Classification of plasma forces and species

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Aim of the lecture

You should learn

- **Types of plasma**
- **Plasma components**
- **Forces in plasma**
- **Examples**
- **Comparison between forces**

Types of plasmas

- **(I) Classical plasma**

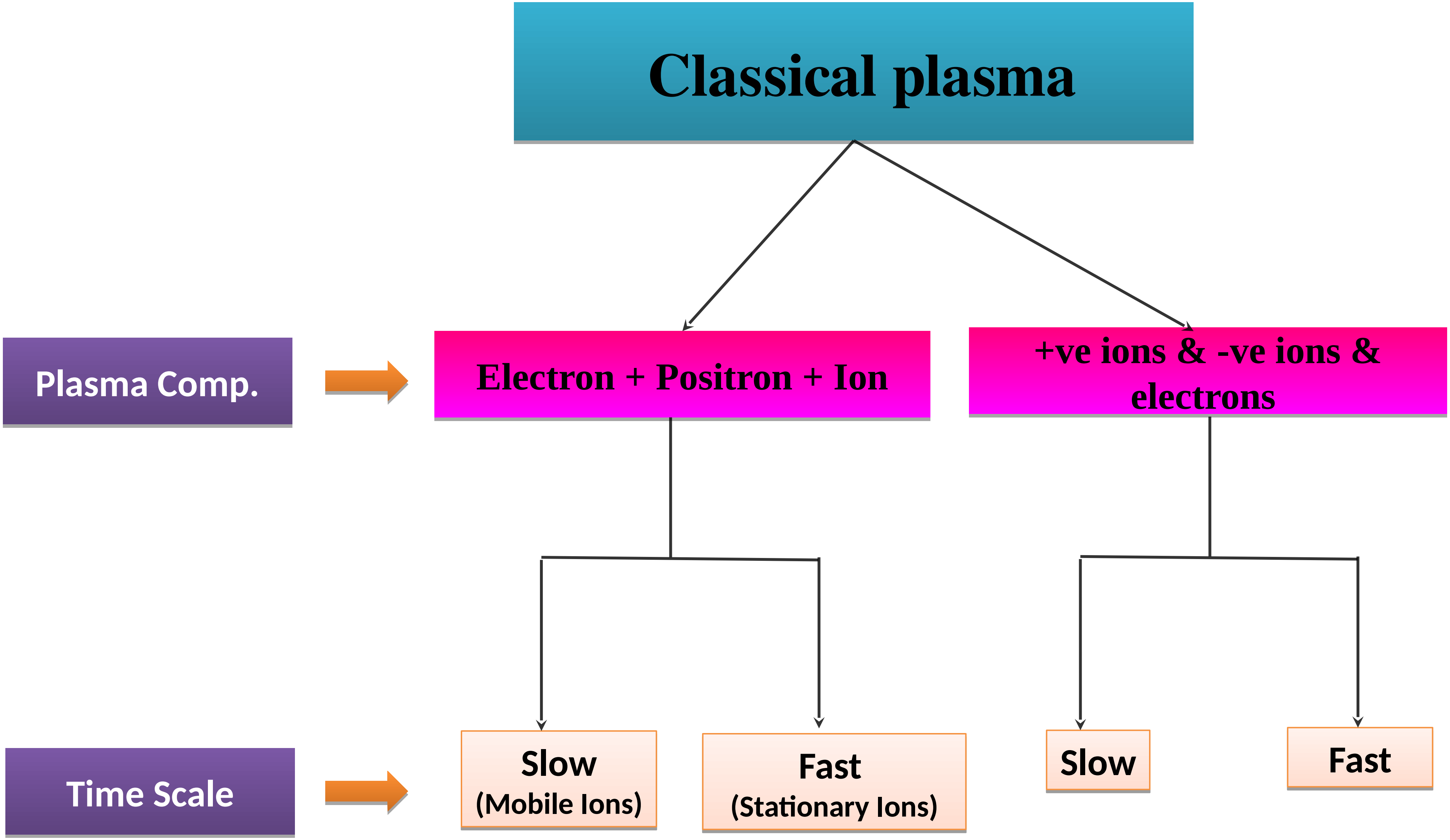
  +ve ions / electrons / -ve ions / positrons

