Effective Scales and Forces in Plasma

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Outline

- Characteristic Scales in Plasma Physics
- Forces in Plasma
- Examples

Characteristic Scales in Plasma Physics

Importance

1) Plasmas are inherently multiscale systems—from nanoseconds and microns to hours and kilometers.

2) Correct modeling, diagnostics, and which scale is dominate.

3) Understand different physical processes in plasmas operate over different scales.

Characteristic Scales in Plasma Physics

What Are Characteristic Scales?

1) Time scale: The typical time over which a given process occurs.
2) Length scale: The distance over which a physical quantity (density, velocity, field) significantly changes.
3) Important Principle: Time and length scales are often coupled via velocity.

Characteristic Scales in Plasma Physics

Key Time Scales in Plasma

1) Plasma Frequency

Definition: The natural oscillation frequency of the plasma's electrons due to perturbations in charge density.

$$\omega_{pe} = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}} \qquad \tau_{pe} = \frac{1}{\omega_{pe}}$$

Characteristic Scales in Plasma Physics

Key Time Scales in Plasma

2) Cyclotron Frequency

Definition: The rate at which charged particles spiral around magnetic field lines due to Lorentz forces.

Significance: Crucial for understanding particle motion in magnetized plasmas

$$\omega_{ce} = \frac{eB}{m_e} \qquad \tau_{ce} = \frac{1}{\omega_{ce}}$$

Characteristic Scales in Plasma Physics

Key Time Scales in Plasma

3) Collision Time

Definition: The average time between Coulomb collisions of particles within the plasma.

Significance: Crucial for understanding energy transfer, and diffusion rates

$$\omega_{ce} = \frac{eB}{m_e} \qquad \tau_{ce} = \frac{1}{\omega_{ce}}$$

Characteristic Scales in Plasma Physics

Key Time Scales in Plasma

4) Debye Shielding Time

Definition: The time required for the plasma to establish electrostatic shielding after a perturbation. This time scale is typically of the same order as the plasma frequency.

Characteristic Scales in Plasma Physics

Key Time Scales in Plasma

5) Ionization and Recombination Times

6) **Transit Time:** The time taken for a particle to cross a characteristic length scale,

$$\tau_{transit} = \frac{L}{v_{th}}$$

where L is the system size and v_{th} is the thermal velocity of the particles.

Characteristic Scales in Plasma Physics

Key Time Scales in Plasma

7) Confinement Time: How long particles or energy remain in the system.

8) Wave Periods: The amount of time needed to complete one full cycle or oscillation in plasma, e.g., Langmuir, Alfvén, and ion-acoustic waves.

Characteristic Scales in Plasma Physics

Key Length Scales in Plasma

1) Debye Length

Definition: The characteristic distance over which electrostatic potentials are screened due to charge separation in the plasma.

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T_e}{n_e e^2}}$$

Characteristic Scales in Plasma Physics

Key Length Scales in Plasma

2) Gyroradius / Larmor Radius

Definition: The radius of the circular motion of a charged particle in a magnetic field.

$$\rho_e = \frac{m_e v_\perp}{eB}$$

Characteristic Scales in Plasma Physics

Key Length Scales in Plasma

3) Skin Depth

Definition: The distance over which an electromagnetic field can penetrate into the plasma before it is attenuated.

$$\delta = \frac{c}{\omega_{pe}}$$

Characteristic Scales in Plasma Physics

Key Length Scales in Plasma

4) Mean Free Path

Definition: The average distance a particle travels before colliding with another particle.

5) System Length Scale (L)

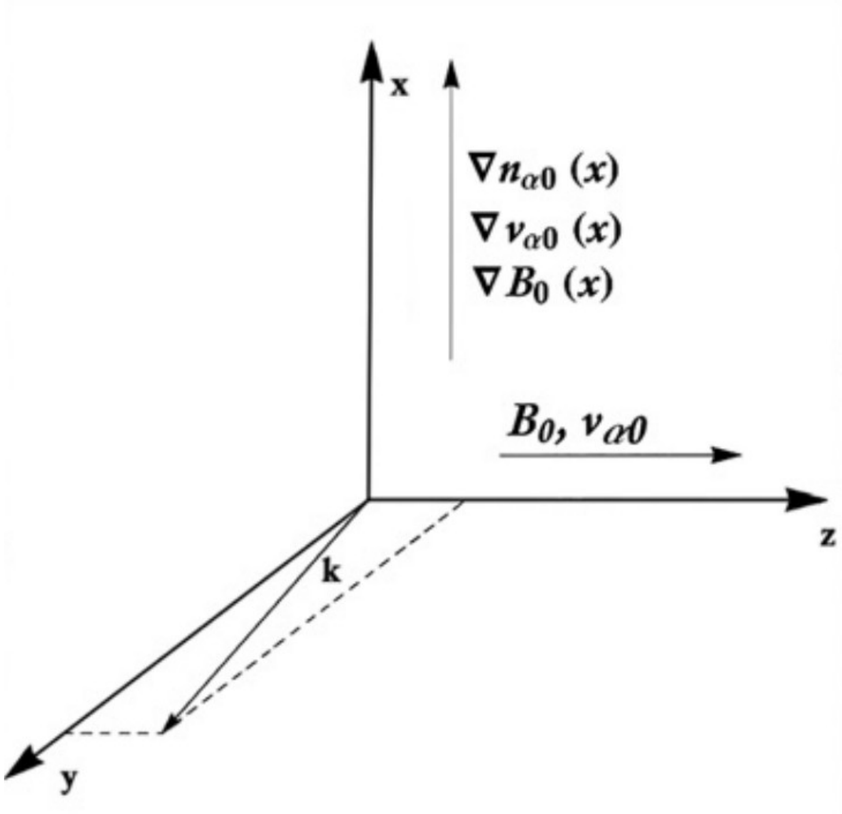
Definition: The overall size of the plasma system, ranging from nanometer up-to kilometers.

