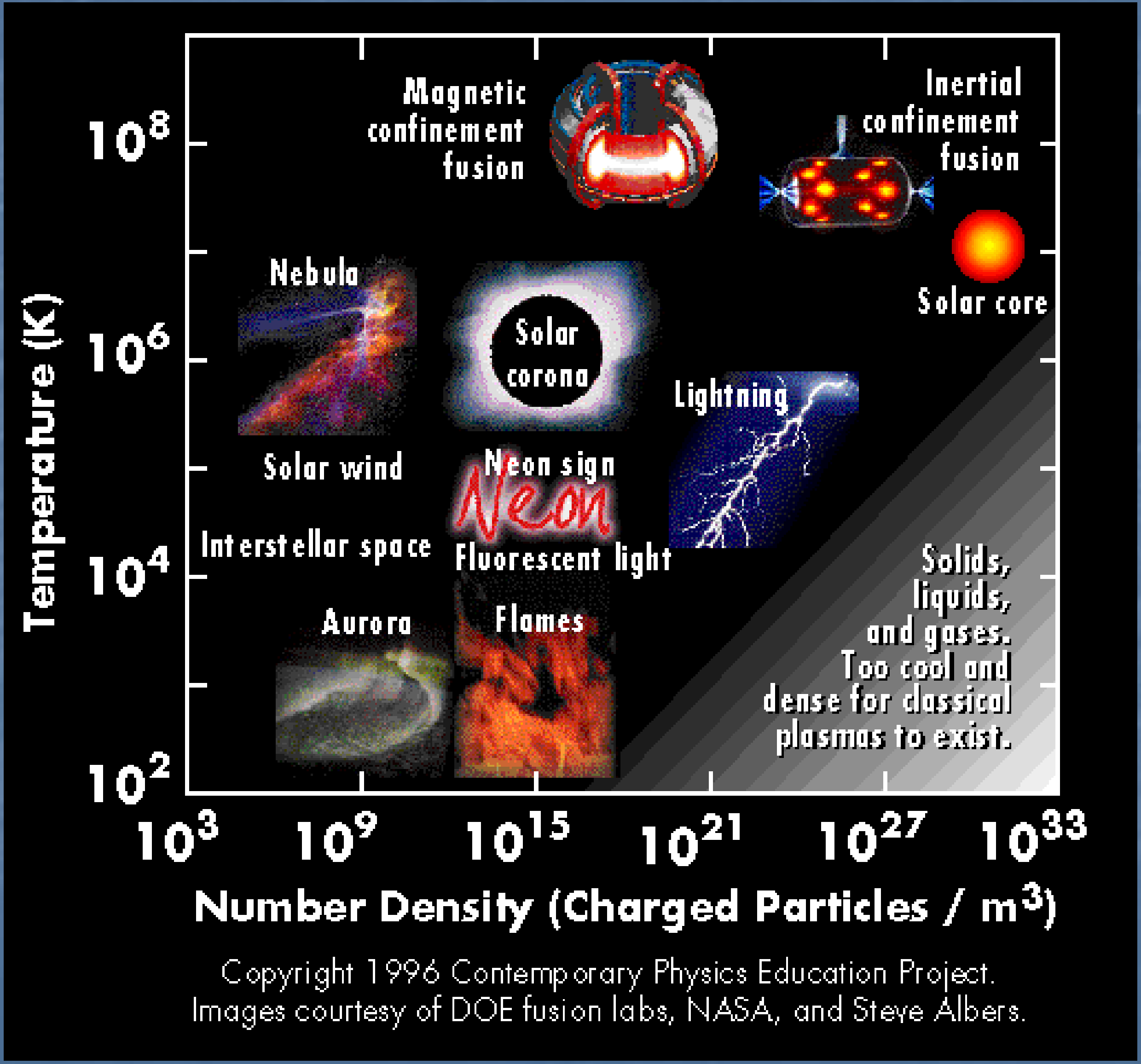
Plasmas



Magnetic confinement fusion
Inertial confinement fusion
Solar core
Nebula
Solar corona
Lightning
Solar wind
Neon sign
Neon
Interstellar space
Fluorescent light
Aurora
Flames
Solids, liquids, and gases. Too cool and dense for classical plasmas to exist.
10^8
10^6
10^4
10^2
Temperature (K)
10^3
10^9
10^{15}
10^{21}
10^{27}
10^{33}
Number Density (Charged Particles / m^3)
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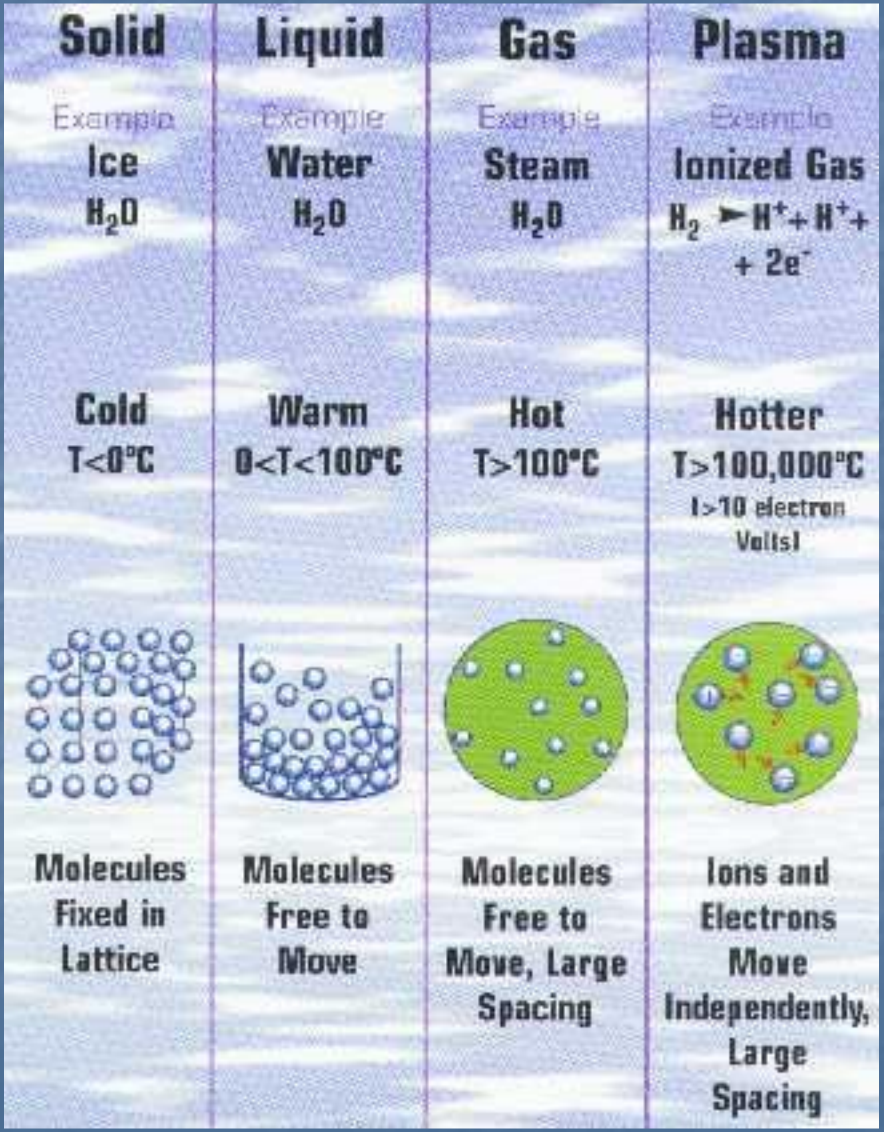
The “Fourth State” of the Matter

- The matter in “ordinary” conditions presents itself in three fundamental states of aggregation: solid, liquid and gas.
- These different states are characterized by different levels of bonding among the molecules.
- In general, by increasing the temperature (=average molecular kinetic energy) a phase transition occurs, from solid, to liquid, to gas.
- A further increase of temperature increases the collisional rate and then the degree of ionization of the gas.