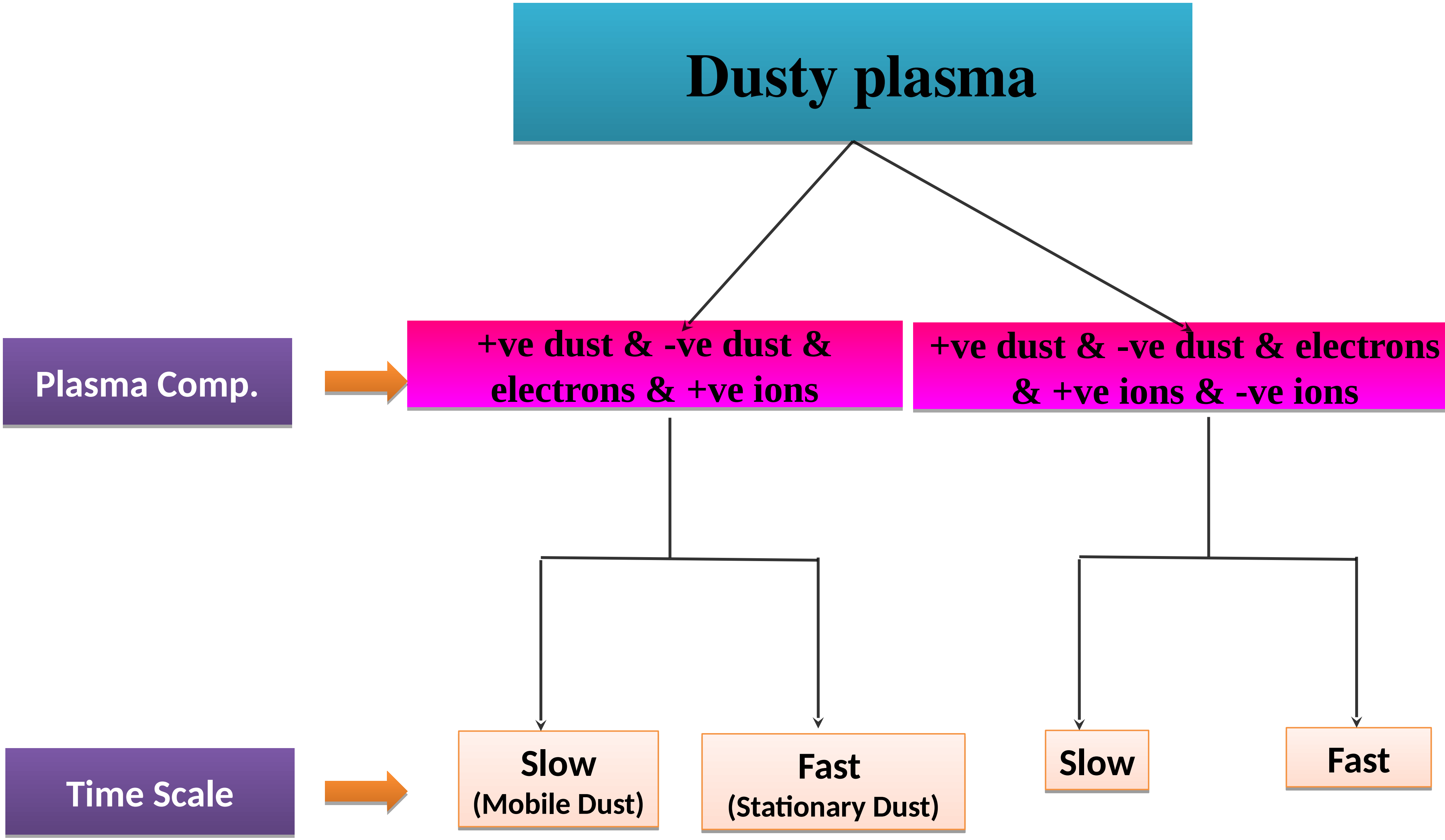
- **(II) Dusty (complex) plasma**

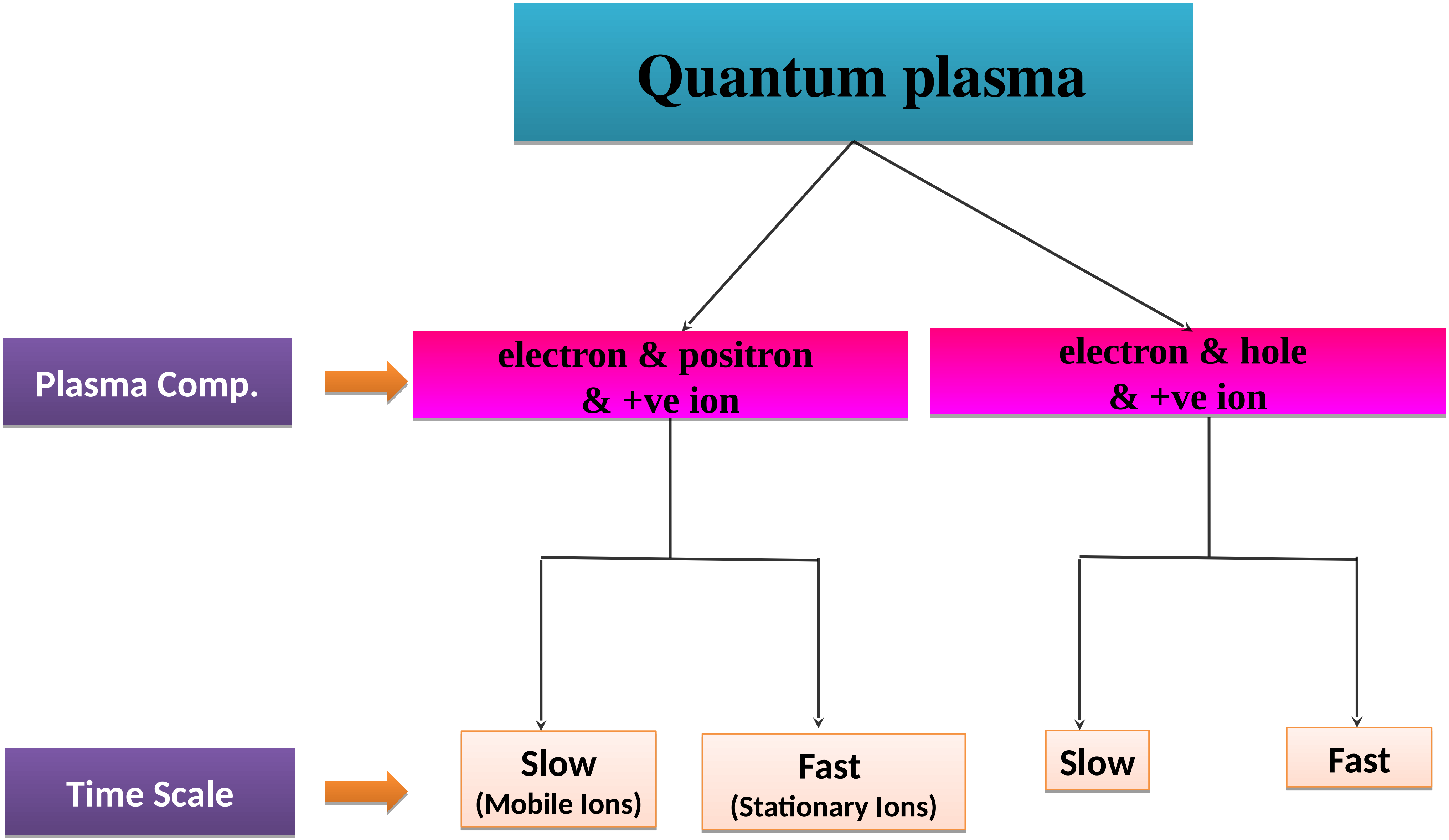
  +ve dust / -ve dust / +ve ions / electrons / -ve ions

- **(III) Quantum plasma**

  Electrons / positrons / holes / +ve ions


Classical plasma
Plasma Comp.
Electron + Positron + Ion
+ve ions & -ve ions & electrons
Time Scale
Slow
(Mobile Ions)
Fast
(Stationary Ions)
Slow
Fast


Dusty plasma
Plasma Comp.
+ve dust & -ve dust & electrons & +ve ions
+ve dust & -ve dust & electrons & +ve ions & -ve ions
Time Scale
Slow (Mobile Dust)
Fast (Stationary Dust)
Slow
Fast


Quantum plasma
Plasma Comp.
electron & positron
& +ve ion
electron & hole
& +ve ion
Time Scale
Slow
(Mobile Ions)
Fast
(Stationary Ions)
Slow
Fast