Characteristic Scales in Plasma Physics

Key Length Scales in Plasma

6) Gradient Length Scales (L_n)

Definition: Defines how quickly plasma properties (e.g., density or temperature) change over space.



$$L_n = \left| \frac{1}{n} \frac{dn}{dx} \right|^{-1}$$

Characteristic Scales in Plasma Physics

Dimensionless Ratios

1) Knudsen Number (Kn)

$$\mathrm{Kn} = \frac{\lambda_{mfp}}{L}$$

$\mathrm{Kn} \ll 1$ implies collisional regime.

$\mathrm{Kn} \gg 1$ implies collisionless regime.

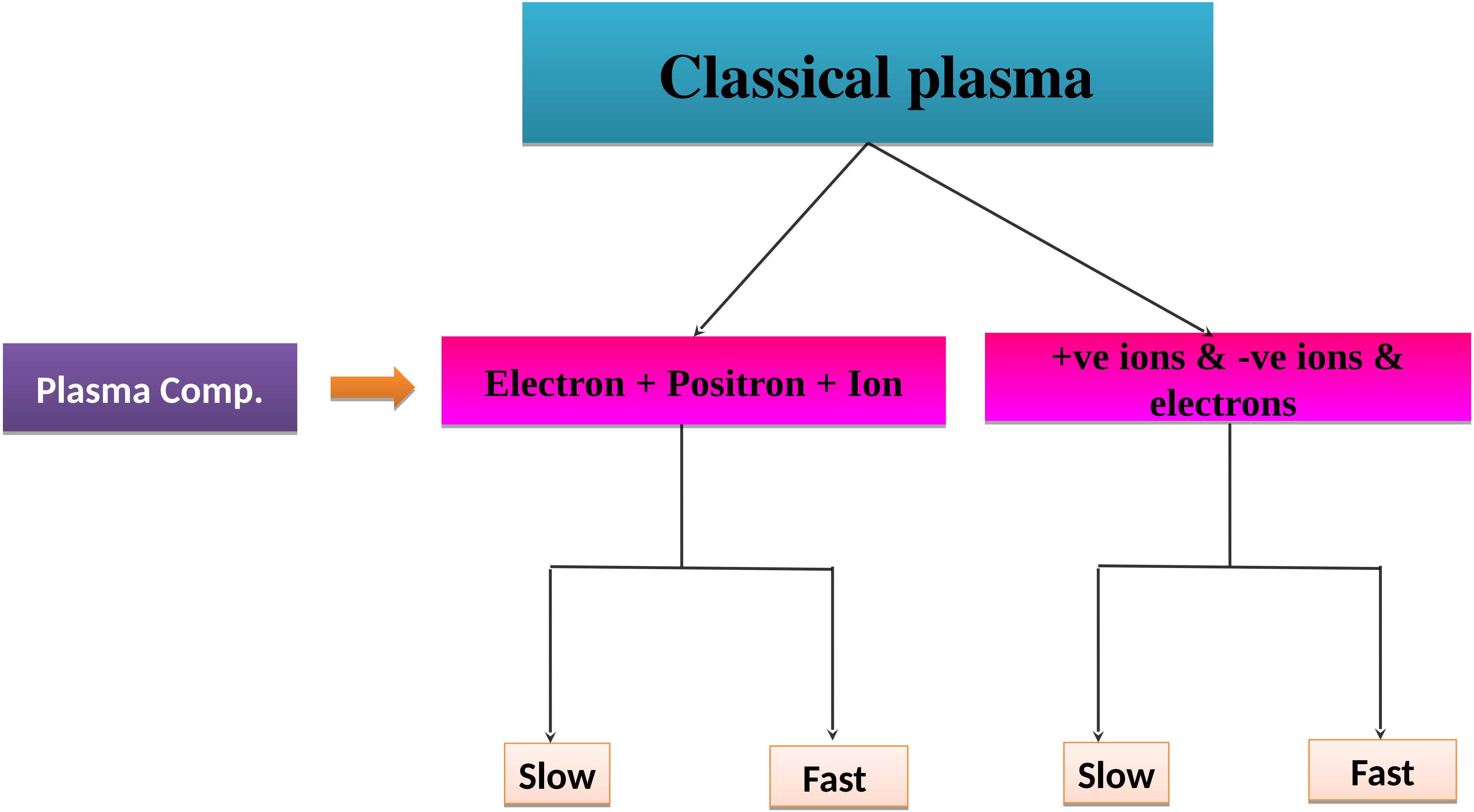
