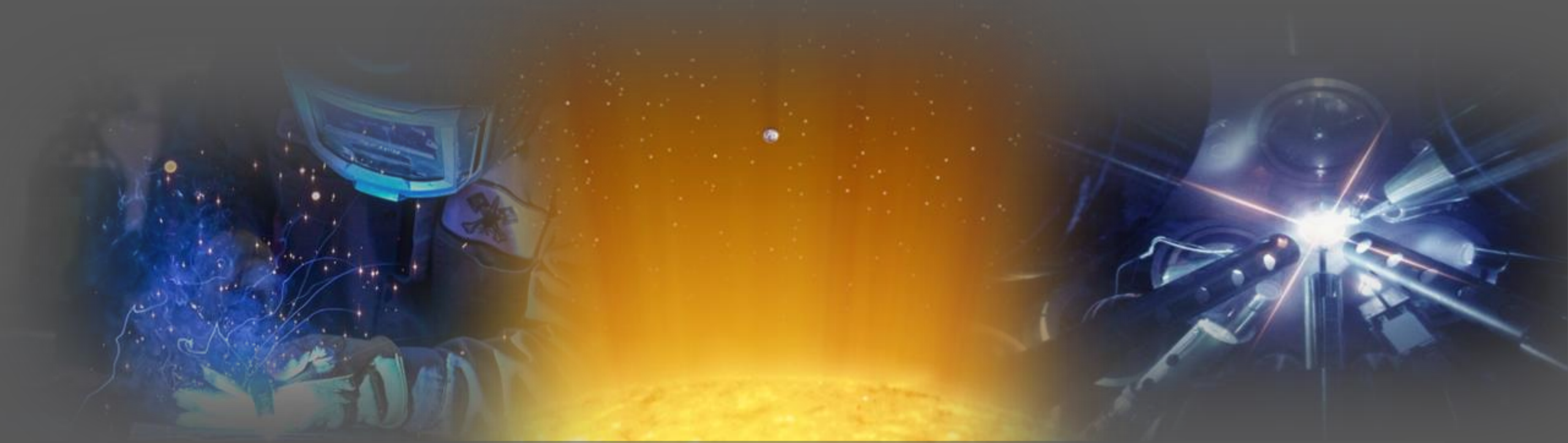

Introduction to Plasma Physics

Carlos Cartagena-Sanchez
Department of Physics and Astronomy
Beloit College

SULI Introductory Plasma and Fusion 2025 Course

June 2 – June 13

Outline

- Who am I?

- My Goals: (Define a Plasma & Introduce you to Plasma Physics)
  - Plasma as the 4^{th} state of matter
  - Provide Examples of Plasmas: Science and Applications
  - Plasma Criteria
  - Influence of the Magnetic Fields

- Summary

Work by Nzeemin from https://commons.wikimedia.org/wiki/File:Relief_Map_of_Caribbean.png with UploadWizard

INTERNATIONAL CYCLOPÆDIA

WCU
WEST CHESTER
UNIVERSITY

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BRYN MAWR COLLEGE

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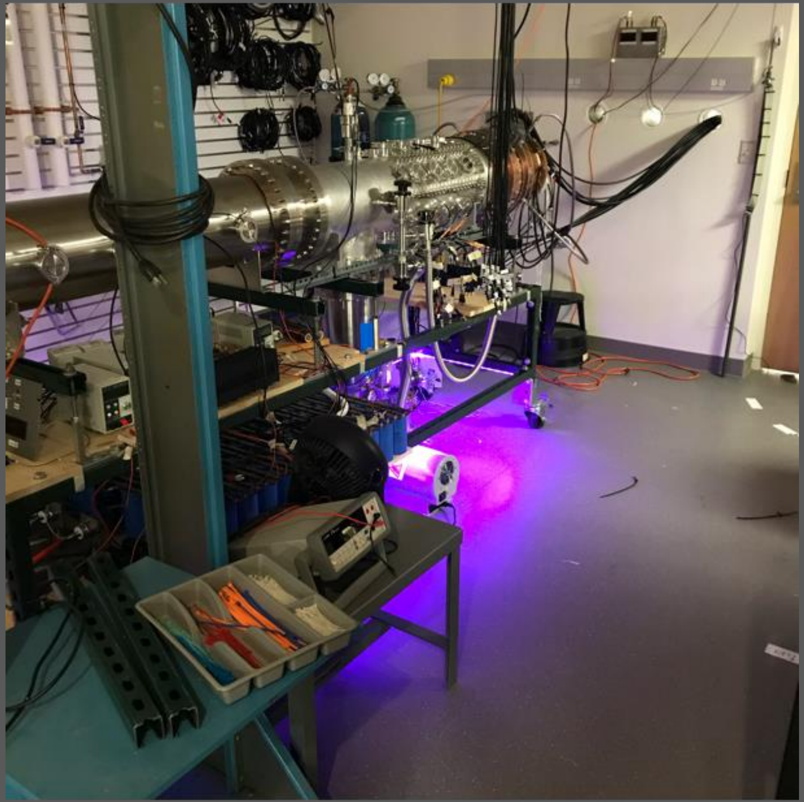

