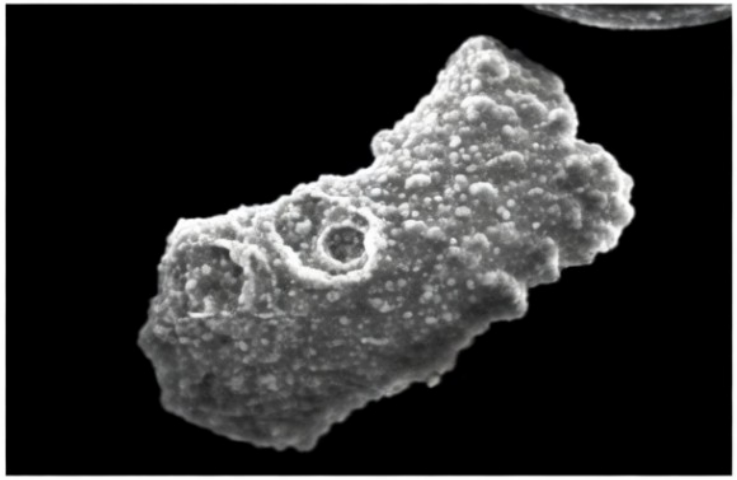
Dust in Tokamak



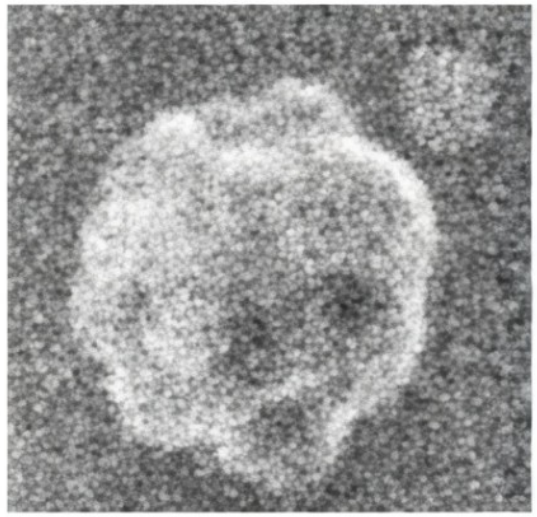
Different shapes of dust grains



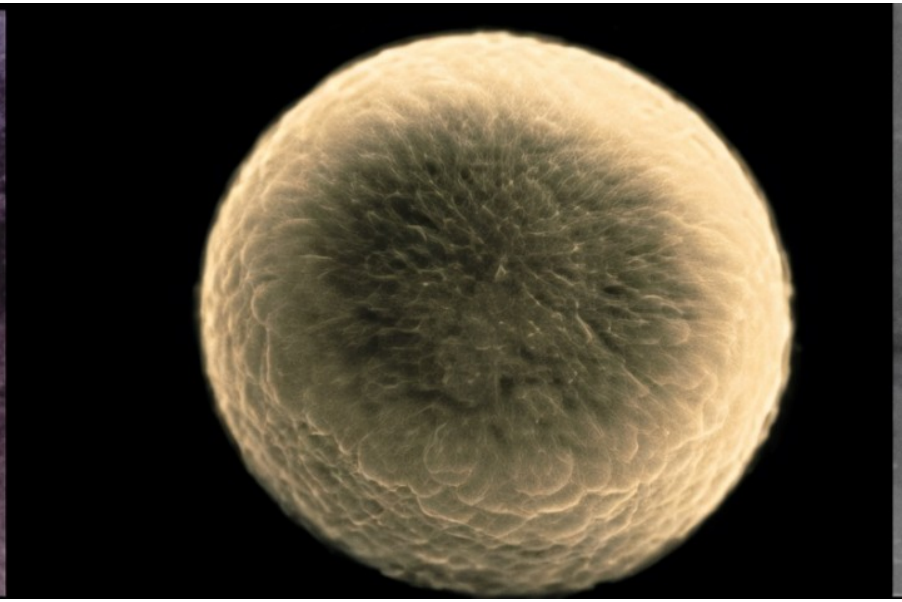
0.1 mm

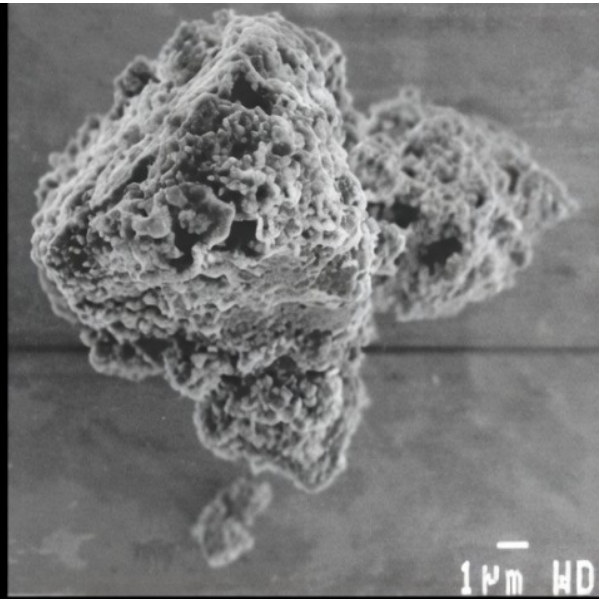


1μm



200 nm

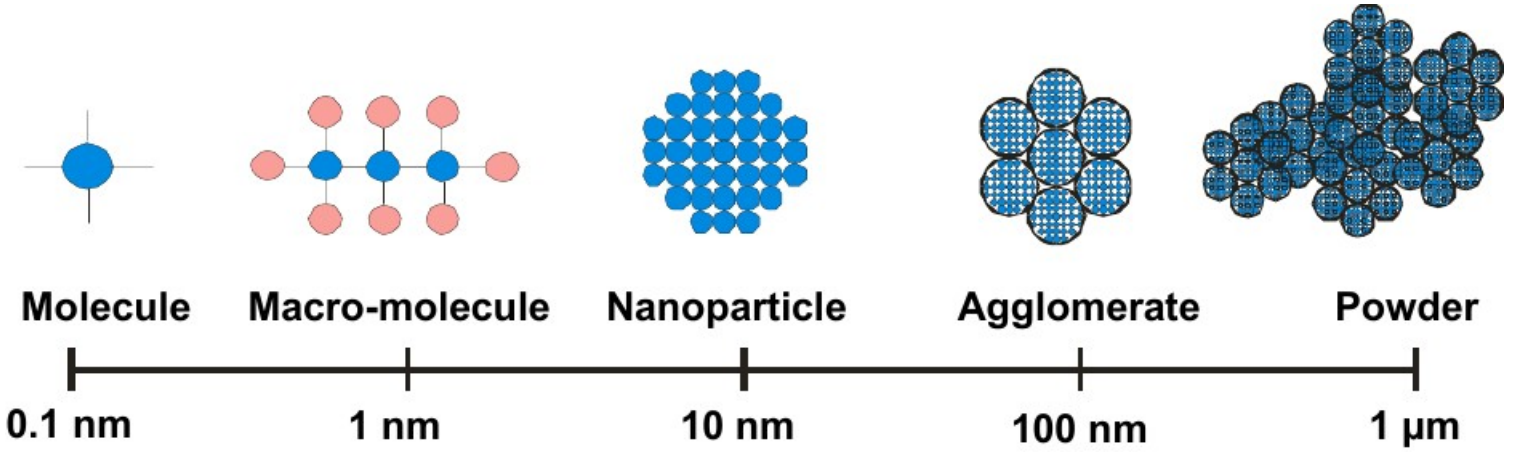




Occurance of dusty plasma

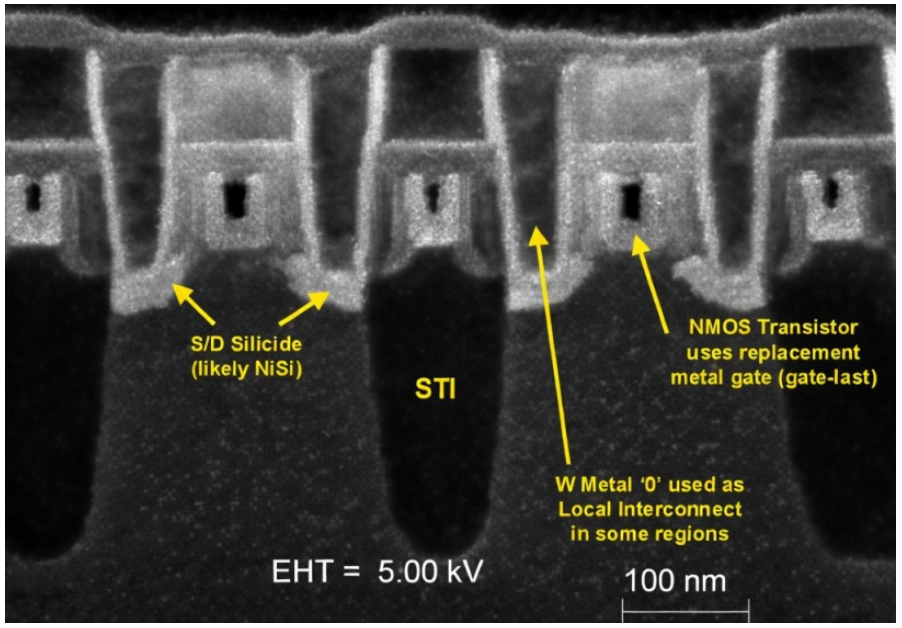