The “Fourth State” of the Matter (II)

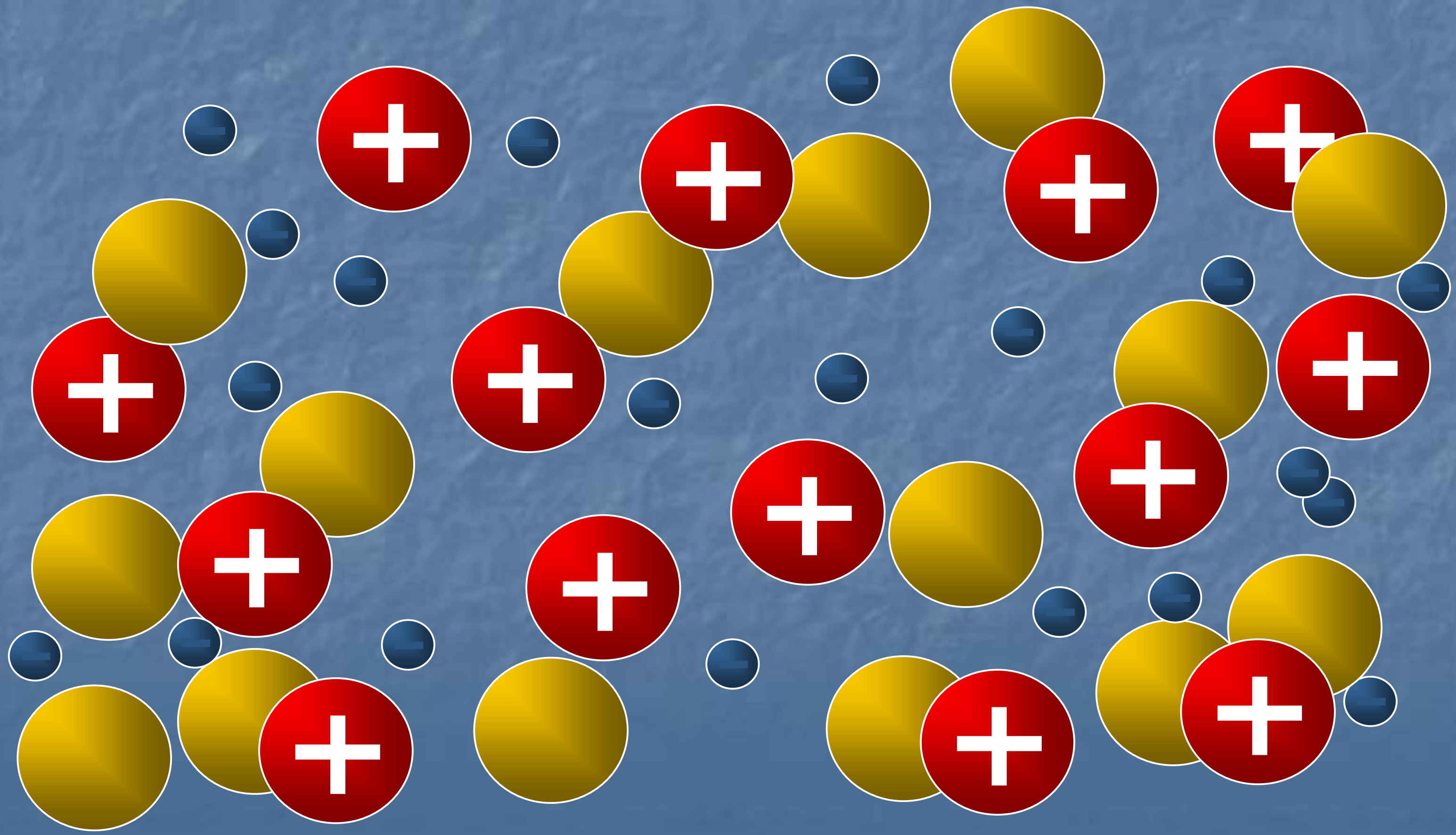
- The ionized gas could then become a plasma if the proper conditions for density, temperature and characteristic length are met (quasineutrality, collective behavior).
- The plasma state does not exhibit a different state of aggregation but it is characterized by a different behavior when subjected to electromagnetic fields.

The "Fourth State" of the Matter (III)