Beloit College

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My Values

- Continue to Learn

- Everyone has something to teach you

- Cherish the world

- Change the culture of individualism

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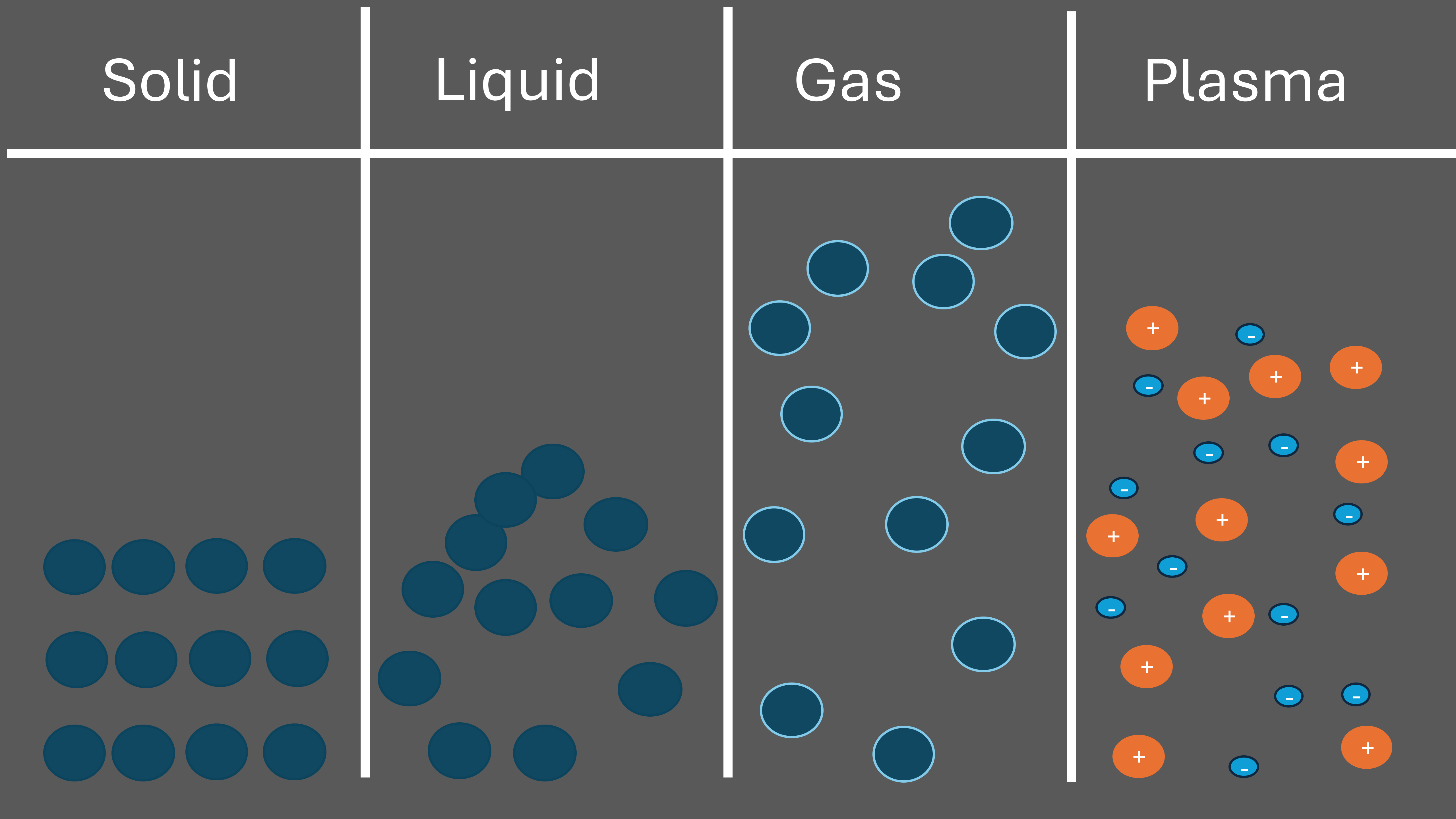
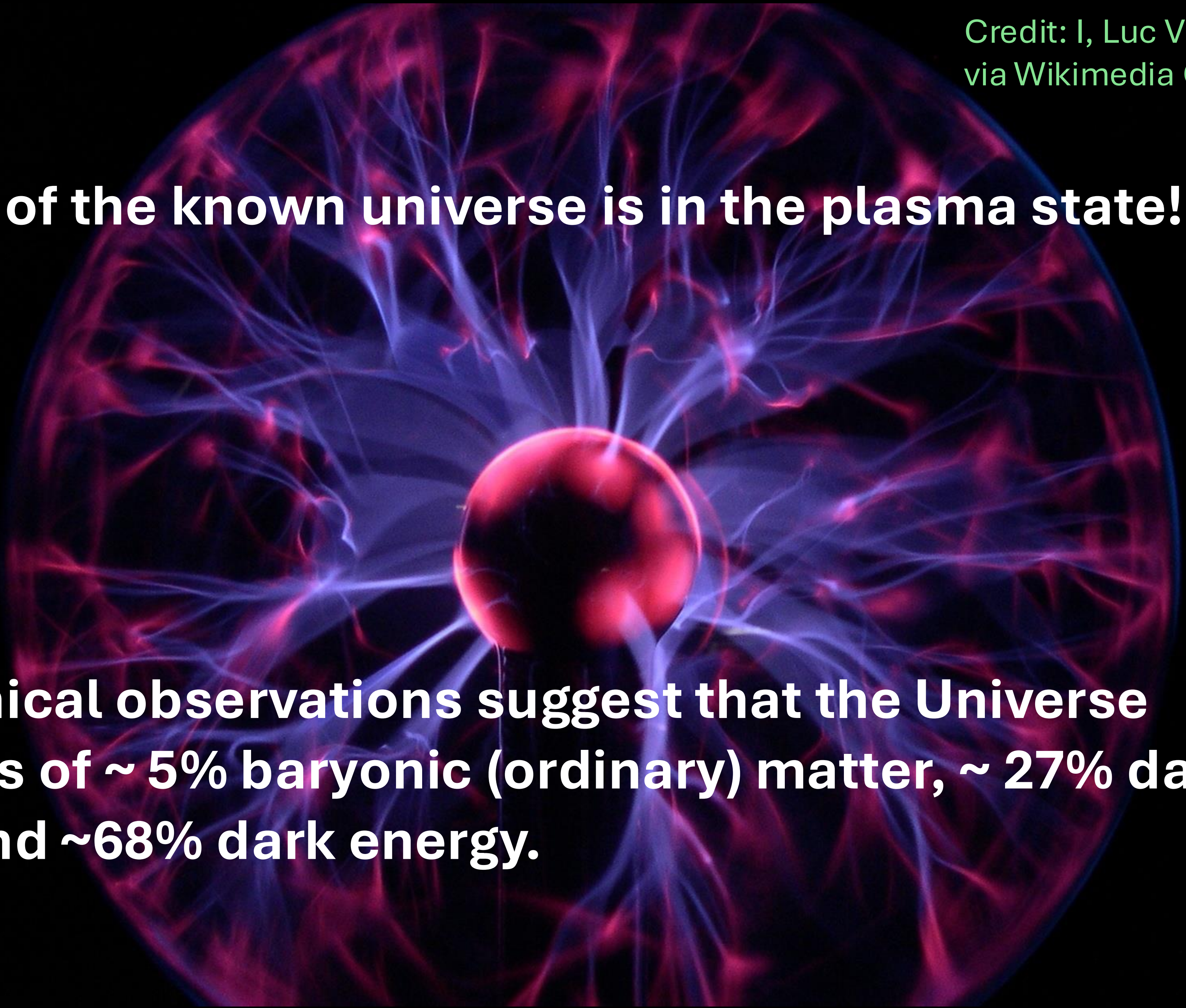

Solid
Liquid
Gas
Plasma

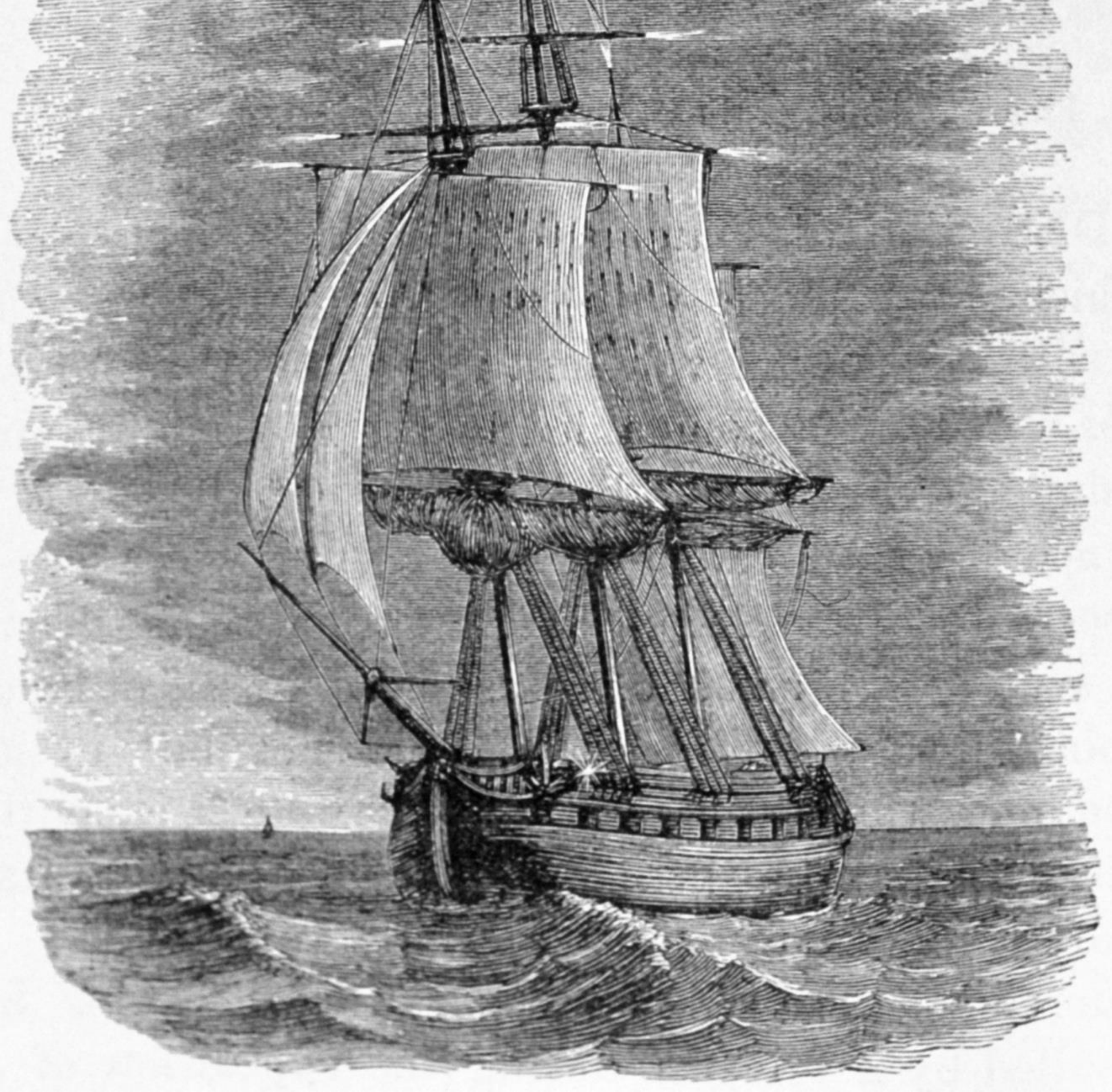


- **Over 99% of the known universe is in the plasma state!**

- **Astronomical observations suggest that the Universe comprises of ~ 5% baryonic (ordinary) matter, ~ 27% dark matter, and ~68% dark energy.**