- The “dust” is a result of the strong interaction between the material walls and energetic plasma.

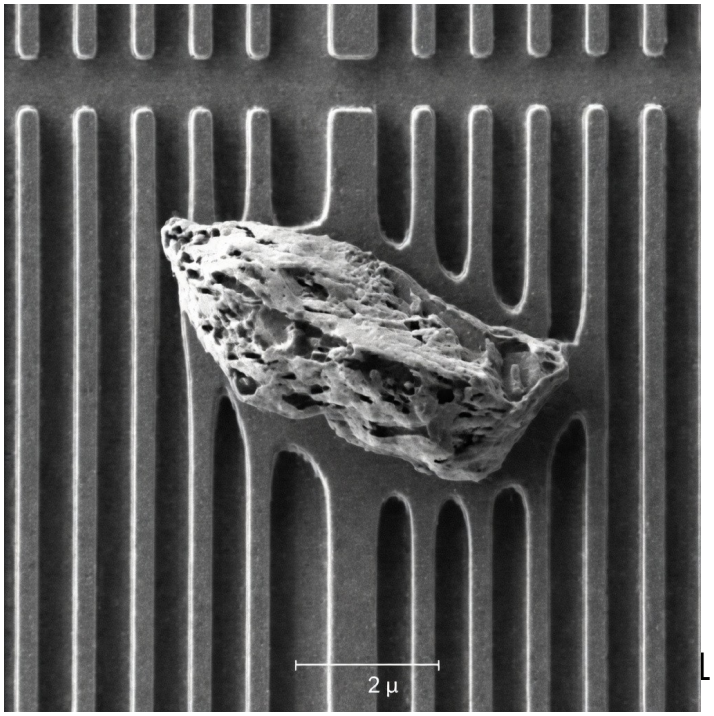
- Studies indicate that dust can be transported deep into the plasma, causing a serious contamination problem.



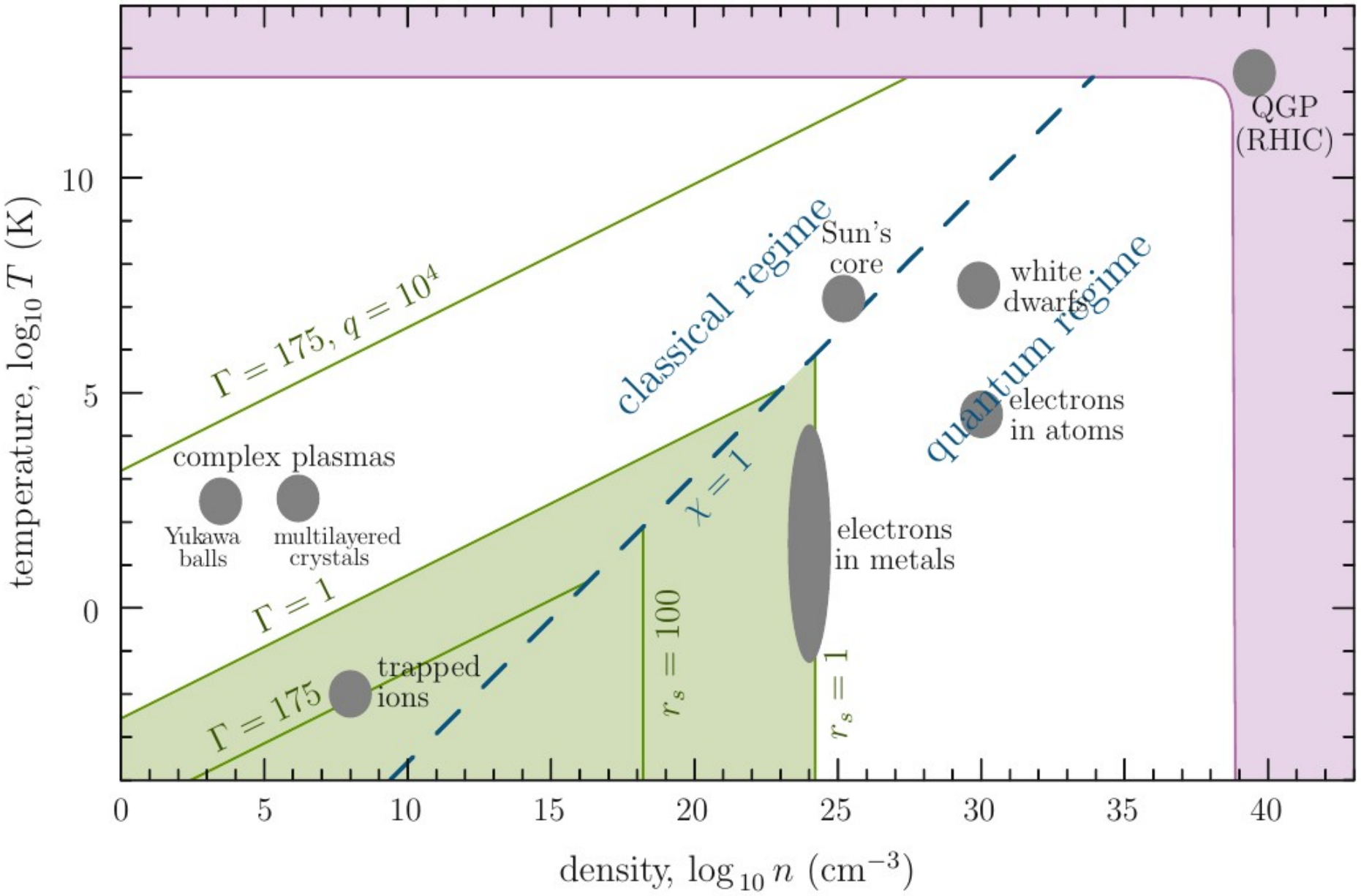
Occurance of dusty plasma

- Microelectronic processing
- Plasma chemistry and nanotechnology → coagulation of macroparticles