Forces in plasma

- Inertial force
- Electric force
- Magnetic force
- Pressure gradient force
- Collisional force
- Drag force
- Corilis force
- Ponderomotive force
- Viscosity
- Tunnling force
- Exchange-correlation force
- Gravitational force
- Thermophoretic force
- Radiation pressure force
- Diffusion force
- **15 Forces**

Inertial Force

- 17th Century: Isaac Newton introduced the concept of inertia in his first law of motion, laying the groundwork for understanding inertial forces.
- Early 20th Century: Inertial forces were recognized as key factors in the behavior of high-speed particles, contributing to early plasma studies.
- 1930s: The development of magnetohydrodynamics (MHD) highlighted the importance of inertial forces in plasma dynamics.
- 1960s: Advances in space exploration and nuclear fusion research emphasized the role of inertial forces in plasma confinement and stability.

Inertial Force

- **Definition:** Inertial force is the force required to change the motion of a mass, crucial in understanding plasma behavior.
- Equation: Force = mass × acceleration, where inertia is the resistance to acceleration.
- **Plasma Confinement:** Inertial forces help contain plasma in magnetic and inertial confinement fusion devices.
- **Wave Propagation:** Inertial forces affect the propagation of waves in plasma, essential for communication and diagnostics.
- **Instability Analysis:** Understanding inertial forces aids in analyzing and mitigating plasma instabilities.

Inertial Force

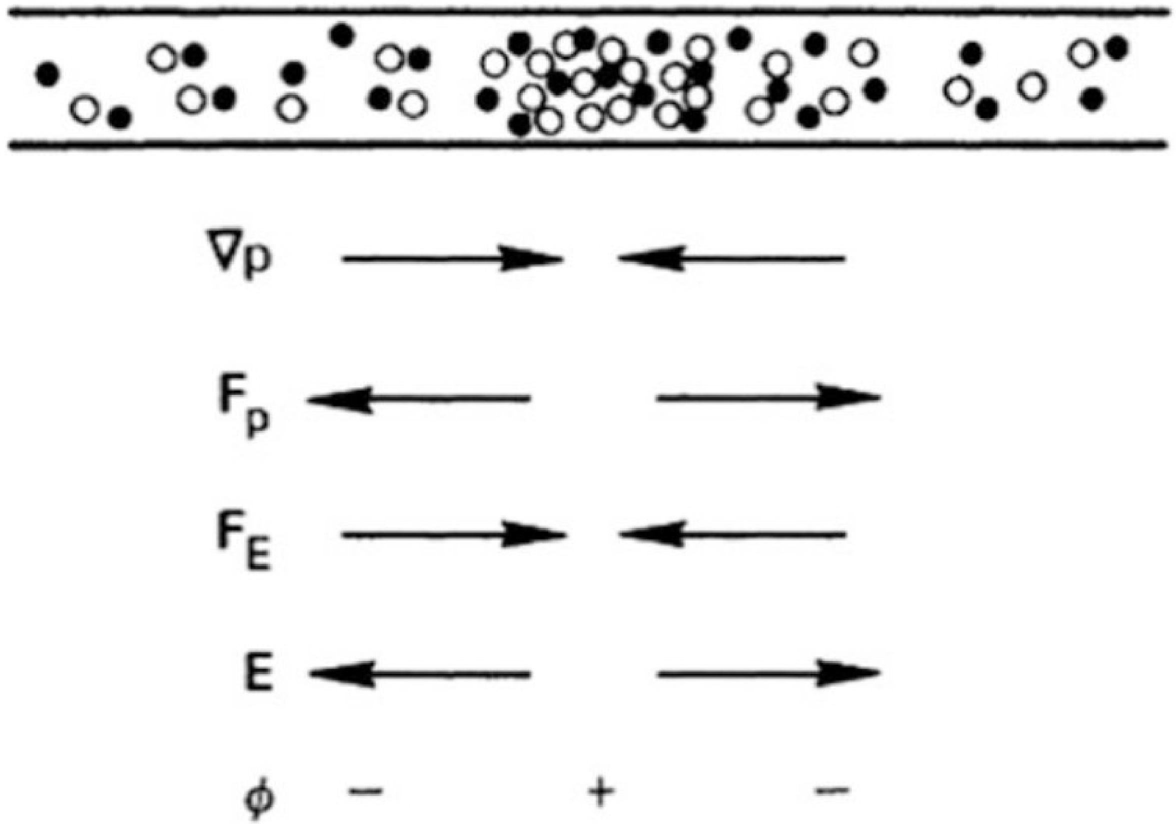
- To understand how dark matter is proven to exist, we need to examine the discrepancies between observed gravitational effects and the amount of visible matter in the universe.
- Newton's second law
- Newton's law of gravitation
- The speed of the Sun’s rotation around the center of the galaxy: 220 km/s.
- Radius of the Sun's orbit around the center of the galaxy: about 30,000 light-years (approximately 9.5×10^{16} km)

Prove it in the H.W.