Lightning

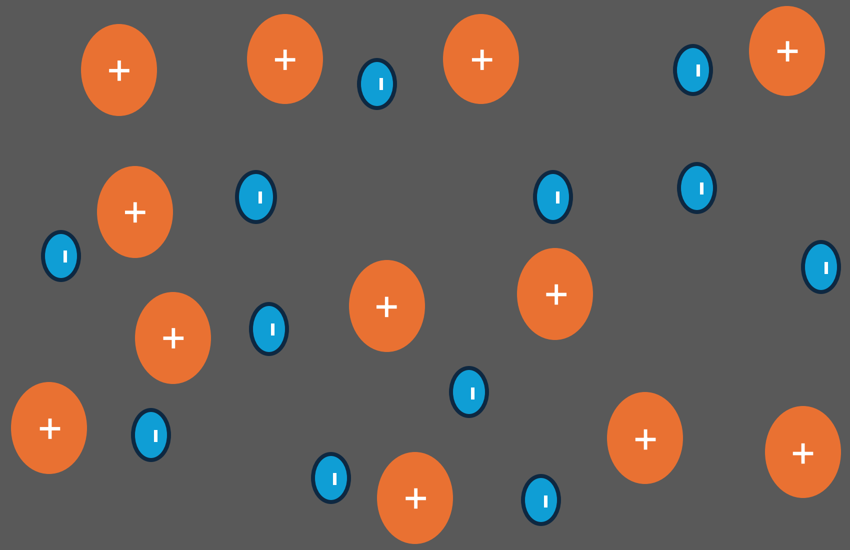
NOAA Photo Library, Public domain, via Wikimedia Commons



St. Elmo’s Fire

Author unknown, derivative work of Saibo, Public domain, Wikicommons

Plasma is the 4^{th} state of matter, but can we be more specific?



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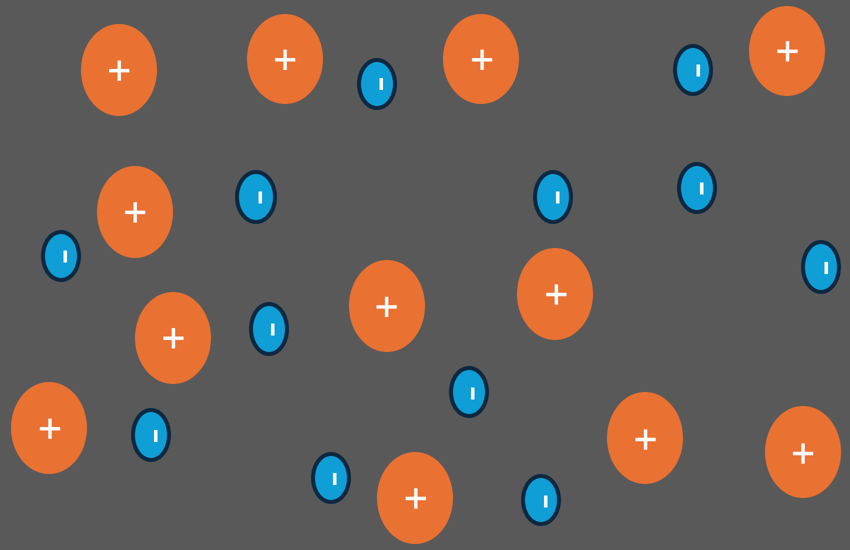


"Physical systems whose intrinsic properties are governed by collective interactions of large ensembles of free charged particles"

- NSF Basic Plasma Science and Engineering Website

Free charged particles

Large Ensembles

Collective Behavior (Collective Interactions)

Great Conductors

Long-range Interactions

Free charged particles

Large Ensembles

Collective Behavior (Collective Interactions)

Great Conductors

Long-range Interactions

Coordinate Motions

Waves

Debye shielding

Magnetic Reconnection

Free charged particles

Large Ensembles

Collective Behavior (Collective Interactions)

Great Conductors

Coordinate Motions

Long-range Interactions

Waves

Electrodynamics

Statistical Mechanics

Debye shielding

Much More

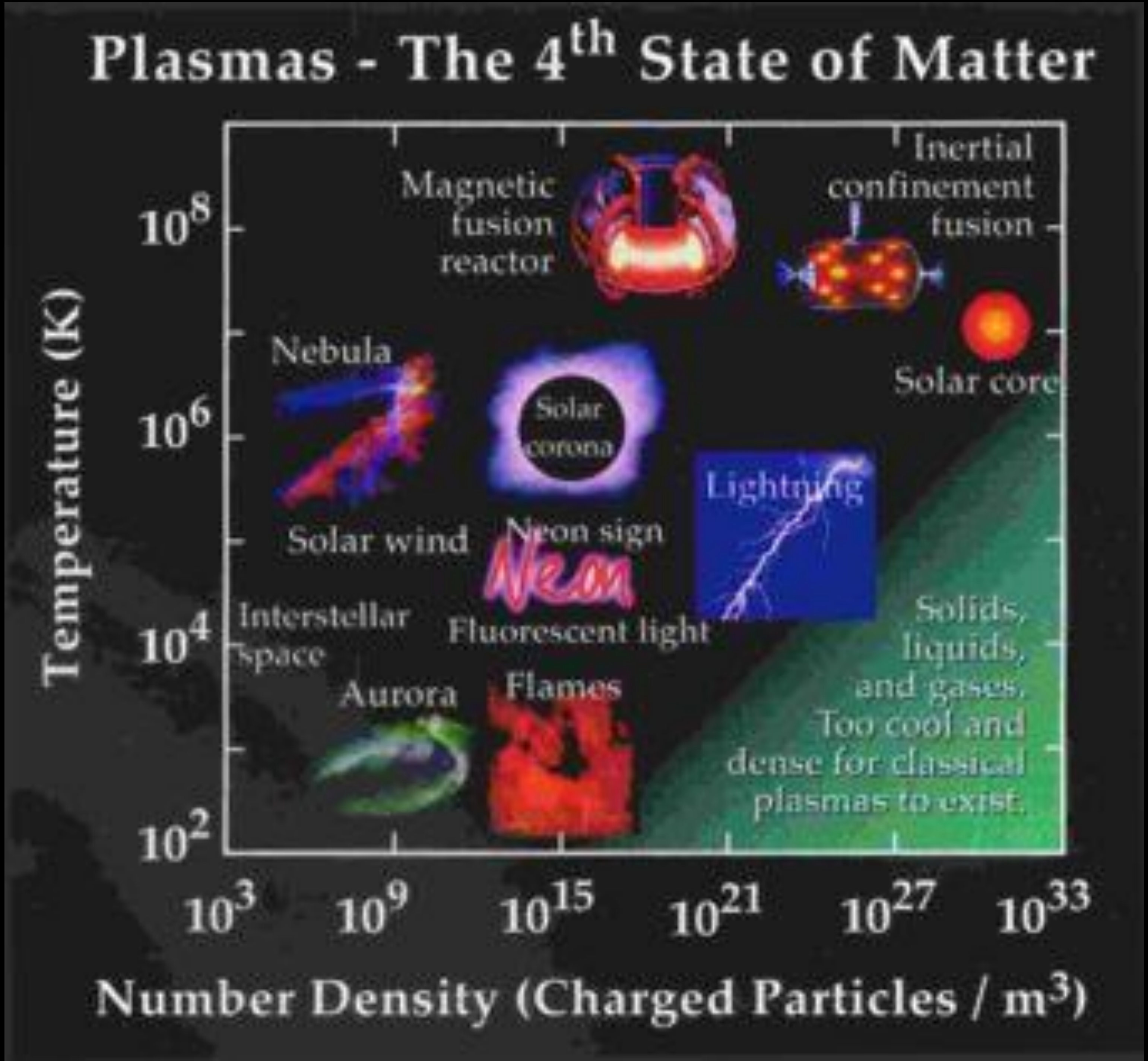
Fluid Mechanics

Magnetic Reconnection

Plasmas are systems that comprise of large ensembles of free charged particles that exhibit collective motions.