Occurance of dusty plasma

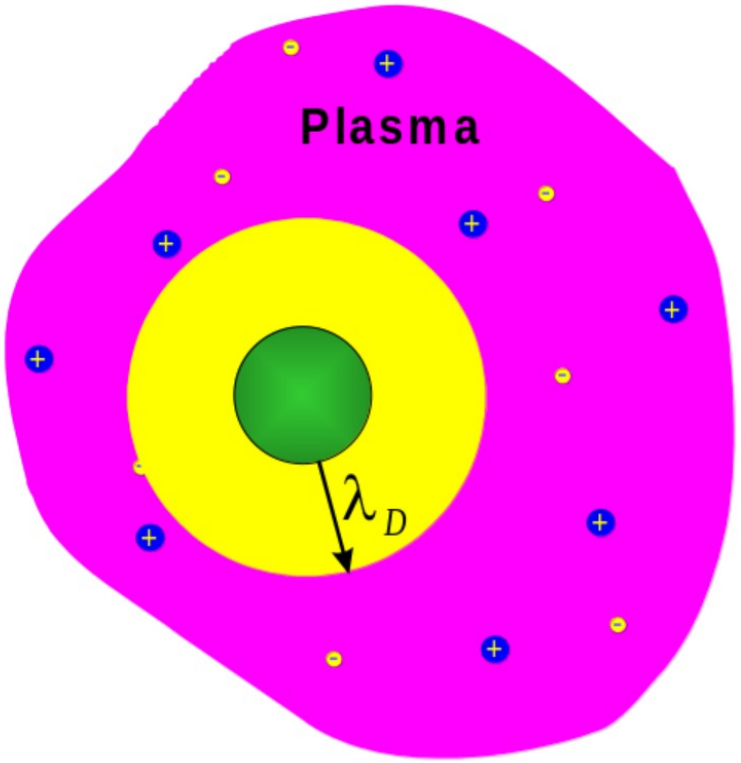


Questions

Dusty Plasma – Why It Is an Unusual State of Matter?

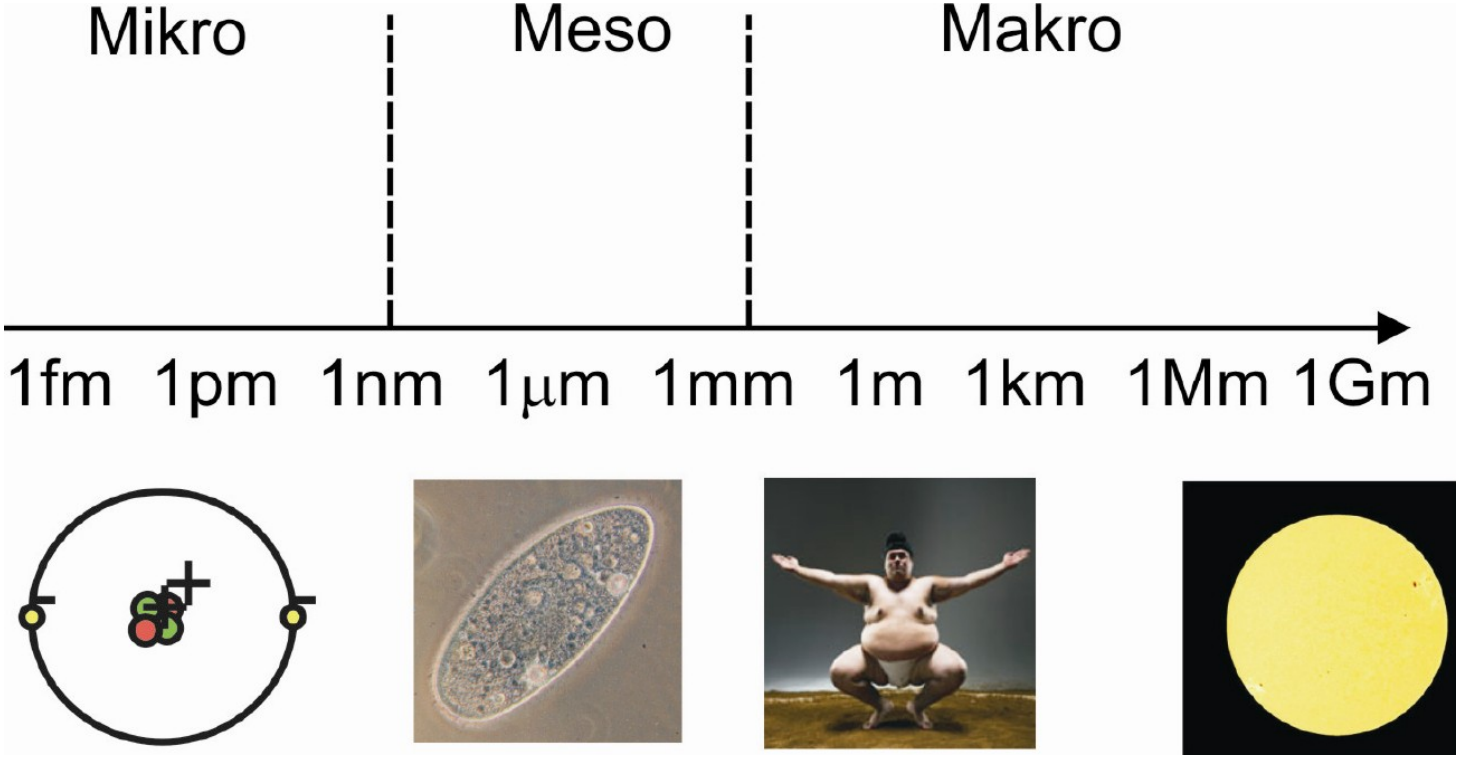
Properties of dusty plasma

- Type
- Dusty plasma is a multi-component plasma
- It contains electrons, ions, neutral atoms/molecules, and micro-particles/charged dust grains