Characteristic Scales in Plasma Physics

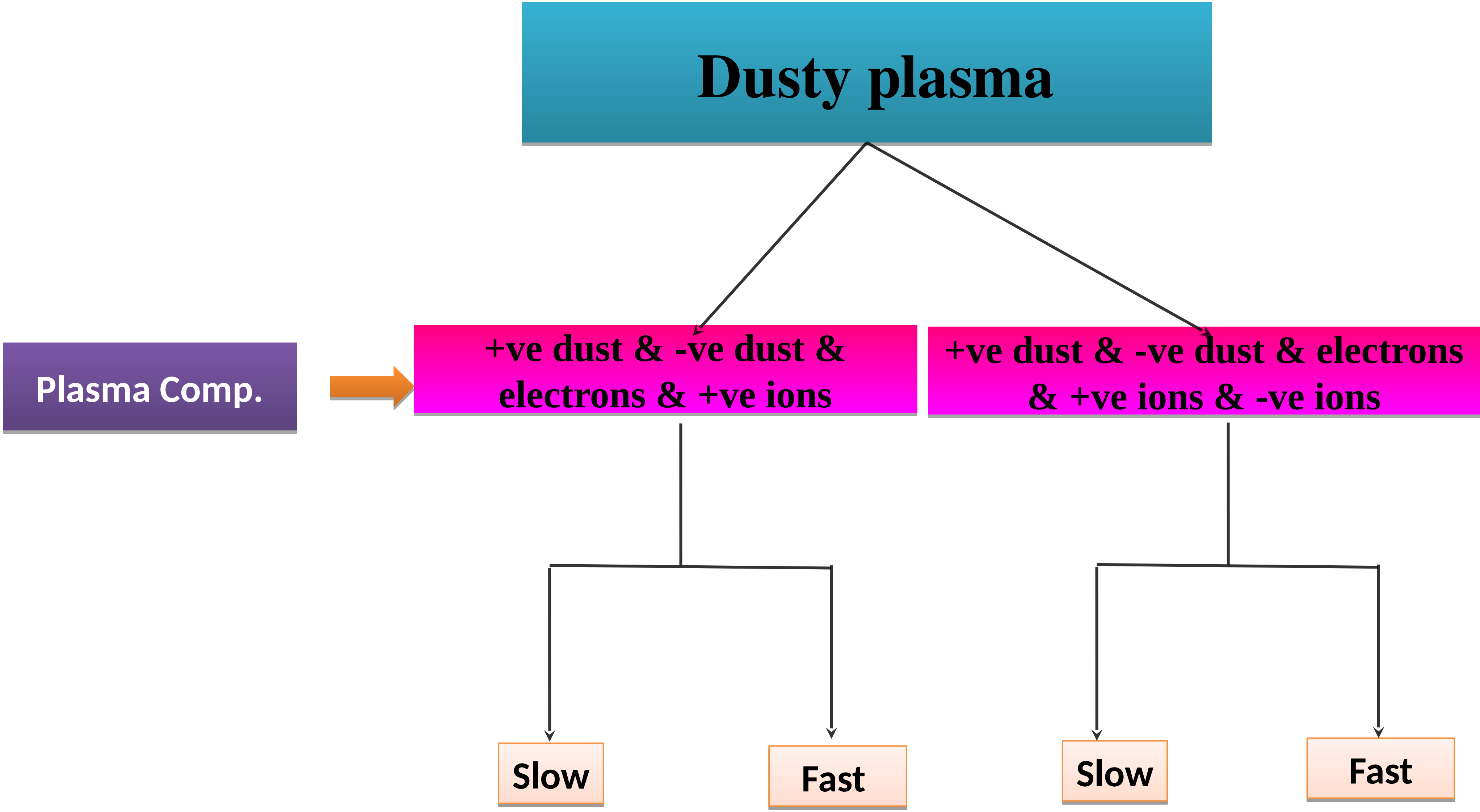
Dimensionless Ratios

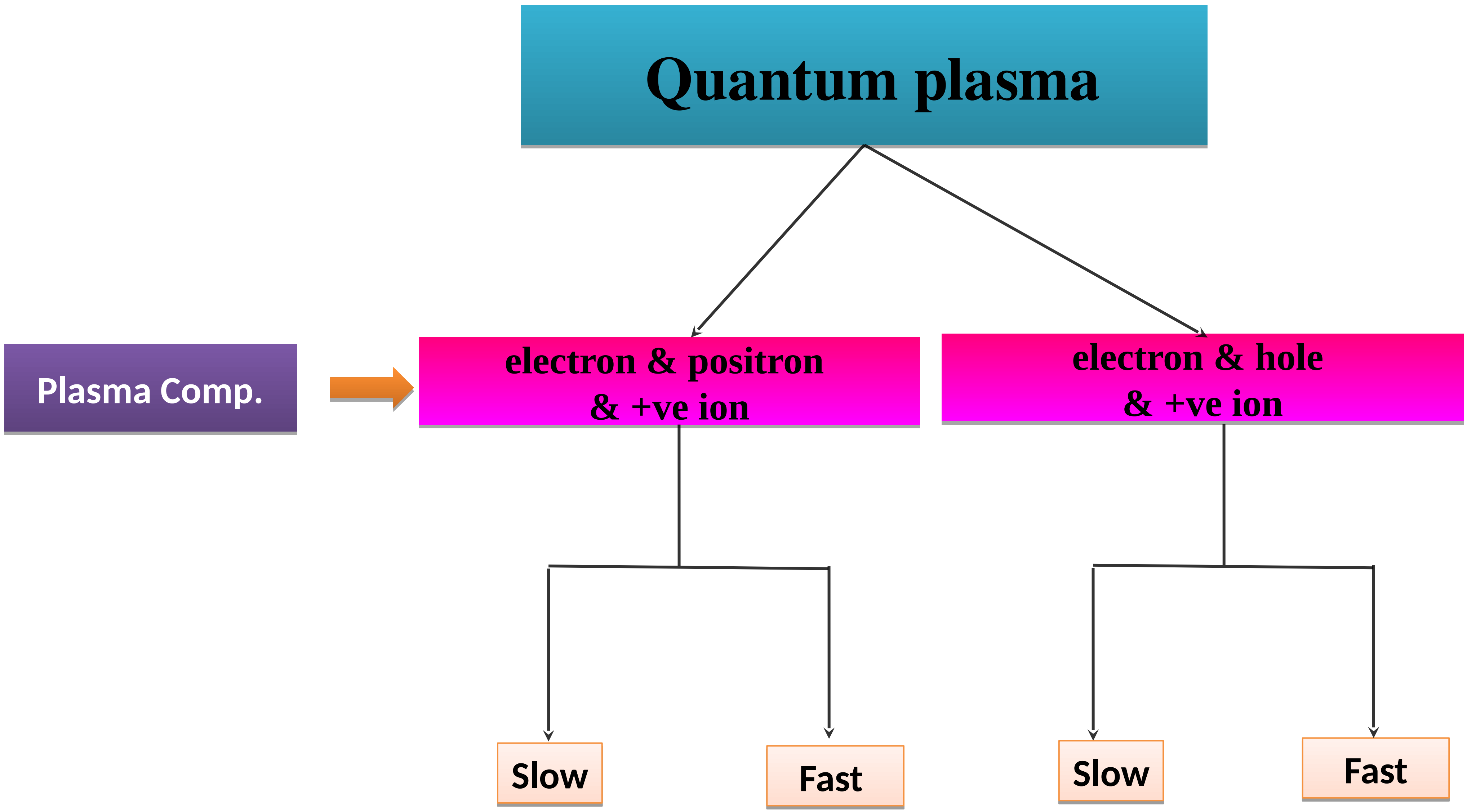
2) Magnetization Parameter $\omega_{ce}\tau_{coll}$

$$\omega_{ce}\tau_{coll} \gg 1$$

Particles are well-magnetized, WHY?


Classical plasma
Plasma Comp.
Electron + Positron + Ion
+ve ions & -ve ions & electrons
Slow
Fast
Slow
Fast


Dusty plasma
Plasma Comp.
+ve dust & -ve dust & electrons & +ve ions
+ve dust & -ve dust & electrons & +ve ions & -ve ions
Slow
Fast
Slow
Fast


Quantum plasma
Plasma Comp.
electron & positron & +ve ion
electron & hole & +ve ion
Slow
Fast
Slow
Fast

Forces in plasma

1) The forces drive plasma dynamics , such as how charged particles move and interact,
2) Understanding energy transport, waves, and instabilities,
3) Control of forces enables technological applications,
4) Correct modeling the plasma, fluid or kinetic model.

Forces in plasma

1) Inertial force

   refers to the resistance of plasma particles (such as electrons and ions) to acceleration or deceleration.