"Physical systems whose intrinsic properties are governed by collective interactions of large ensembles of free charged particles"

- NSF Basic Plasma Science and Engineering Website


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

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Welcome

Plasma Science and Engineering

Welcome

Plasma Science and Engineering

Multidisciplinary Field

Welcome

Plasma Science and Engineering

Multidisciplinary Field

Biology/Medicine   Physics   Chemistry

Space/Astronomy   Engineering   Computing

Welcome

Plasma Science and Engineering

Multidisciplinary Field

Biology/Medicine

Welcome

Plasma Science and Engineering

Multidisciplinary Field

Biology/Medicine

Sterilization

Wound Healing

Soil Remediation

Plant Growth

Welcome

Plasma Science and Engineering

Multidisciplinary Field

Physics

Welcome

Plasma Science and Engineering

Multidisciplinary Field

Physics

Turbulence

Instabilities and Waves

Heating & Resonances

Reconnection

Welcome and Thank you

Plasma Science and Engineering

Multidisciplinary Field

Chemistry

Welcome and Thank you

Plasma Science and Engineering

Multidisciplinary Field

Chemistry

Catalysis

Surface Etching

Carbone Capture

Welcome and Thank you

Plasma Science and Engineering

Multidisciplinary Field

Space/Astronomy

Welcome and Thank you

Plasma Science and Engineering

Multidisciplinary Field

Space/Astronomy

Jets and Shocks

Solar Wind

Accretion Disks

Coronal Mass Ejections

Welcome and Thank you

Plasma Science and Engineering

Multidisciplinary Field

Engineering

Welcome and Thank you

Plasma Science and Engineering

Multidisciplinary Field

Engineering

Controlled Fusion

Ultra-Fast Lasers

Material Science

Particle Accelerators

Welcome and Thank you

Plasma Science and Engineering

Multidisciplinary Field

Computing

Welcome and Thank you

Plasma Science and Engineering

Multidisciplinary Field

Computing

Machine Learning/Artificial Intelligence

High-Performance Computing

Challenges in Plasma Science

- Understanding and predicting plasma behaviors under extreme conditions
- Quantify, and in the laboratory, control how plasma processes direct the conversion of energy from one form to another, the transfer of energy across scales, and the transport of energy in the laboratory and nature.
- Predict self-organization of plasmas and, where needed, control that self-organization.
- Control and predict interactions between plasmas and solids, liquids and neutral gases.

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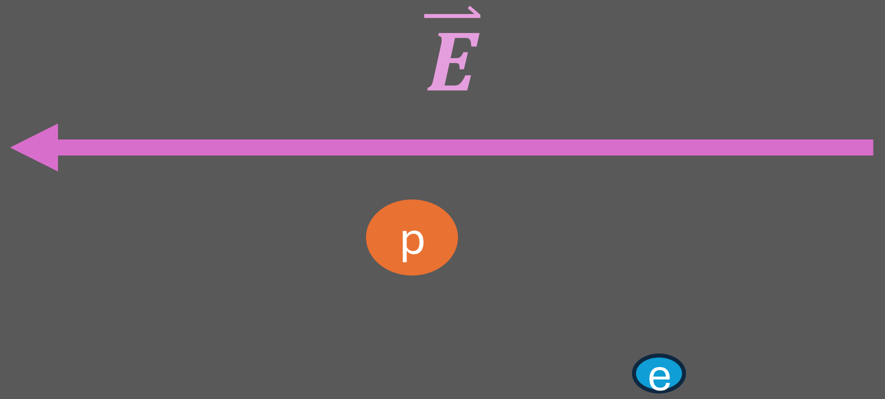
Plasmas:

Electrons and ions behave differently (The masses are drastically different)



$$\vec{F} = q\vec{E}$$

Electric force

$$\vec{F} = m\vec{a}$$

Newton's 2nd Law

Plasmas:

Electrons and ions behave differently (The masses are drastically different)

$$m\vec{a} = q\vec{E}$$

$$|\vec{a}_e| = \frac{e\vec{E}}{m_e}$$

$$|\vec{a}_p| = \frac{e\vec{E}}{m_p}$$

Plasmas:

Electrons and ions behave differently (The masses are drastically different)