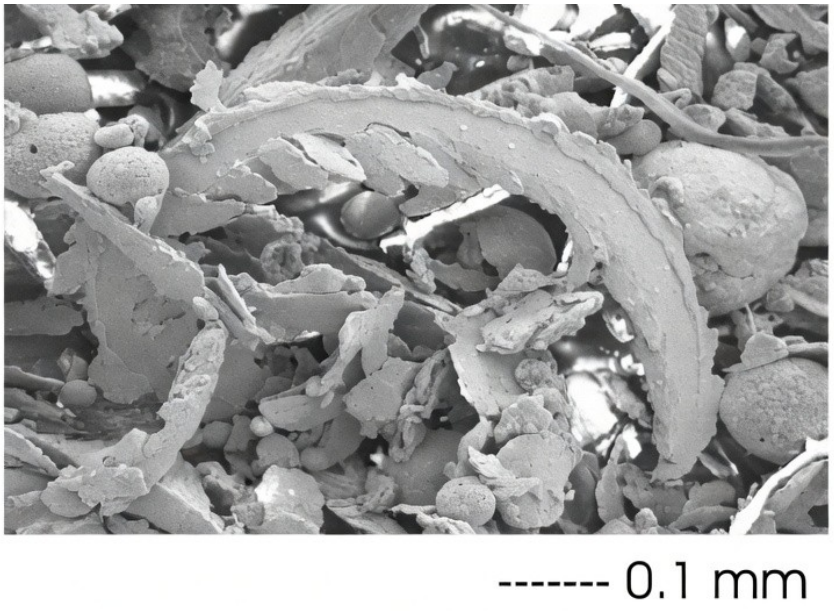
Properties of dusty plasma

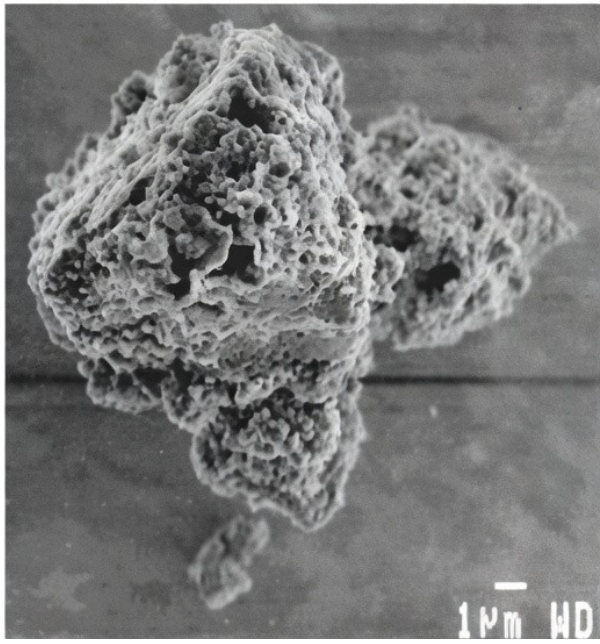
- Range size



Properties of dusty plasma

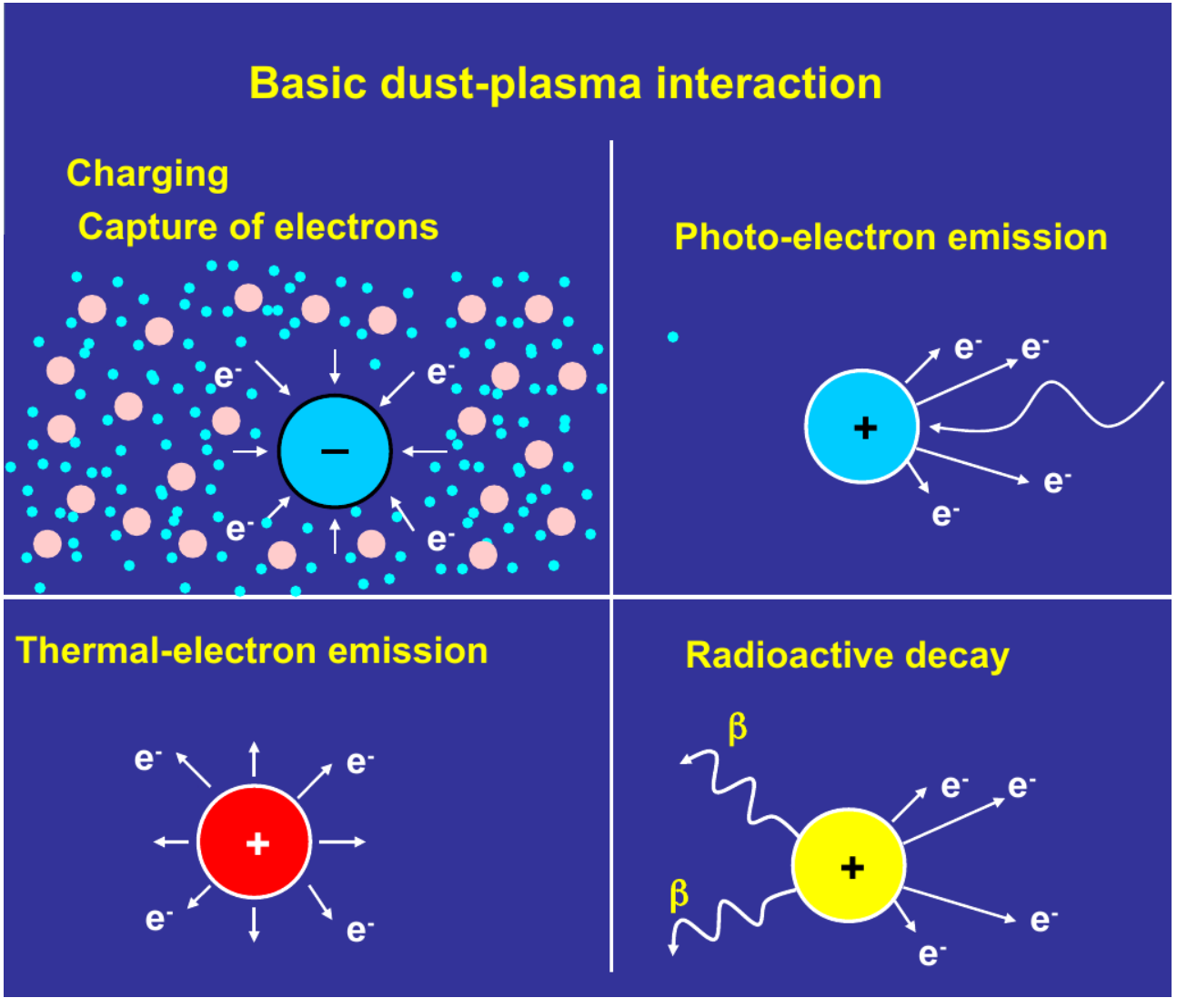
- Dust size distributions





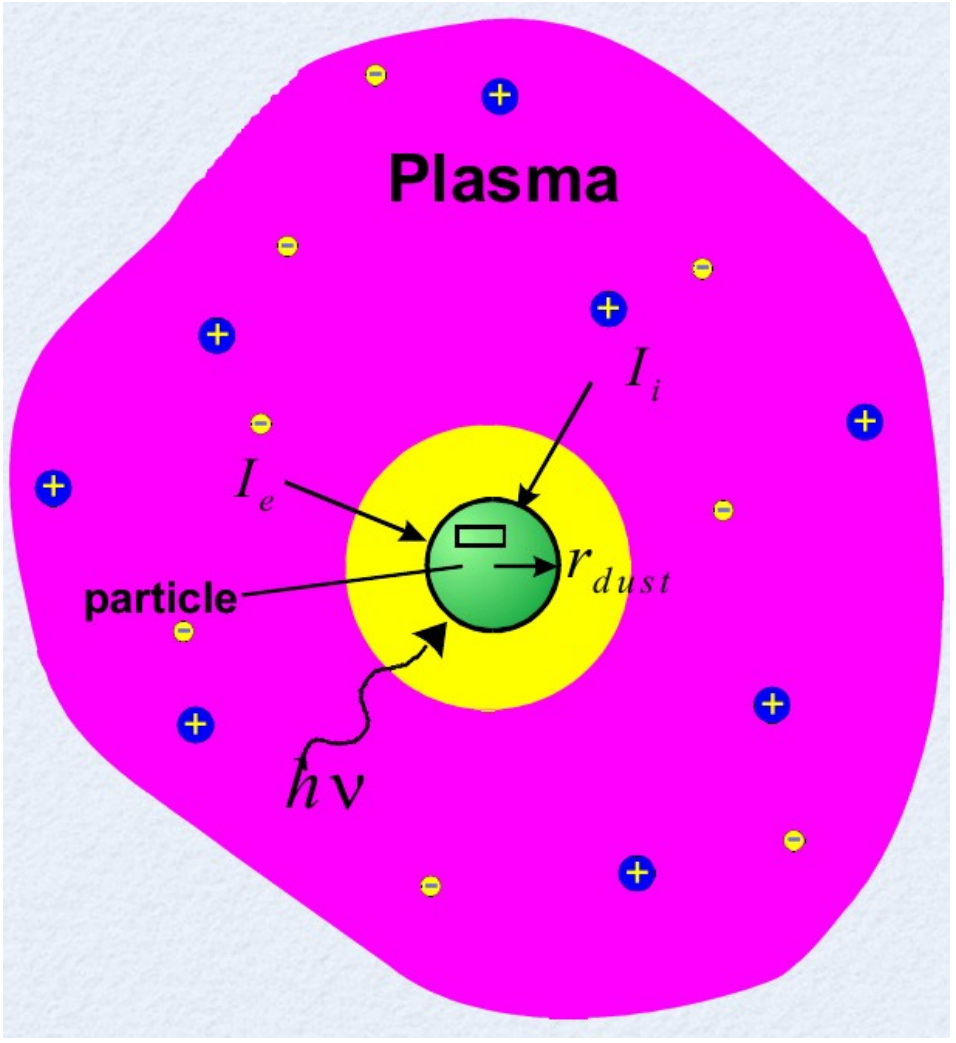
Properties of dusty plasma

- Dynamic dust charging



Properties of dusty plasma

- Dynamic dust charging



Dusty plasma terminology

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