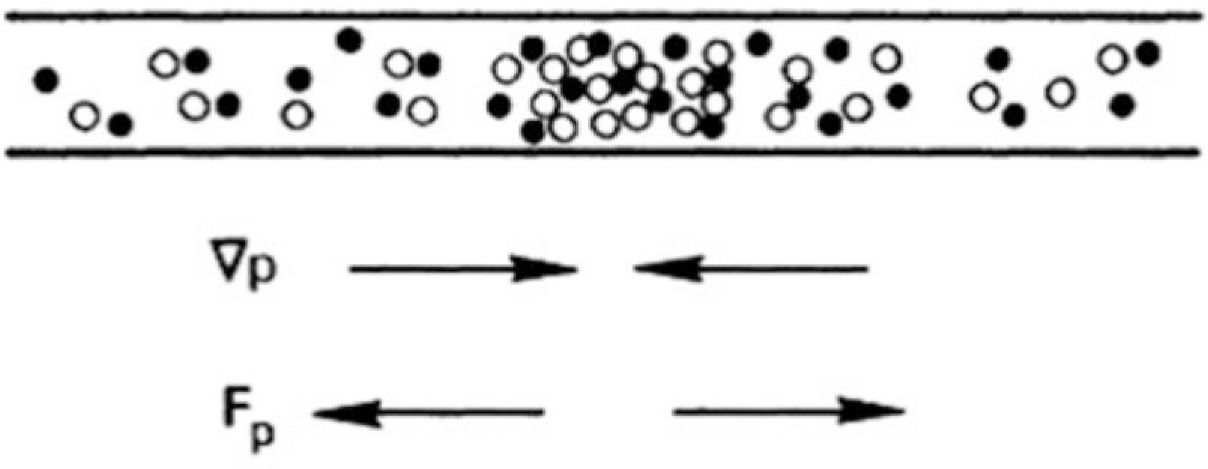
2) Electric Force

3) Magnetic force

4) Collisional Force

Forces in plasma

5) Pressure Gradient Force

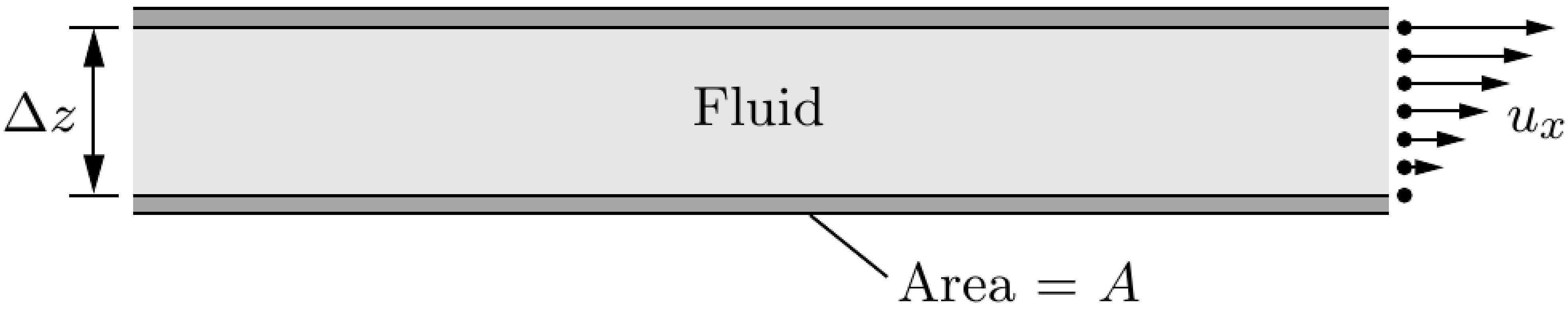


$$F_{pressure} = -\nabla P$$

Forces in plasma

6) VISCOSITY

- Viscosity = Resistance to Shear Flow
- Momentum Transfer Between Layers
- Each fluid layer gives some of its momentum to the layer below it.
- Highly viscous fluids (like corn syrup) transfer momentum better than low-viscosity fluids (like air).