$$|\vec{a}_e| = \frac{e\vec{E}}{m_e}$$

$$|\vec{a}_p| = \frac{e\vec{E}}{m_p}$$

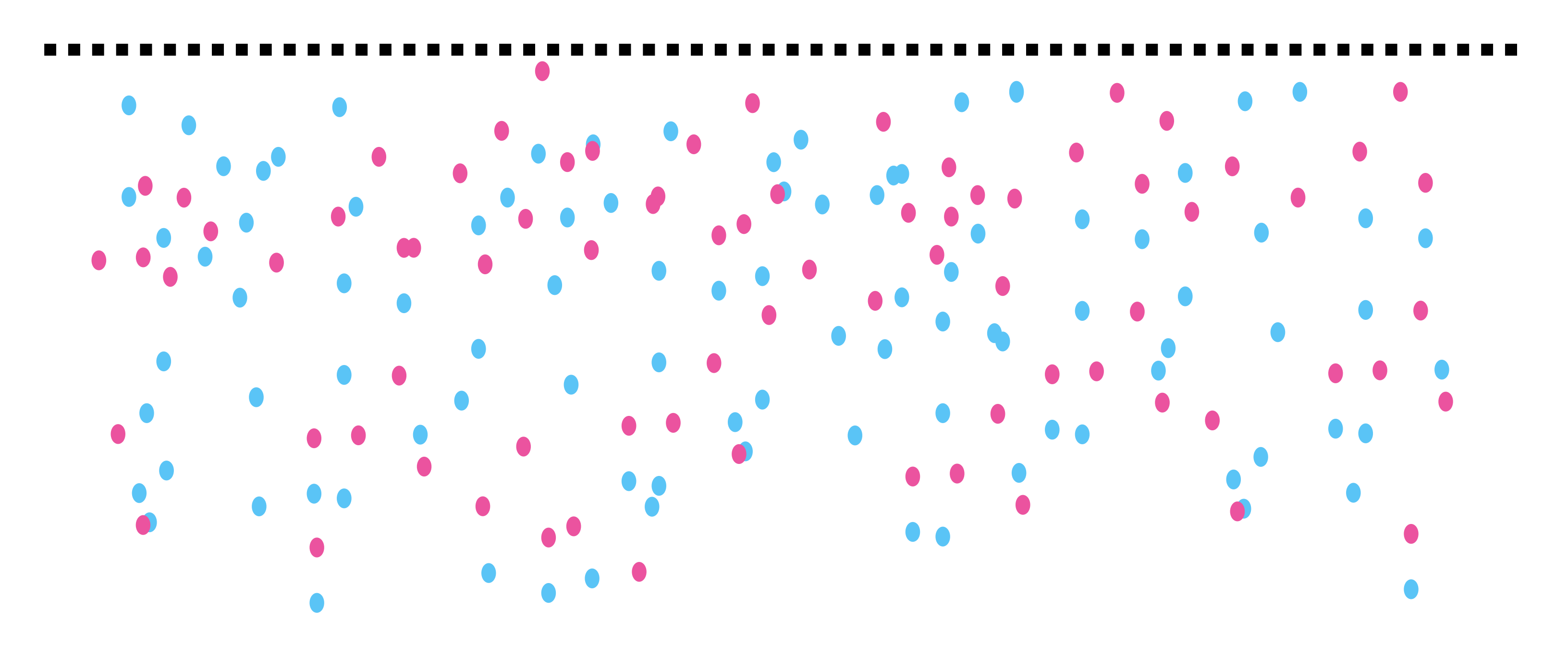
$$m_p \approx 2000 m_e$$

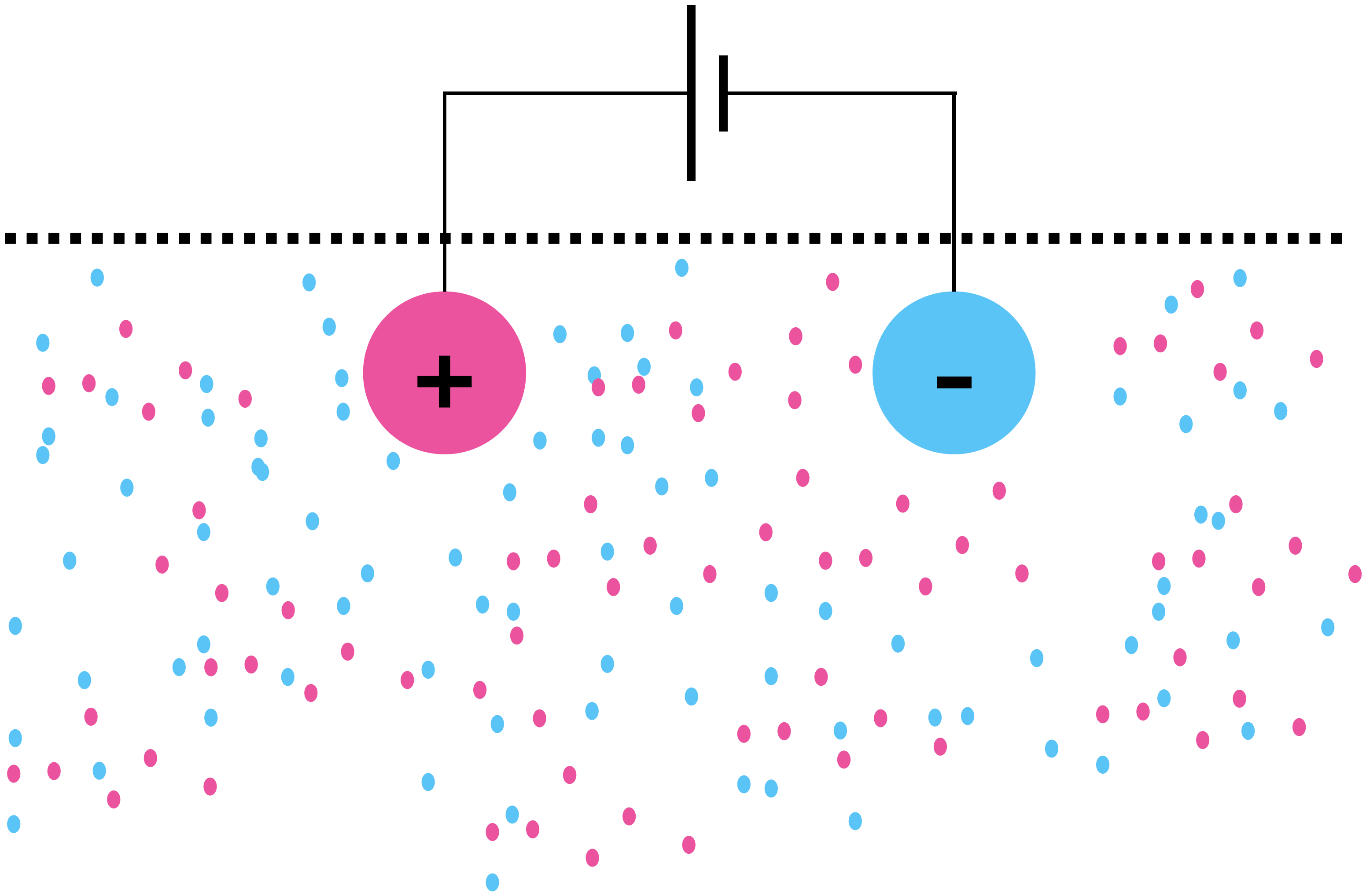
$$|\vec{a}_e| = 2000|\vec{a}_p|$$

Problem:

Consider a hydrogen plasma where both the ions and electrons are in thermal equilibrium ($T_e = T_i$). Estimate the ratio of the velocities ($^{v_e}/_{v_i}$)?

Criteria for Plasmas

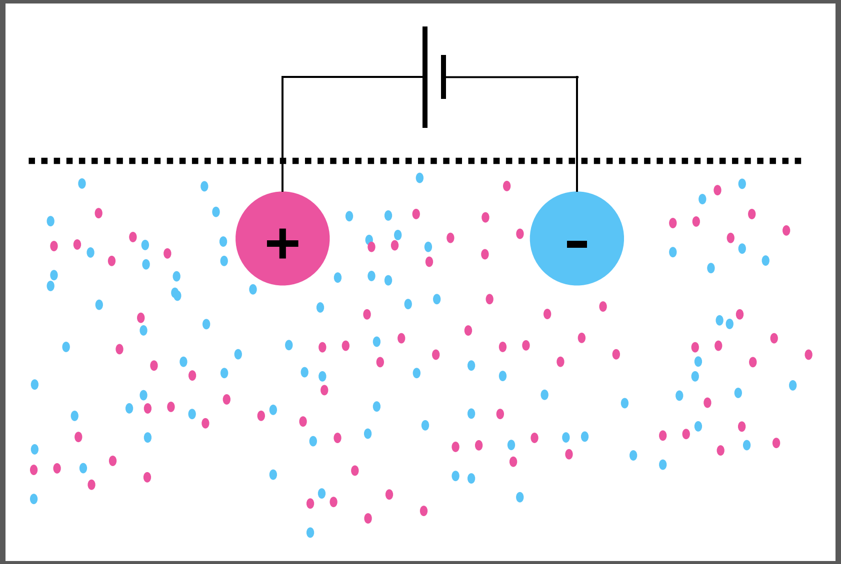




Assume that only the electrons respond, and ions are stationary.

i.e. the ion number density remains unchanged

$$n_i = n_o$$



Since we assume we are in thermal equilibrium the electron density follows the Boltzmann distribution

$$n_e = n_o e^{e\varphi/k_B T_e}$$

k_b - Boltzmann constant

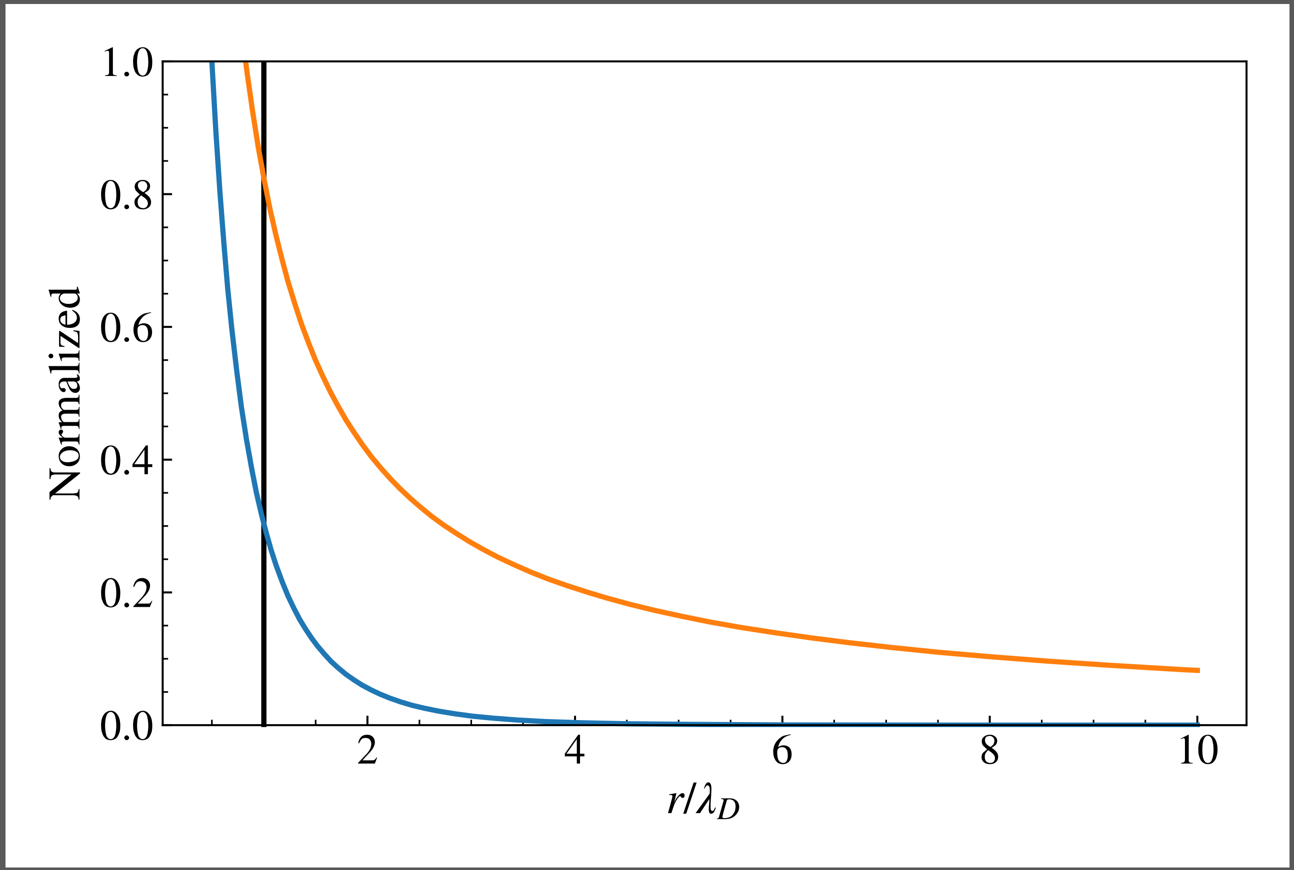
$$T[°K] \longrightarrow k_B T[eV]$$

$$11600°K \sim 1eV$$

$$\nabla^2\varphi = \frac{1}{r}\frac{\partial^2(r\varphi)}{\partial r^2} = \frac{-e}{\varepsilon_o}(n_i - n_e)$$