Pressure Gradient Force

- **Definition**: A difference in pressure inside a plasma creates the pressure gradient force, which moves particles from high-pressure regions to low-pressure regions.

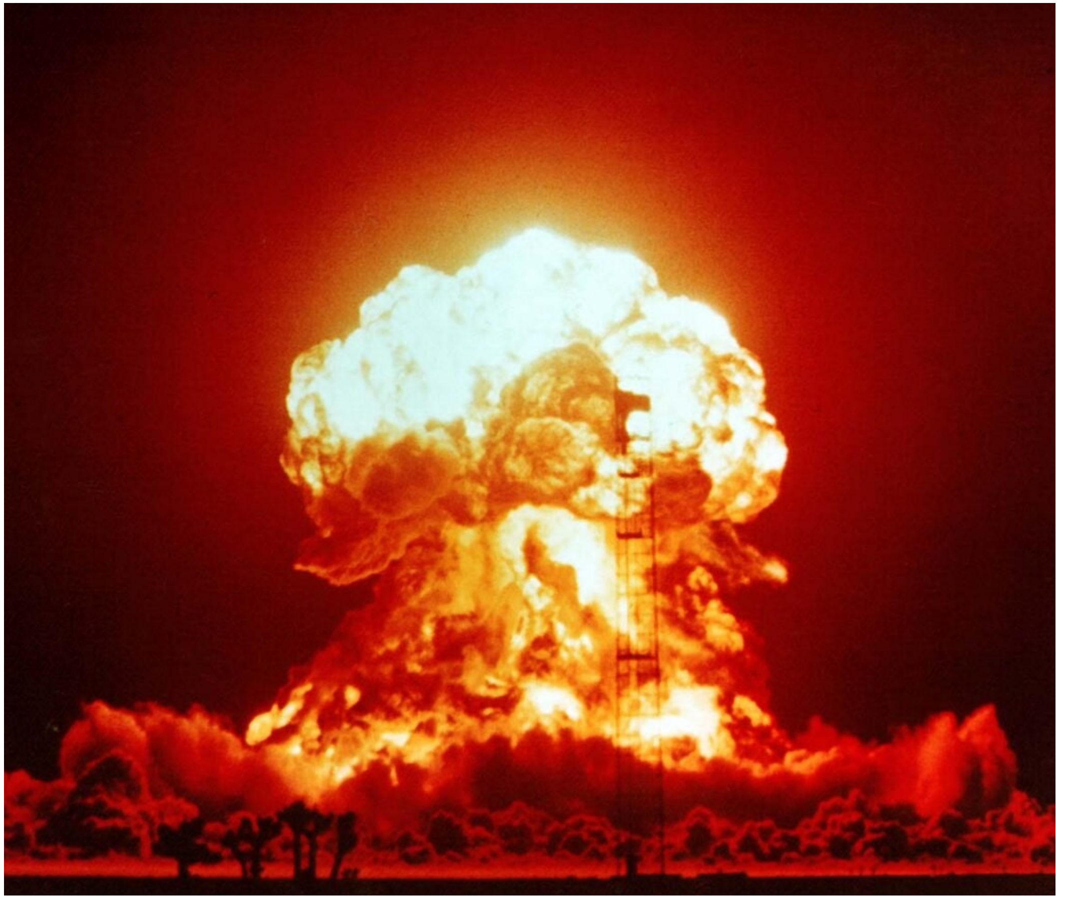
$$\mathbf{F}_{pg} = -\nabla P$$



Pressure Gradient Force

Equilibrium and Stability:

- **Force Balance:** Pressure gradient force balances other forces (e.g., magnetic tension, inertial forces) in plasma, maintaining equilibrium.
- **Stability Analysis:** Helps in understanding instabilities such as the Rayleigh-Taylor instability.