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

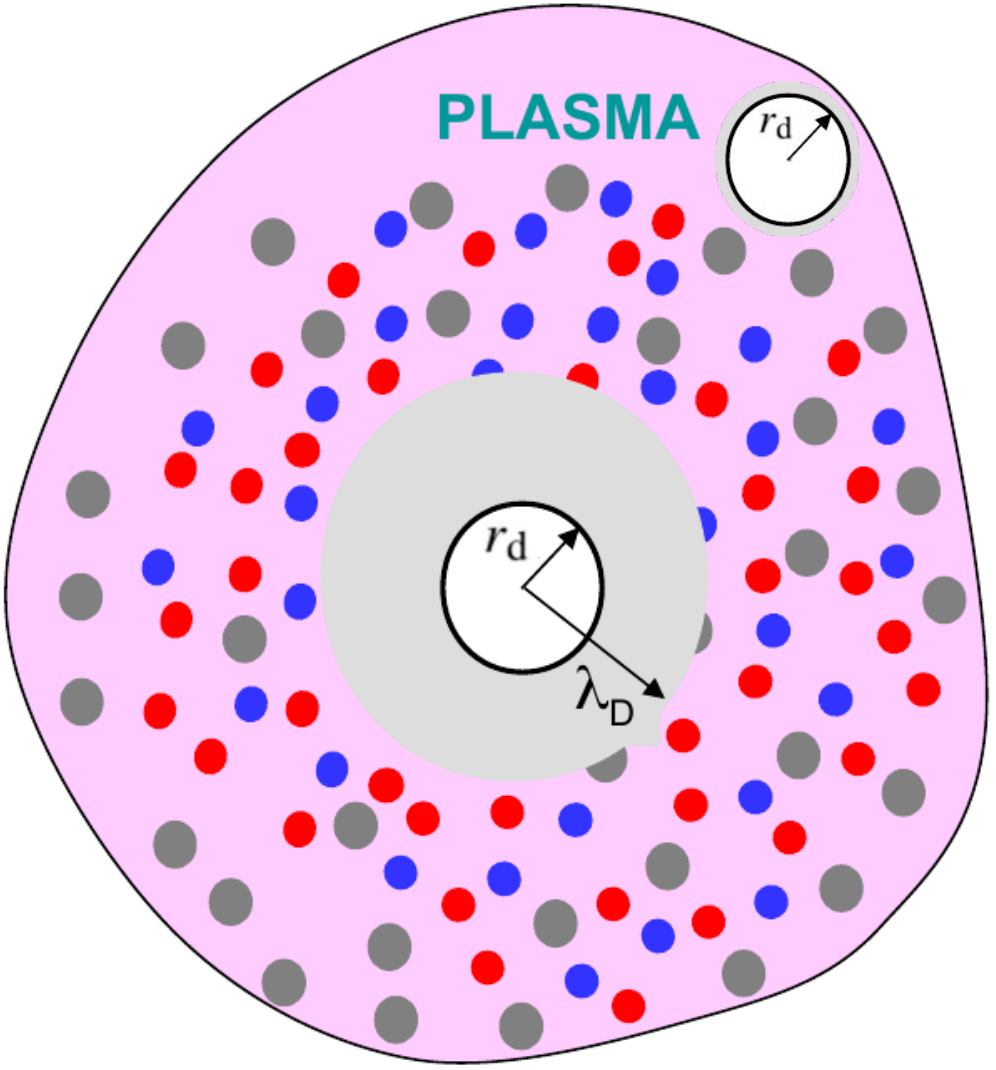
- −ve dust → what happen?
- +ve dust → what happen?

- Dusty plasma frequency

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

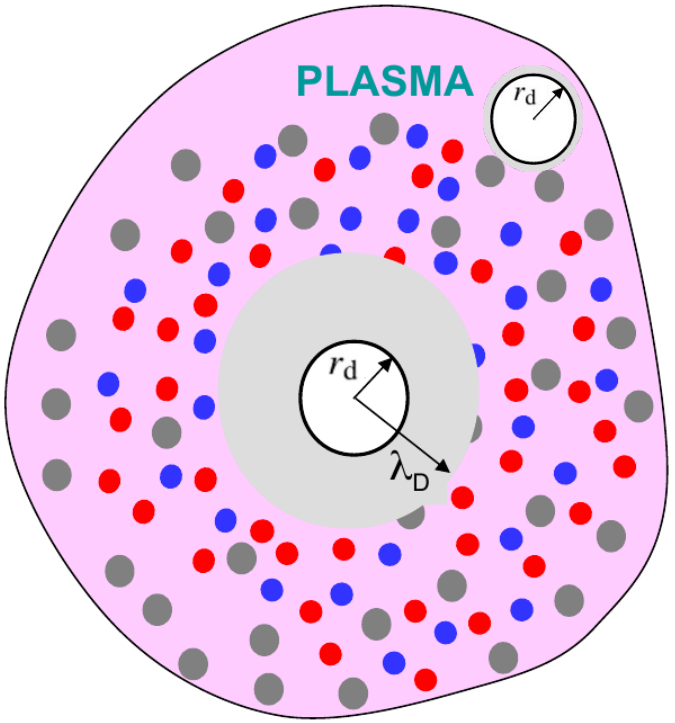
Dusty plasma terminology

Dust radius & Intergrain distance & Debye length (shielding)



Dusty plasma terminology

- **Intergrain distance > Debye length**
- **Intergrain distance < Debye length**