Poisson Equation

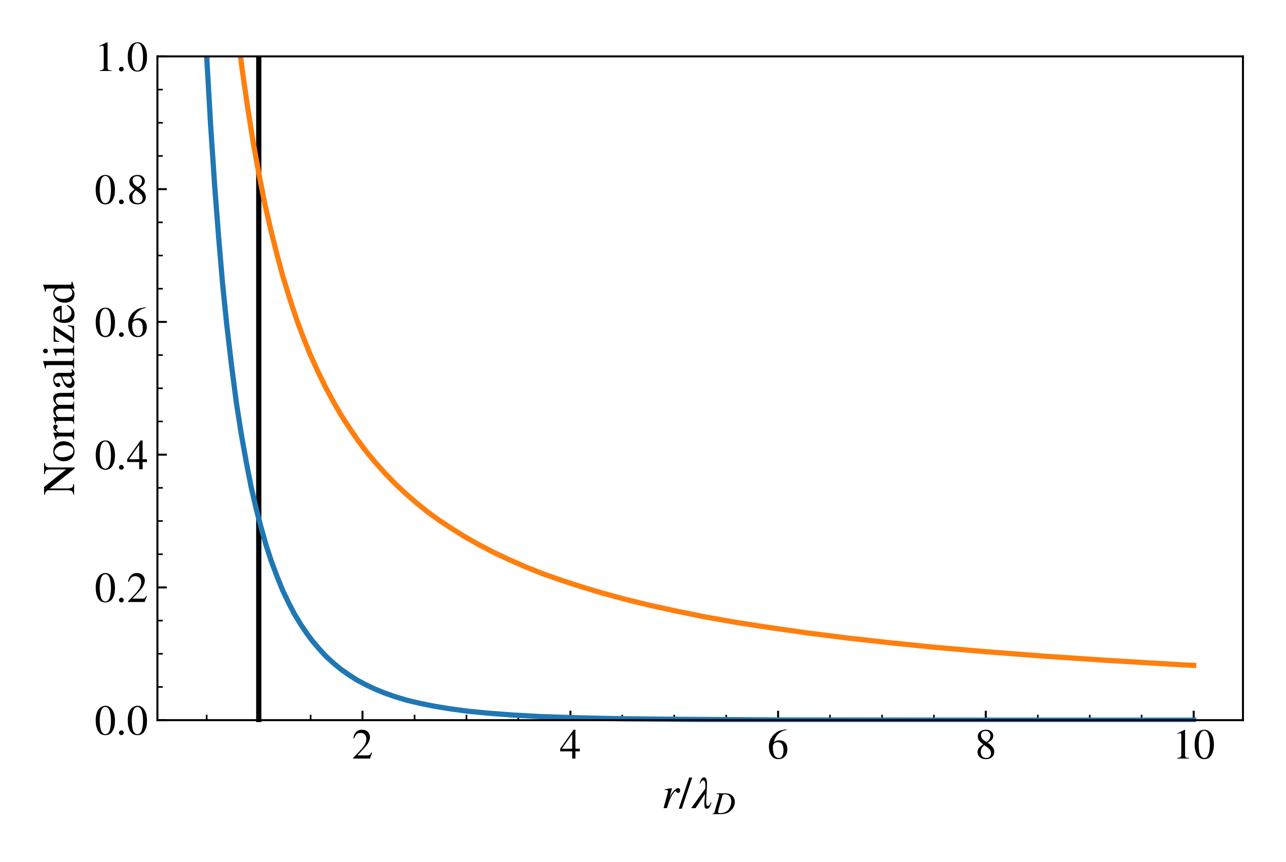
$$\varphi_D \propto \frac{e^{-r/\lambda_D}}{r}$$



Electron Distribution around the potential perturbation

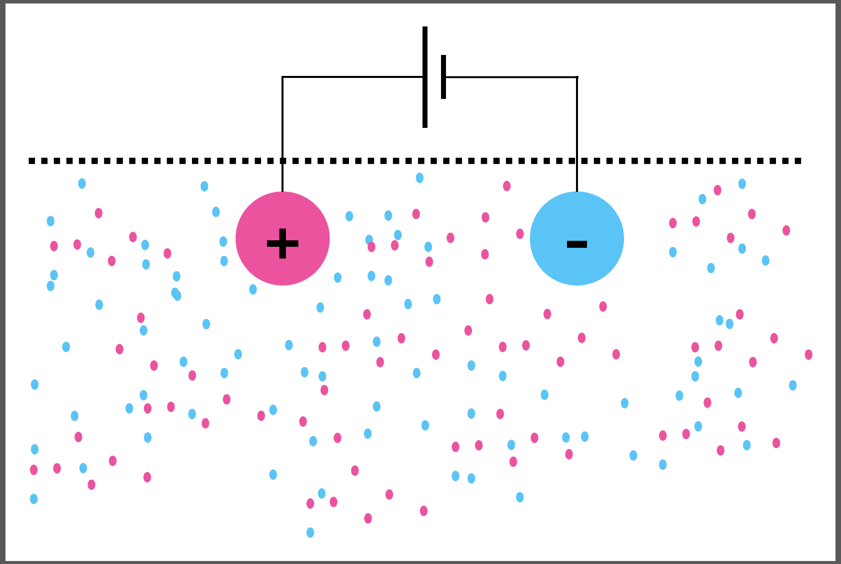
$$\varphi_D \propto \frac{e^{-r/\lambda_D}}{r}$$

$$\lambda_D = \left(\frac{\epsilon_o k_B T_e}{e^2 n_e}\right)^{1/2}$$



In running through this situation there were implicit assumptions:

- The system size (L) is large
- Large number of particles



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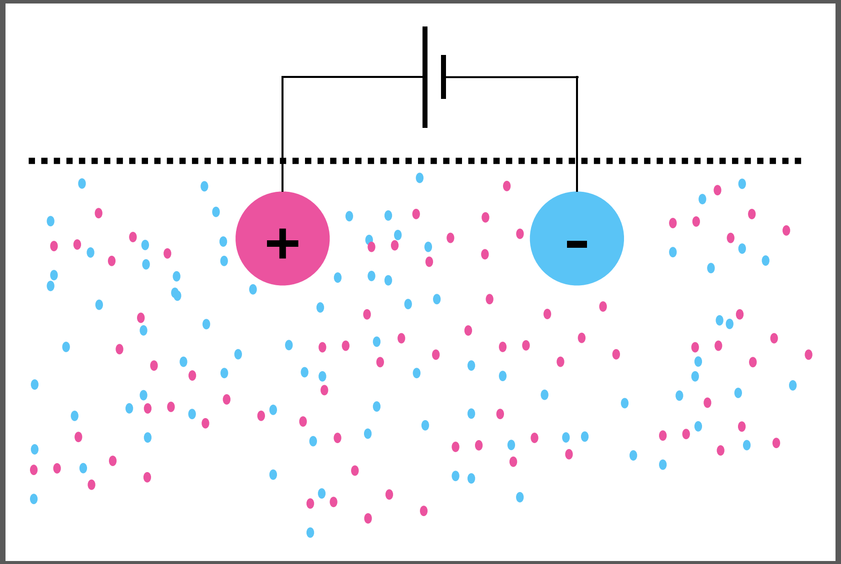