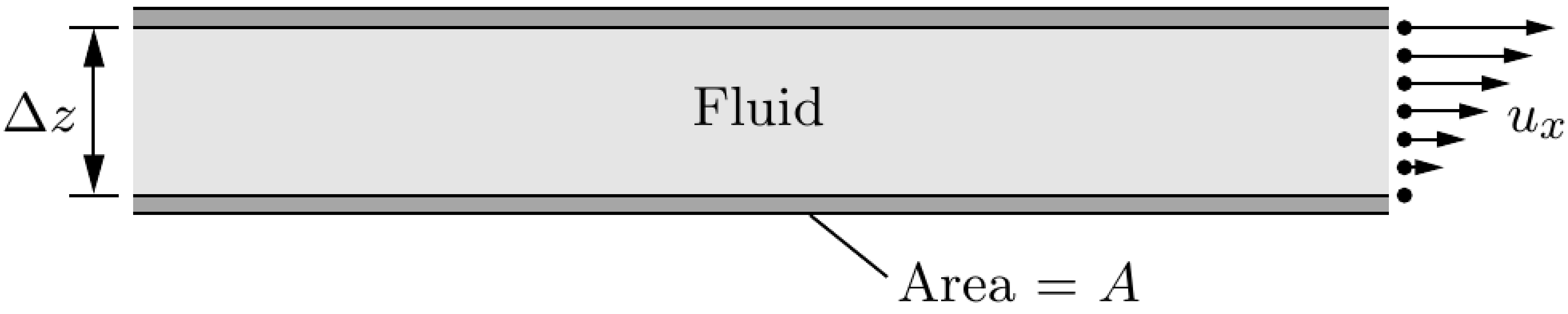


Forces in plasma

6) VISCOSITY

$$F_x \propto \frac{A \cdot (u_{x,\text{top}} - u_{x,\text{bottom}})}{\Delta z} \qquad \text{or} \qquad \frac{F_x}{A} \propto \frac{\Delta u_x}{\Delta z}$$

$$\frac{|F_x|}{A} = \eta \frac{du_x}{dz}$$



Forces in plasma

6) Viscosity

- Force per Unit Area = Pressure Units
- Pressure acts perpendicular to a surface.
- Shear stress acts parallel to a surface.
- Correct Term: Shear Stress (τ)

$$\frac{|F_x|}{A} = \eta \frac{du_x}{dz}$$

$$\tau = \eta \frac{du_x}{dz}$$

Forces in plasma

6) VISCOSITY

$$\tau = \eta \frac{du_x}{dz}$$

$$\vec{f}_{\text{viscous}} = \nabla \cdot \vec{\tau}$$

$$f_x = \frac{d}{dz}\left(\eta \frac{du_x}{dz}\right) \approx \eta \frac{d^2 u_x}{dz^2}$$