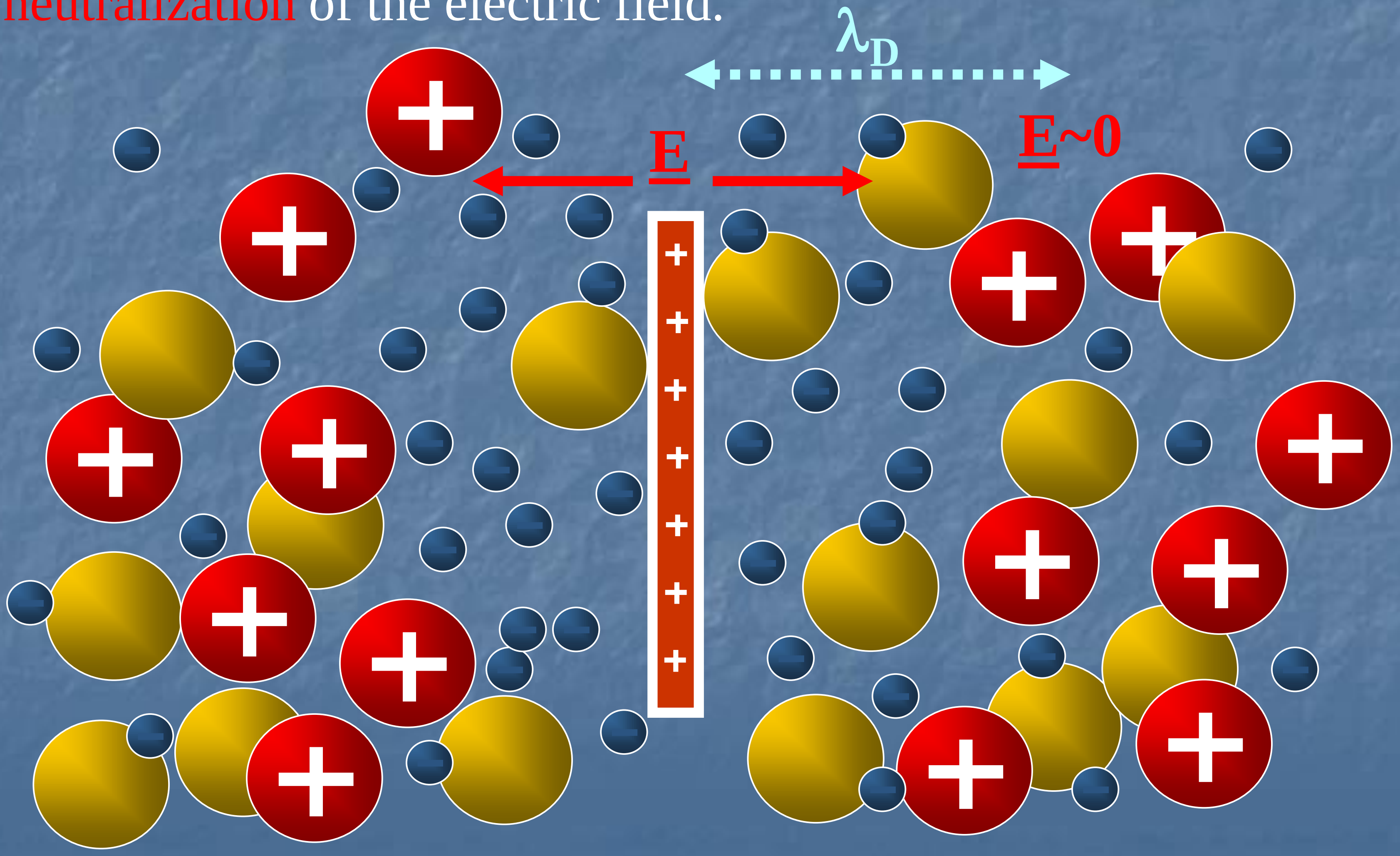
Debye Shielding

- An ionized gas has a certain amount of free charges that can move in presence of electric forces



Debye Shielding (II)

- Shielding effect: the free charges move towards a perturbing charge to produce, at a large enough distance λ_D, (almost) a neutralization of the electric field.



Debye Shielding (IV)

- The quantity

$$\lambda_{De} = \sqrt{\frac{\varepsilon_0 k_B T}{n q_e^2}}$$

  is called the (electron) Debye length of the plasma

- The Debye length is a measure of the effective shielding length beyond which the electron motions are shielding charge density fluctuations in the plasma

Debye Shielding (IV)

- Typical values of the Debye Length under different conditions:

	n [m^{-3}]	T[eV]	Debye Length [m]
Interstellar	10^6	10^{-1}	1
Solar Wind	10^7	10	10
Solar Corona	10^{12}	10^2	10^{-1}
Solar atmosphere	10^{20}	1	10^{-6}
Magnetosphere	10^7	10^3	10^2
Ionosphere	10^{12}	10^{-1}	10^{-3}