When the lighter fluid is pushing the heavier fluid

Pressure Gradient Force

Equilibrium and Stability:

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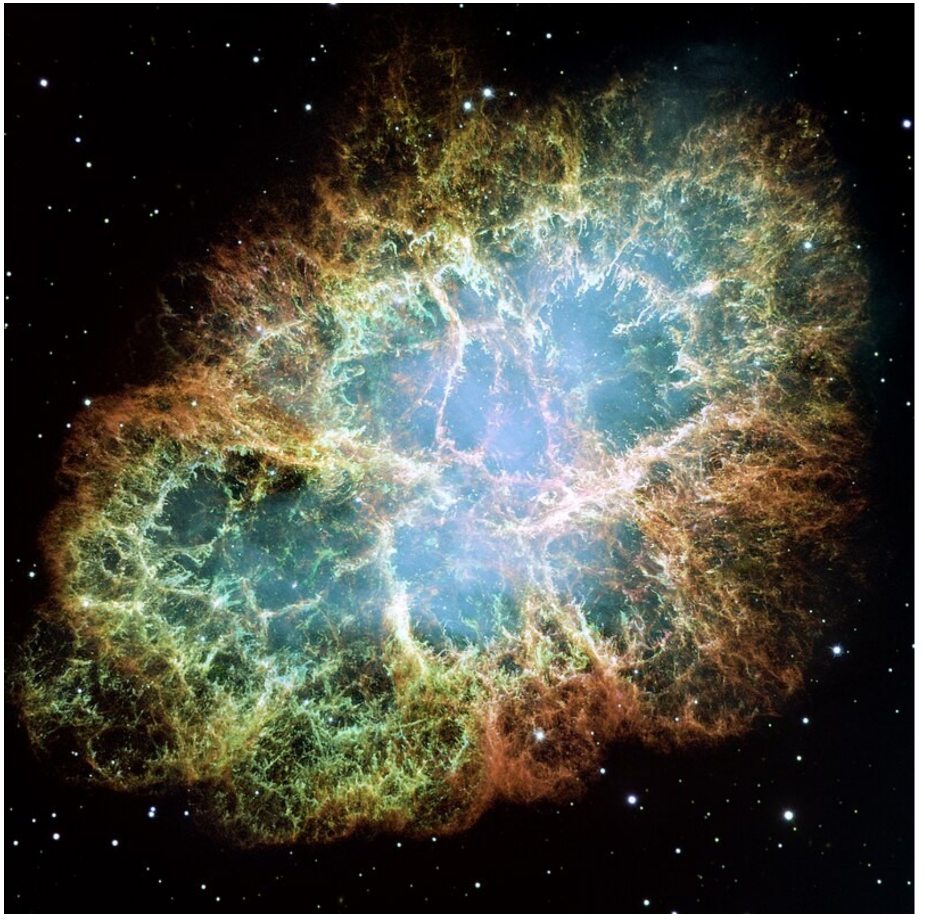
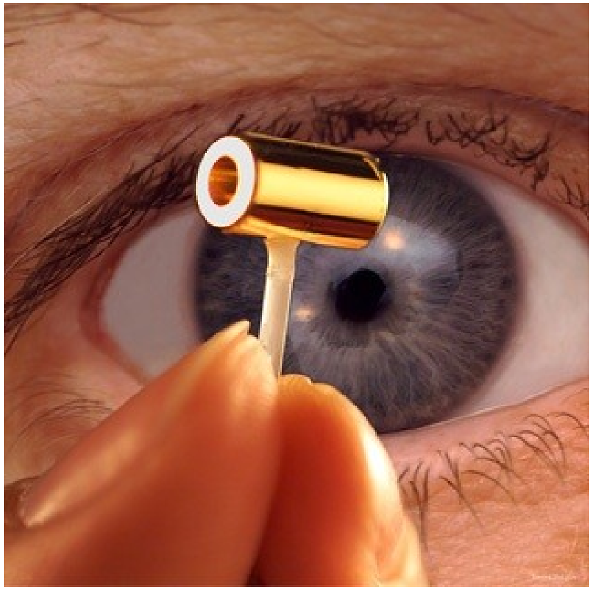


When the lighter fluid is pushing the heavier fluid

Pressure Gradient Force

Plasma Confinement:

- Magnetic Confinement: Pressure gradients are crucial in maintaining the equilibrium of confined plasma, influencing the shape and stability of the confinement.
- Inertial Confinement: In ICF, pressure gradients drive the implosion of the fuel pellet.