Criteria for Plasmas

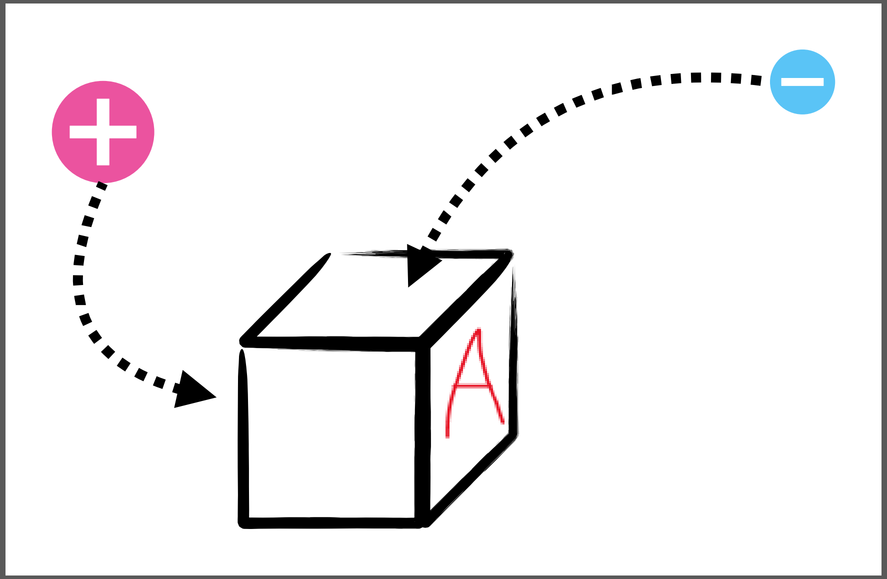
The system size must be much larger than the Deby Length

$$\lambda_D \ll L$$

The number of particles in a Debye sphere must be much larger than unity.