Dusty plasma terminology

- **Intergrain distance > Debye length → Dust-in-a plasma**

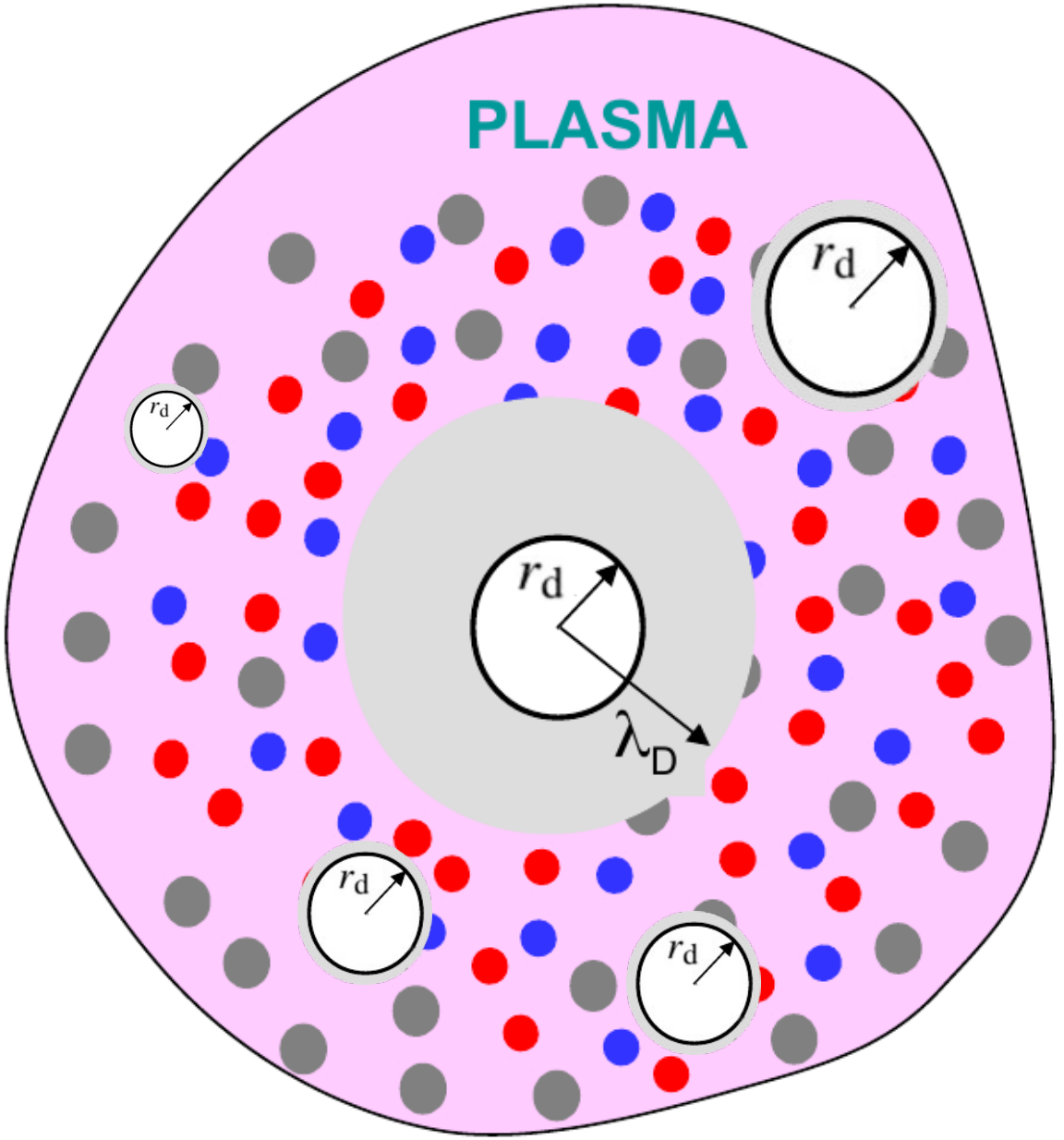
$$r_d \ll \lambda_D < a$$

- **Intergrain distance < Debye length → Dusty plasma**

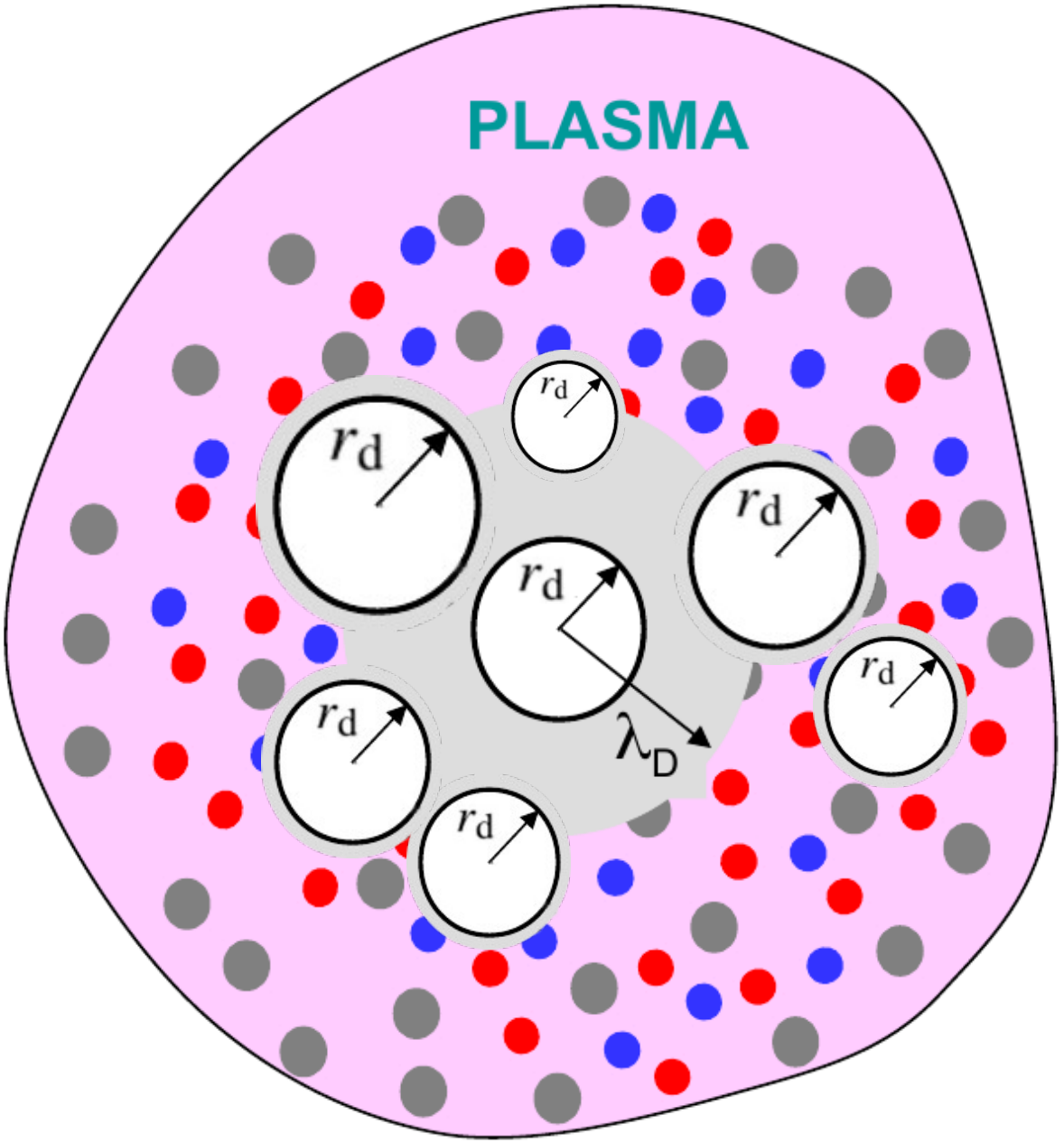
$$r_d \ll a < \lambda_D$$

(collective behavior)