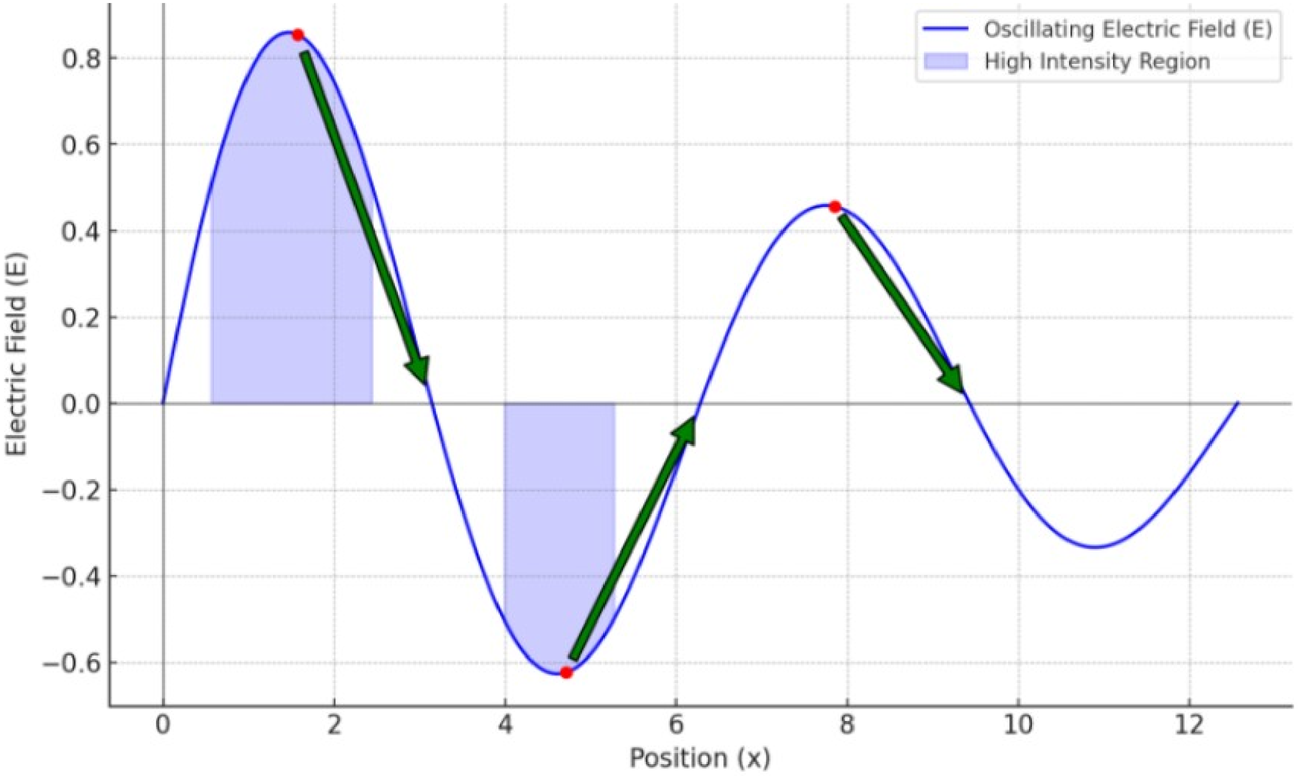
🧠 **Think of it This Way:**

- **Shear stress (1st derivative)** = how much "pull" one fluid layer puts on another.
- **Viscous force (2nd derivative)** = how that pull *changes* across the fluid → leading to a **net force.**

Forces in plasma

7) Ponderomotive force

- Force pushes particles away from regions of higher field intensity to low field intensity



Forces in plasma

7) PONDEROMOTIVE FORCE

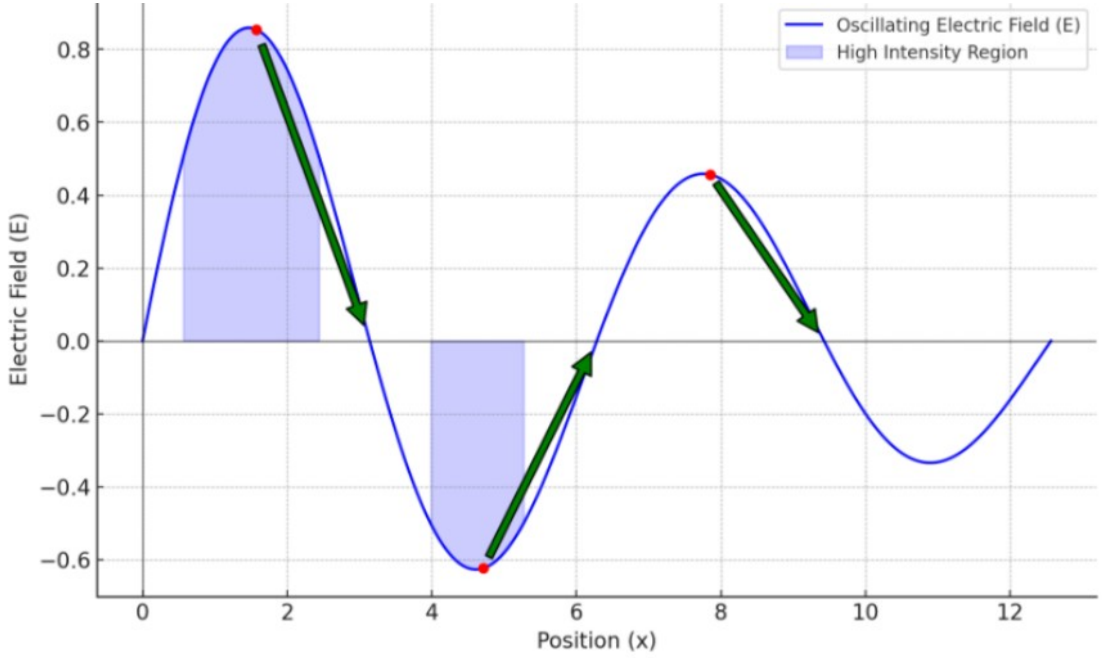
$$\mathbf{F}_p = -\frac{q^2}{4m\omega^2}\nabla E^2$$

q: Charge of the particle

m: Mass of the particle

ω: Angular frequency of the oscillating field

E: Electric field strength



Forces in plasma

1) Inertial Force
2) Electric Force
3) Magnetic Force
4) Collisional Force
5) Pressure Gradient Force
6) Viscosity
7) Ponderomotive Force
8) Drag Force
9) Corilis Force
10) Gravitational Force
11) Quantum Bohm Force
12) Exchange-Correlation Force
13) Spin Force
14) Thermophoretic Force
15) Radiation Pressure Force
16) Diffusion Force
17) Polarization Force
18) Anisotropic Pressure Force
19) Gyroviscous Force
20) Ambipolar Electric Force!