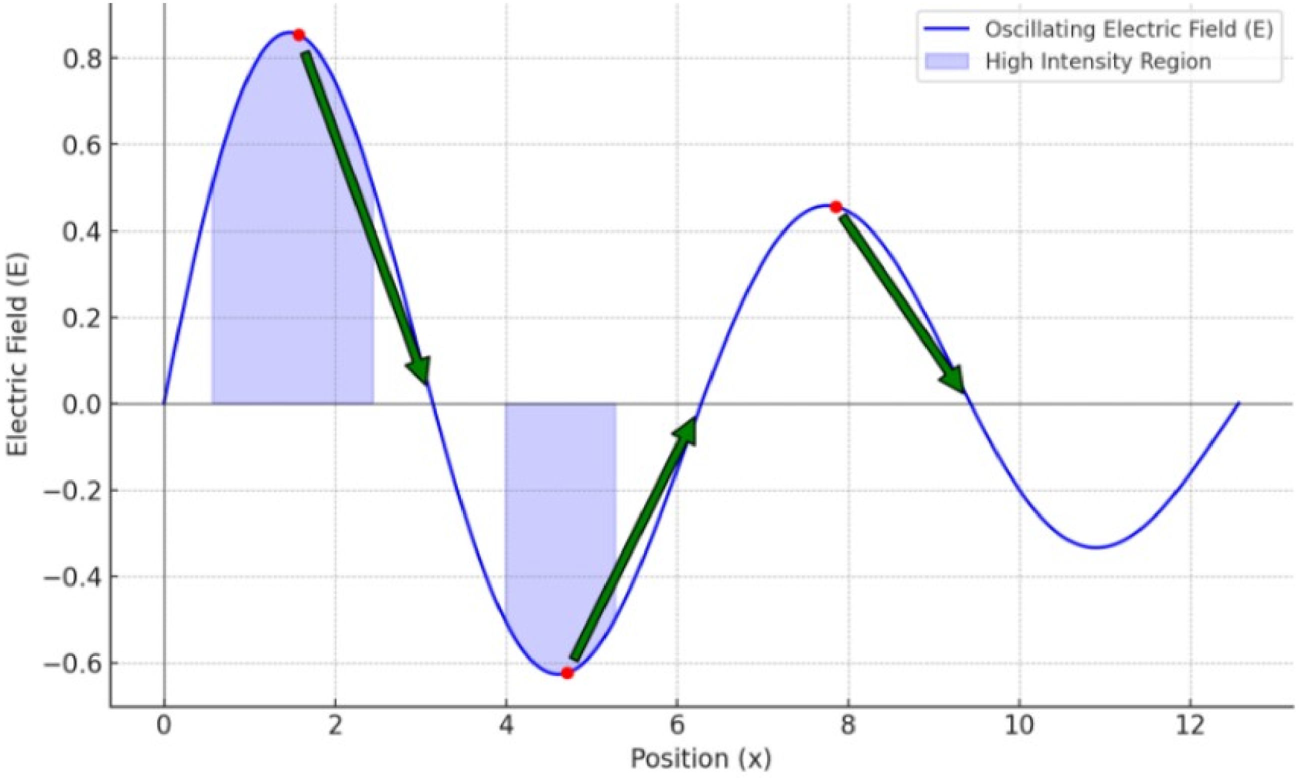
Ponderomotive Force

Basic Principle of Ponderomotive Force

- When charged particles are placed in an oscillating electromagnetic field, they experience rapidly changing forces.
- The ponderomotive force is the time-averaged effect of these oscillations, resulting in a net force.
- This net force pushes particles away from regions of higher field intensity.

Ponderomotive Force

Definition: The ponderomotive force is a nonlinear force experienced by a charged particle in an oscillating electromagnetic field (like laser or RF field). This force pushes the particle toward lower field strengths.



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

Ponderomotive Force

Applications: Particle Acceleration

- Overview: Particle accelerators are used to speed up charged particles to high velocities for various applications, including scientific research and medical treatments.
- Ponderomotive Force: Pushes particles along selected directions to accelerate.
- Focuses particle beams and reduces beam divergence, enhancing accelerator efficiency.