Dusty plasma terminology



Dusty plasma terminology



Dusty plasma terminology

- Coupling parameter

$$\Gamma = \frac{|E_{\text{int}}|}{E_{\text{therm}}}$$

$$\Gamma = \frac{\text{interparticle potential energy}}{\text{particle kinetic energy}} = \frac{Q^2 / 4\pi\varepsilon_0 r_w}{k_B T}$$

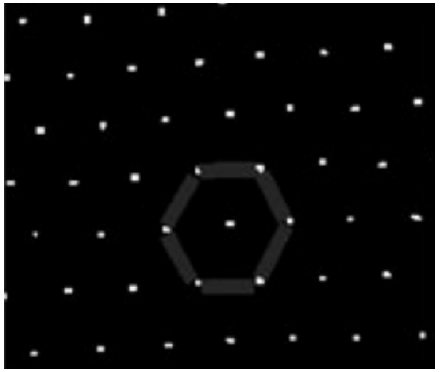
- E_{int} is the interparticle potential energy
- E_{therm} is the particle kinetic energy

Dusty plasma terminology

$\Gamma \ll 1$ gas-like
CB
(waves)

$\Gamma \gtrsim 1$ liquid-like
Strongly Coupled

$\Gamma \geq \Gamma_{cr} \approx 100$ solid-like
crystalline



DIFFERENCES

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

DIFFERENCES

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
IAW, EIC, f ~1 kHz	DAW, DLW, f ~10 Hz,

Questions

Dusty Plasma – Why It Is an Unusual State of Matter?

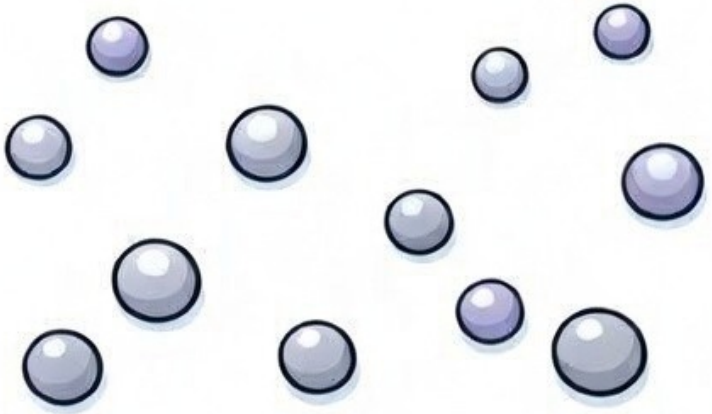
Complex Plasma vs. Ordinary Matter

1) *The grain charges are very high* (~$10^6 e$) → strong grain-grain interactions, i.e., strong Coulomb force → *collective behavior*

2) *The grains strongly absorb plasma components* → making the system *highly dissipative and thermodynamically open* → high tendency to *self-organize into complex structures* (*waves or crystals*).

Ordinary Matter

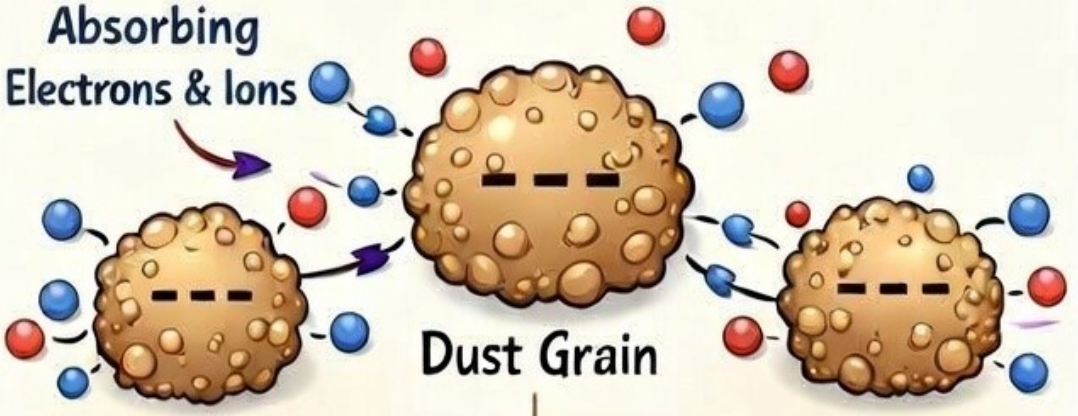
Random, No Interaction



Neutral Atoms & Molecules

Complex Plasma

Collective Behavior



Strong Coupling & Self-Organization

Dust Waves

Dust Crystal

Dissipative System
& Thermodynamincally Open

Questions

Why Complex Plasmas Have Many Applications?

- Semiconductor manufacturing
- Nanotechnology
- New materials and photonic crystals
- Fusion energy reactors
- Soft matter physics
- Non-equilibrium thermodynamics research
- Self-assembling materials
- Plasma processing technology
- Space exploration and planetary science
- Dust mitigation on the Moon and Mars

Semiconductor Manufacturing

- Plasma etching and deposition are essential for microchip fabrication.
- Understanding the dusty plasma helps control contamination and nanoparticle formation.

Materials Today Nano 27 (2024) 100503

Contents lists available at ScienceDirect

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Avoiding dust contamination by near-plasma chemical surface engineering

Dirk Hegemann [a,**], Michał Góra [a,b], Flaela Kalemi [a], Paula Navascués [a,*]

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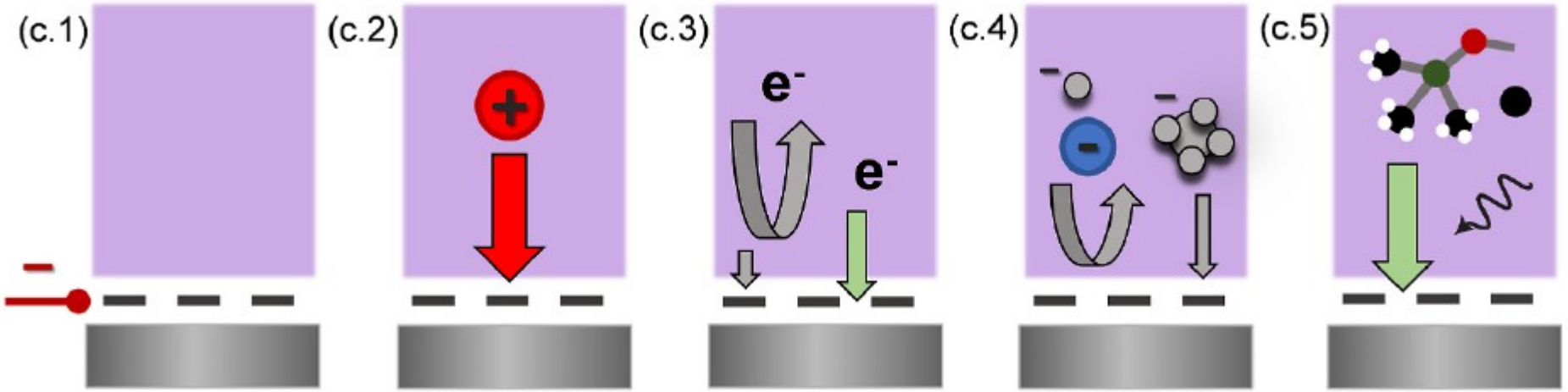
Semiconductor Manufacturing



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Nanotechnology

- Plasma enables synthesis of nanoparticles and quantum structures.
- Used in nanoelectronics and advanced coatings.