From Ionized Gas to Plasma

- An ionized gas is characterized, in general, by a mixture of neutrals, (positive) ions and electrons.
- For a gas in thermal equilibrium the Saha equation gives the expected amount of ionization:

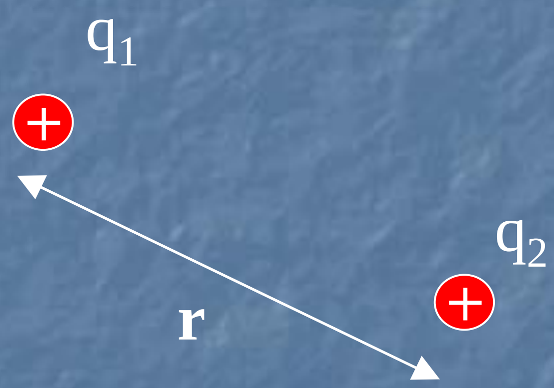
$$n_i^2 \cong 2.4 \cdot 10^{21} n_n T^{3/2} e^{-U_i/k_B T}$$

- The Saha equation describes an equilibrium situation between ionization and (ion-electron) recombination rates.

From Ionized Gas to Plasma (II)

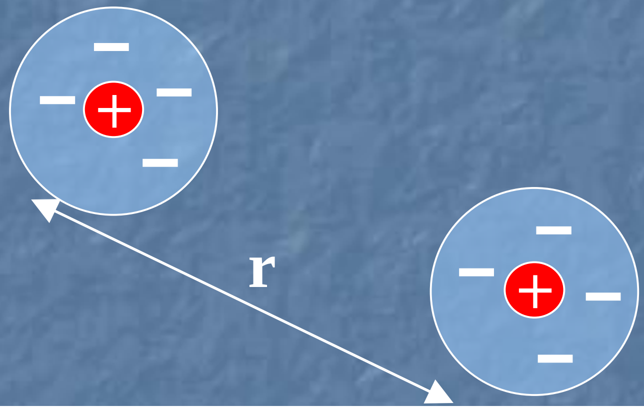
- (Long range) Coulomb force between two charged particles q_1 and q_2 at distance r:

$$F = \frac{q_1 q_2}{4\pi\varepsilon_0 r^2}$$



From Ionized Gas to Plasma (III)

- (Short range) force between two neutral atoms (*e.g.* from Lenard-Jones interatomic potential model)



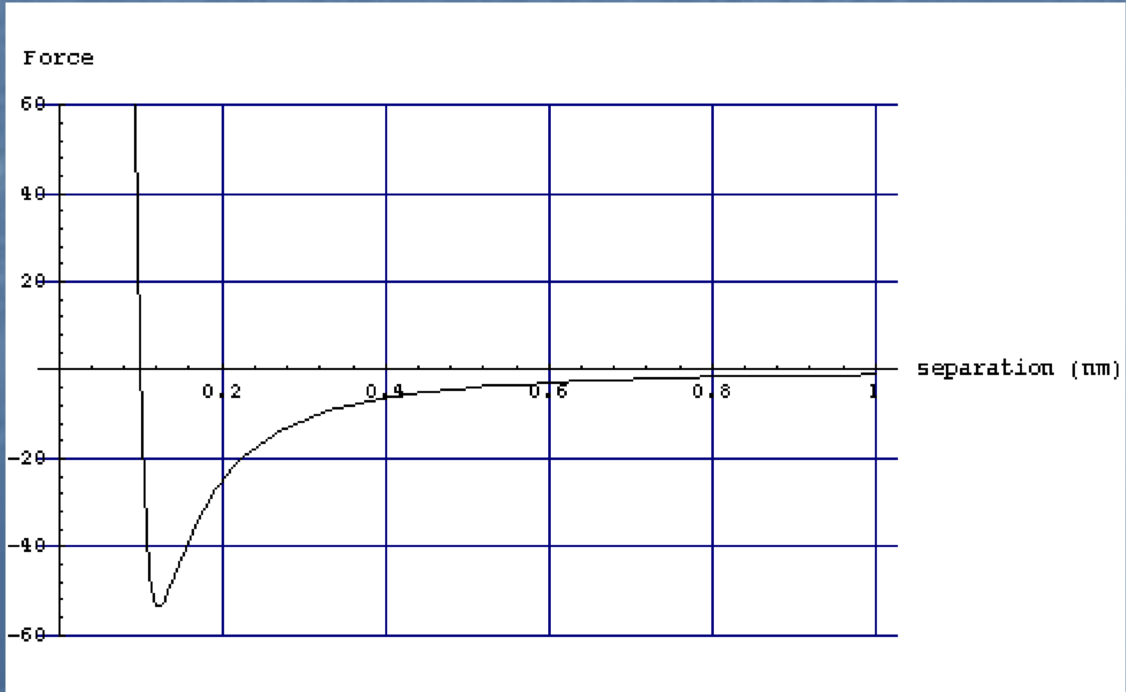
$$U = 4\varepsilon\left[\left(\frac{\sigma}{r}\right)^{12} - \left(\frac{\sigma}{r}\right)^{6}\right]$$