Collisional Force

- **Definition:** Collisional force in plasma physics refers to the interactions between charged particles (ions and electrons) that result in momentum transfer and energy dissipation.
- **Types of Collisions:**
- Elastic Collisions are interactions between particles where the total kinetic energy and momentum are conserved.
- Characteristics: No loss of kinetic energy & Particles merely change direction and possibly speed, but the total kinetic energy remains the same.

Collisional Force

- **Types of Collisions:**
- Inelastic Collisions transform part of the colliding particles' kinetic energy into internal energy, excitation, or ionization.
- Importance: Inelastic collisions play a crucial role in energy transfer, ionization processes, and plasma dynamics.
- Collision Frequency: Number of collisions per unit time.
- Inverse of Collision Frequency = Collision time-scale
- Mean Free Path: Average distance a particle travels between collisions.

Collisional Force

$$\nu_{ei} = \frac{4\sqrt{2\pi}}{3} \frac{n_i e^4 \ln \Lambda}{(4\pi\epsilon_0)^2 m_e^{1/2} (k_B T_e)^{3/2}}$$

- Collisions in space, laboratory, stars....??
- Density increase --> collision frequency --> collision time
- Temperature increase --> collision frequency --> collision time
- We have a time-scale to compare but with what???

1. $\lambda_D \ll L$.
2. $N_D \ggg 1$.
3. $\omega\tau > 1$.

Collisional Force

Importance of Collisional Force in plasma

- Plasma Confinement & Impurity Control
- Diagnostics: Techniques like Langmuir probes measure collisional parameters.
- Space Plasmas: Observations of space plasmas provide insights into natural collisional processes such as solar wind interaction with planets.
- Collisions play a significant role in energy transport within stars.
- Interstellar Medium: Collisional interactions affect the dynamics and chemistry of the interstellar medium.

Comparison Between Forces

$$\cancel{mn}\,\frac{du}{dt} \;:\; \frac{qnE}{mn} \;:\; \frac{\nabla P}{mn}$$

$$\frac{V}{\tau} \;:\; \frac{q\phi}{mL} \;:\; \frac{\cancel{n} k_B T}{L m \cancel{n}}$$

$$1 \;:\; \frac{q\phi}{mL}\frac{\tau}{V} \;:\; \frac{k_B T}{m}\frac{\tau}{LV}$$

$$1 \;:\; \frac{e\phi}{m}\frac{1}{V^2} \;:\; \frac{V_t^2}{V^2}$$

For cold plasma $V_t << V$

$$V_t >> V \qquad \frac{e\phi}{k_B T_e m} >> \frac{V^2 m}{V_t^2 k_B T_e}$$

$$\frac{F}{m} = \frac{qE}{m}$$

$$L a = \frac{eEL}{m}$$

$$V^2 = \frac{e\phi}{m}$$

Comparison Between Forces

- **Boltzmann relation for electrons**

$$mn\left[\frac{\partial v_z}{\partial t} + (\mathbf{v}\cdot\nabla)v_z\right] = qnE_z - \frac{\partial p}{\partial z}$$

$$\frac{\partial v_z}{\partial t} = \frac{q}{m}E_z - \frac{\gamma KT}{mn}\frac{\partial n}{\partial z}$$

$$\mathbf{E} = -\nabla\phi$$

$$m \longrightarrow 0 \quad q = -e$$

$$qE_z = e\frac{\partial \phi}{\partial z} = \frac{\gamma KT_e}{n}\frac{\partial n}{\partial z}$$

$$n = n_0 \exp\left(e\phi/KT_e\right)$$

Comparison Between Forces

- **Cold plasma**

Approximation: Ignore thermal motion of particles

$$\text{`Cold Plasma'} \qquad \nabla p = 0 \quad (e.g.\ T \simeq 0)$$

$$m_e N_e \left[\frac{\partial \mathbf{u}_e}{\partial t} + (\mathbf{u}_e \cdot \nabla)\mathbf{u}_e \right] = -\nabla p_e + q_e N_e (\mathbf{E} + \mathbf{u}_e \times \mathbf{B})$$

Generally requires wave phase velocity $\gg v_{\text{thermal}}$

Prove it in the H.W.

Summary

Terminology	Concept
Plasma components	????
Time scale	????
Forces in plasma	????
Inertial force	????
Pressure gradient force	????
Ponderomotive force	????
Collisional force	????
Collision frequency and Collision time-scale	????
Comparison between forces	????