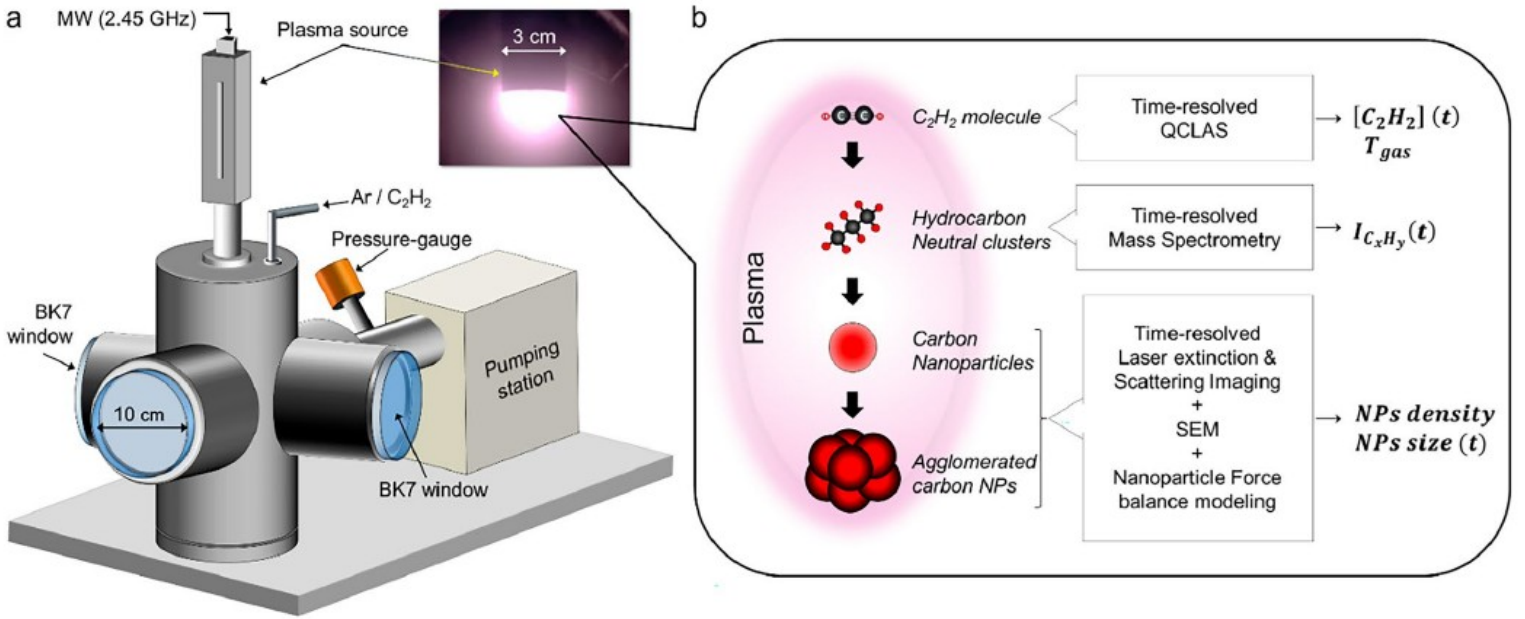
scientific reports

OPEN

Nanoparticles synthesis in microwave plasmas: peculiarities and comprehensive insight

Karim Ouaras[1,2]✉, Guillaume Lombardi[1] & Khaled Hassouni[1]

Nanotechnology



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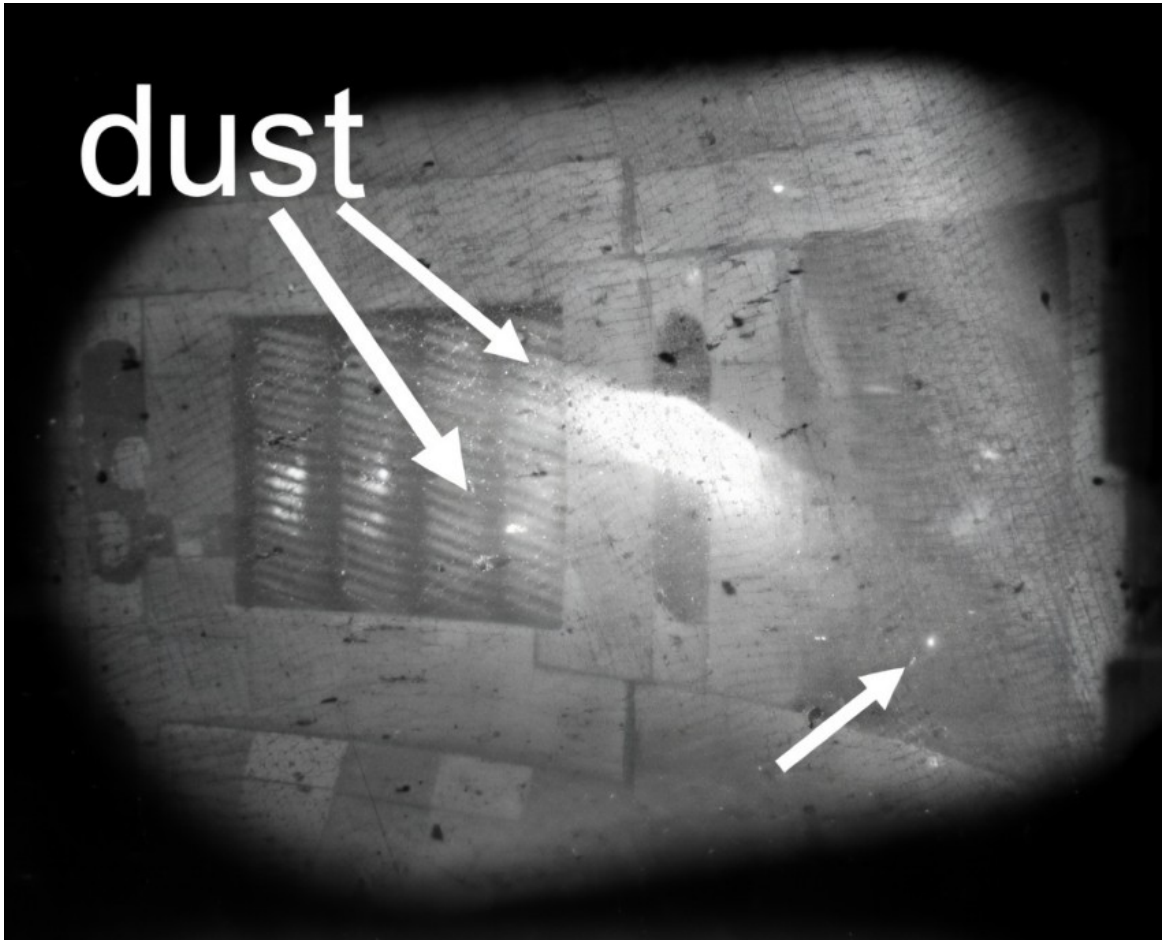
Nanoparticles synthesis in microwave plasmas: peculiarities and comprehensive insight

Karim Ouaras[1,2]✉, Guillaume Lombardi[1] & Khaled Hassouni[1]

Fusion Energy Reactors

- Dust affects plasma stability and reactor safety.



Space Exploration

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DUSTY PLASMA

Nonlinear Periodic Wave Structures in the Dusty Earth's Ionosphere

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Summary

Terminology

- Dusty plasma (collective behavior)
- Dust-in-a plasma
- Dust size distribution
- Multicomponent plasma
- Dynamic dust charging
- +ve & −ve dust
- Dusty plasma frequency
- Dust radius & Intergrain distance
- Coupling parameter

Concept

- ????
- ????
- ????
- ????
- ????
- ????
- ????
- ????
- ????