Types & Forces

- Classical
- Dusty
- Quantum

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2) Electric Force
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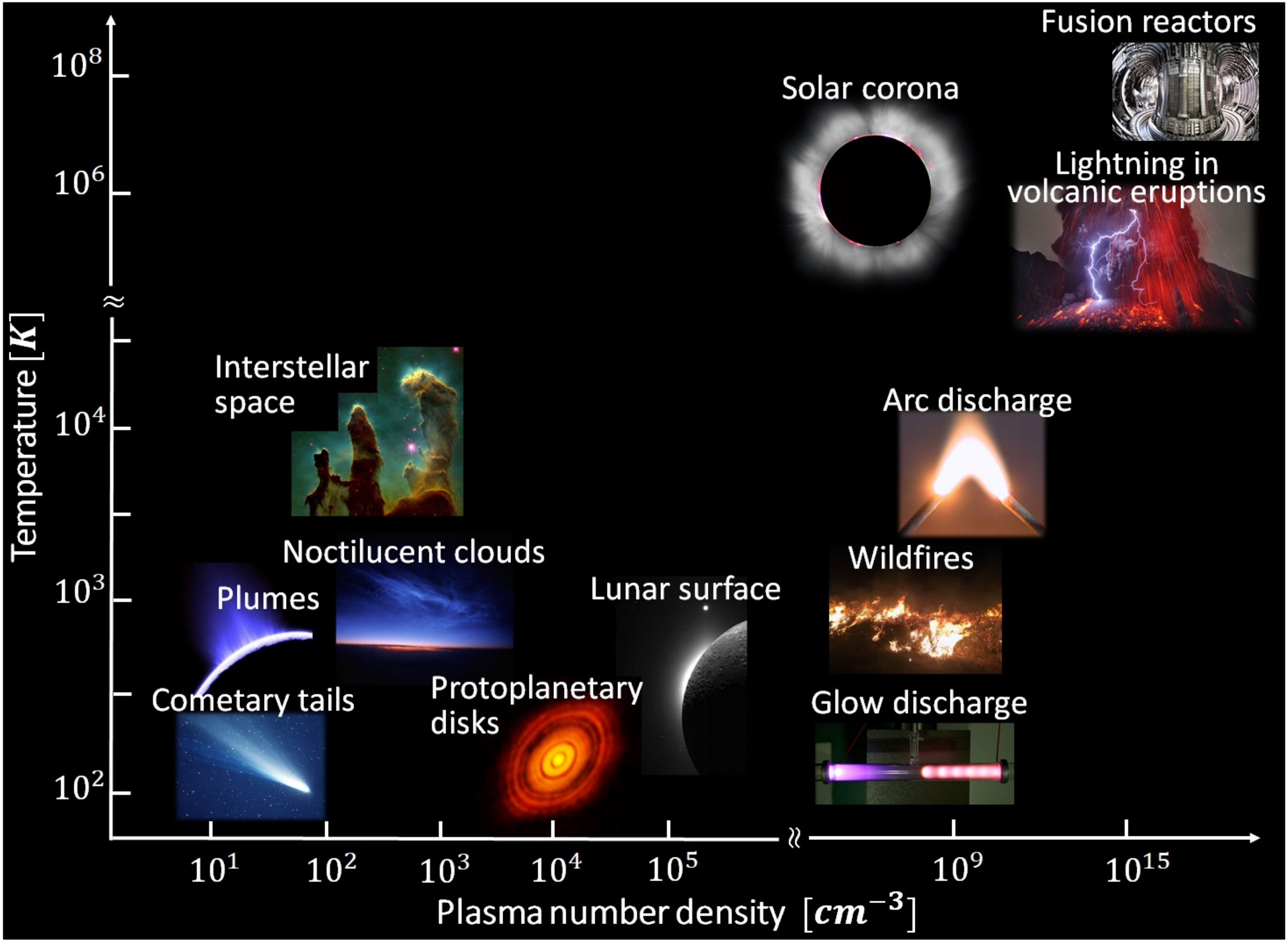

Fusion reactors
Solar corona
Lightning in volcanic eruptions
Interstellar space
Arc discharge
Noctilucent clouds
Wildfires
Plumes
Lunar surface
Cometary tails
Protoplanetary disks
Glow discharge
10^8
10^6
10^4
10^3
10^2
Temperature $[K]$
10^1
10^2
10^3
10^4
10^5
10^9
10^{15}
Plasma number density $[cm^{-3}]$

Types & Forces

- Classical
- Dusty
- Quantum

Experiment

OR

Application

OR

Observation

1) Inertial Force
2) Electric Force
3) Magnetic Force
4) Collisional Force
5) Pressure Gradient Force
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7) Ponderomotive Force
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20) Ambipolar Electric Force!

Examples

$$\omega \ll \omega_{ci}$$

$$\omega_{pi} \gg \omega_{ci}$$

$$\nu_{in} \gg \omega_{ci}$$

$$\nu_{ee} \ll \omega_{ce}$$

$$\left|\frac{\partial}{\partial t}\right| \gg \omega_{pi}, \omega_{ci}$$

$$\left|\frac{\partial}{\partial t}\right| \ll \nu_{ei}$$

$$\nu_{ee} > \nu_{ei} > \nu_{ii}$$

$$\lambda_{\mathrm{mfp}} \gg L$$

$$\delta \ll \lambda_D$$

$$L_T \gg L$$

$$\rho_i \ll L$$

$$L \gg \lambda_D$$

$$L \sim \lambda_D$$