$$\mathbf{F} = -\nabla U$$

$$\mathbf{F} = 4\varepsilon\left[12\left(\frac{\sigma}{r}\right)^{12} - 6\left(\frac{\sigma}{r}\right)^{6}\right]\frac{\hat{\mathbf{r}}}{r^2}$$

repulsive

attractive



From Ionized Gas to Plasma

- If L is the typical dimension of the ionized gas, a condition for an ionized gas to be "quasineutral" is:

$$\lambda_D << L$$

- The "collective effects" are dominant in an ionized gas if the number of particles in a volume of characteristic length equal to the Debye length (Debye sphere) is large:

$$N_D = n\frac{4}{3}\pi\lambda_D^3 >> 1$$

- N_D is called "plasma parameter"

From Ionized Gas to Plasma (II)

- A plasma is an ionized gas that is "quasineutral" and is dominated by "collective effects" is called a plasma:

$$\lambda_D << L$$

$$N_D = n\frac{4}{3}\pi\lambda_D^3 >> 1$$

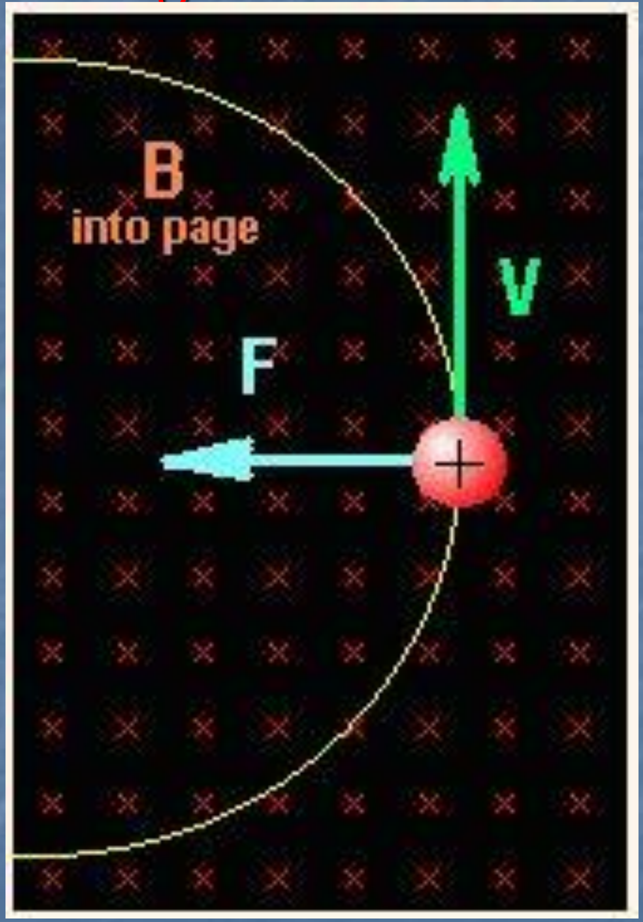
From Ionized Gas to Plasma (III)

- An ionized gas is not necessarily a plasma
- An ionized gas can exhibit a "collective behavior" when the long-range electric forces are sufficient to maintain overall neutrality
- An ionized gas could appear quasineutral if the charge density fluctuations are contained in a limited region of space
- A plasma is an ionized gas that exhibits a collective behavior and is quasineutral

Plasma Confinement: the Lorentz Force

Force on a charged particle in a magnetic field

<u>F</u> = q **<u>v</u>** x **<u>B</u>**



Plasma Confinement: the Magnetic Mirror

Magnetic Mirror: charged particles (protons and electrons) move in helical orbits at their cyclotron frequency