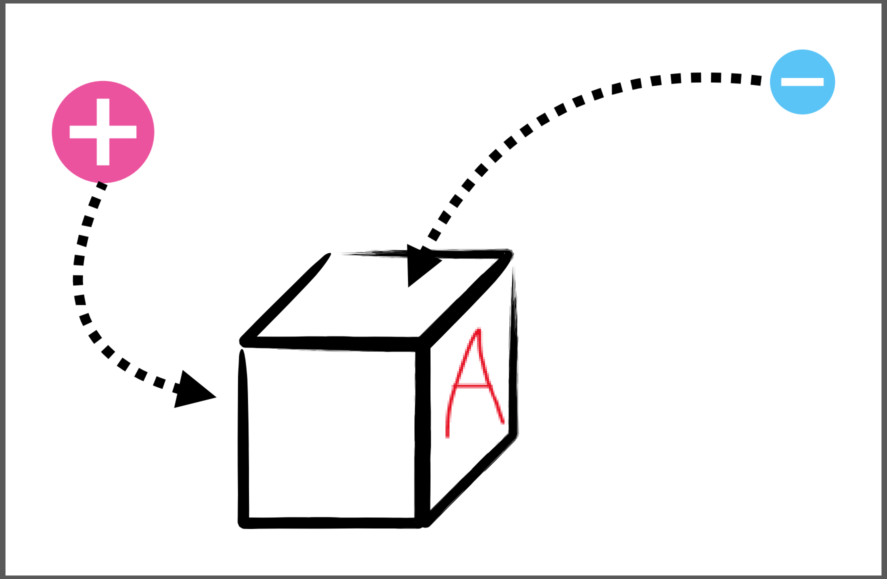
$$N_D \sim n_e \lambda_D^3 \gg 1$$

Plasma Oscillations



Perturbation

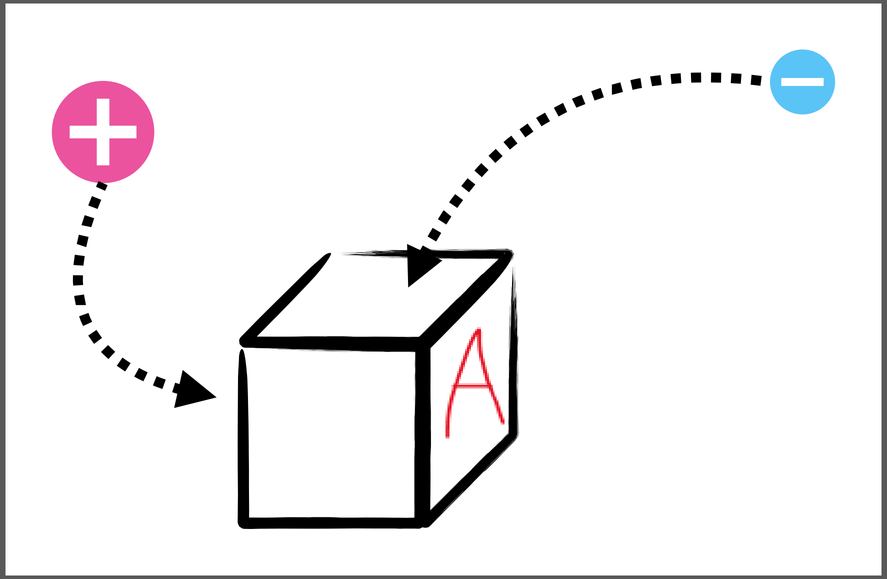
Plasma Oscillations



Perturbation

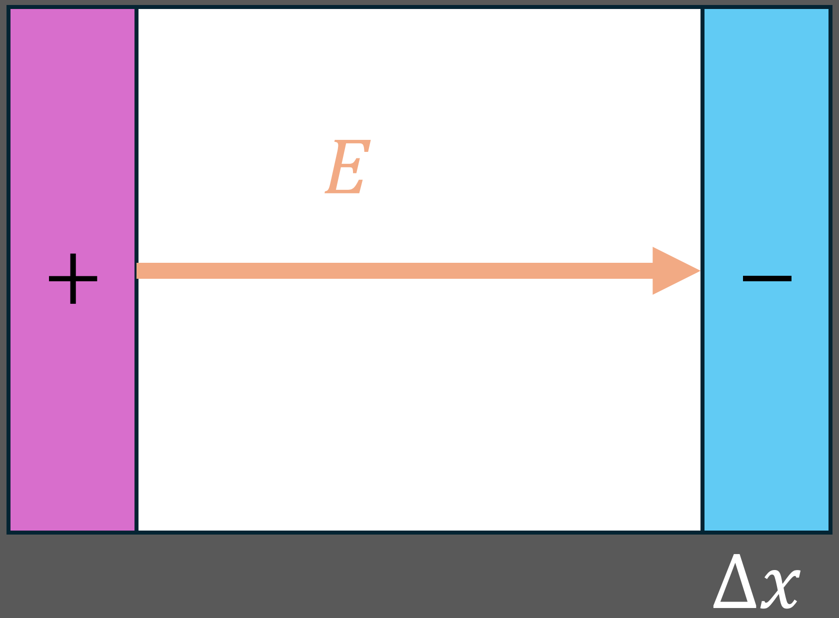
$\Delta x \sim 0$

Plasma Oscillations



Perturbation

Resembles a Capacitor

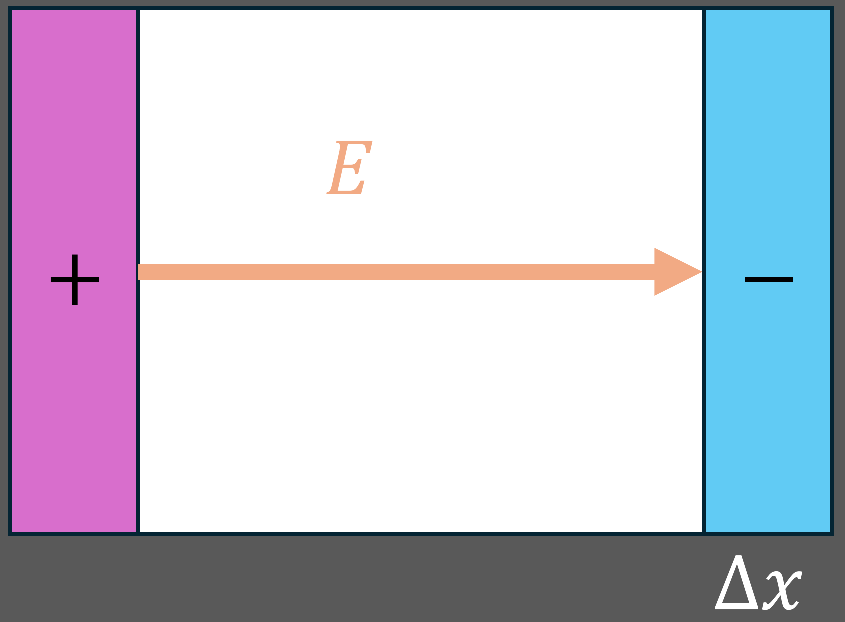


Resembles a Capacitor

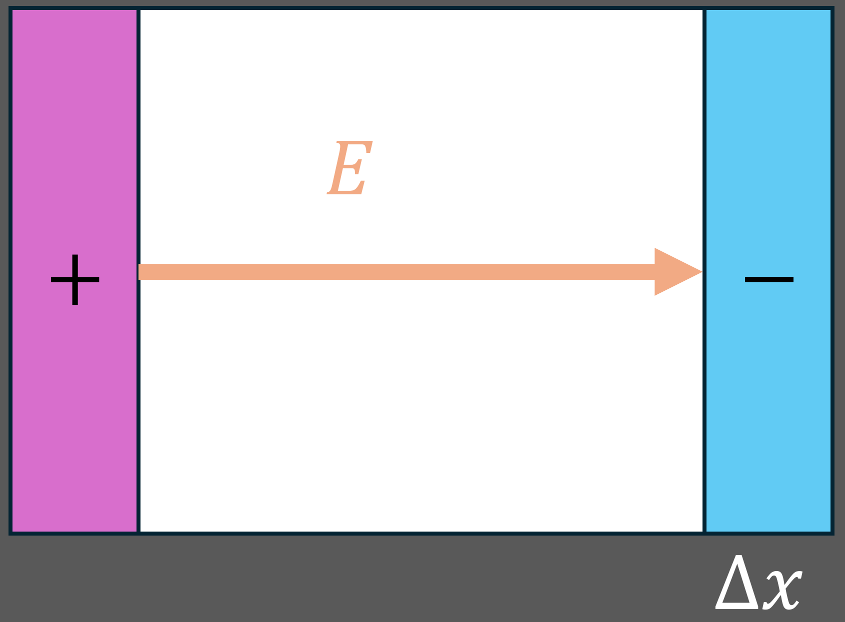
$$E = \frac{\sigma}{\epsilon_o}$$

$$\sigma = en_e \Delta x$$

$$E = \frac{en_e \Delta x}{\epsilon_o}$$



Resembles a Capacitor



$$E = \frac{\sigma}{\epsilon_o}$$

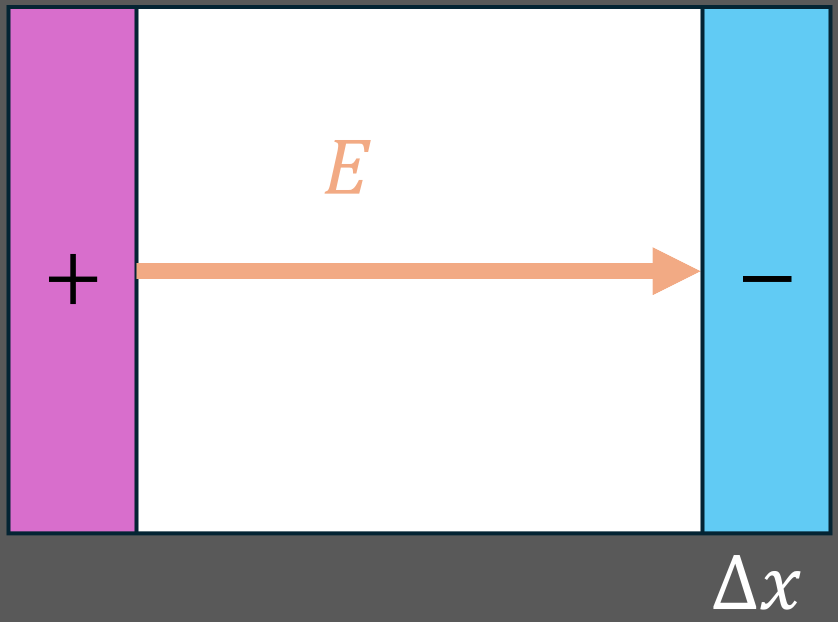
$$\sigma = e n_e \Delta x$$

$$E = \frac{e n_e \Delta x}{\epsilon_o}$$

$$F_{net} = m_e a_e$$

$$F_{net} = -eE$$

Resembles a Capacitor



$$E = \frac{\sigma}{\epsilon_o}$$

$$\sigma = e n_e \Delta x$$

$$E = \frac{e n_e \Delta x}{\epsilon_o}$$

$$F_{net} = m_e a_e = m_e \frac{d^2(\Delta x)}{dt^2}$$

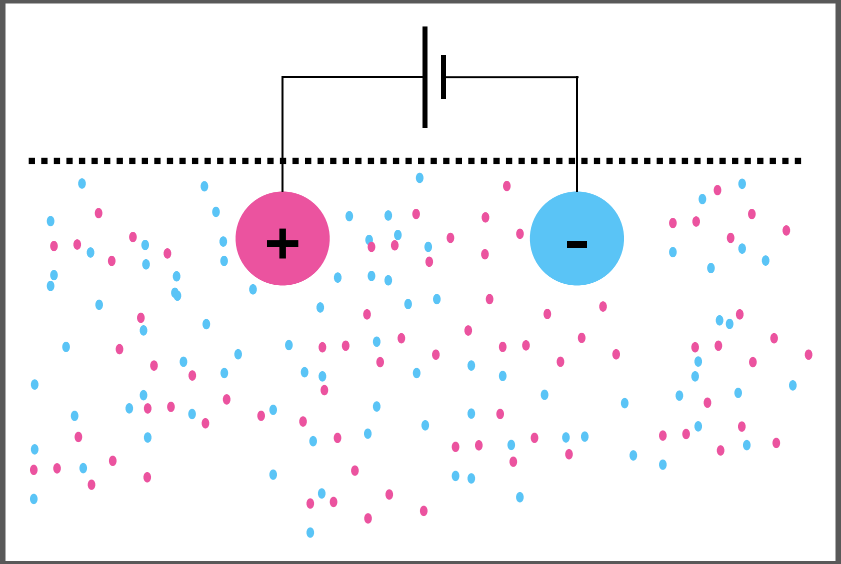
$$F_{net} = -eE$$

$$\frac{d^2(\Delta x)}{dt^2} = -\left(\frac{e^2 n_e}{\varepsilon_o m_e}\right)(\Delta x) = -w_{pe}^2(\Delta x)$$ Simple Harmonic Motion

$$w_{pe} \equiv \left(\frac{e^2 n_e}{\varepsilon_o m_e}\right)^{1/2}$$ Electron plasma frequency

Plasmas try to maintain charge neutrality that result in plasma oscillations

Plasmas try to maintain charge neutrality that result in plasma oscillations



What is the response of the plasma to a disturbance to its charge neutrality?

We know the characteristic screening length is the Debye length

The electrons move with thermal speed

We know the characteristic screening length is the Debye length

$$\lambda_D = \left(\frac{\epsilon_o k_B T_e}{e^2 n_e}\right)^{1/2}$$

The electrons move with thermal speed

$$v_{eT} = \left(\frac{k_B T_e}{m_e}\right)^{1/2}$$

$$t_{response} \sim \frac{\lambda_D}{v_{eT}} = \left(\frac{\epsilon_o k_B T_e}{e^2 n_e} * \frac{m_e}{k_B T_e}\right)^{1/2} = \left(\frac{\epsilon_o m_e}{e^2 n_e}\right)^{1/2} = \frac{1}{w_p}$$

$$t_{response} \sim \frac{1}{w_p}$$

Criteria for Plasmas

- The system size must be much larger than the Deby Length

$$\lambda_D \ll L$$

- The number of particles in a Debye sphere must be much larger than unity.

$$N_D \gg 1$$

- Plasma physics must dominate collisional physics

$$w_p > \nu_{collision}$$

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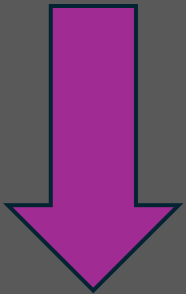
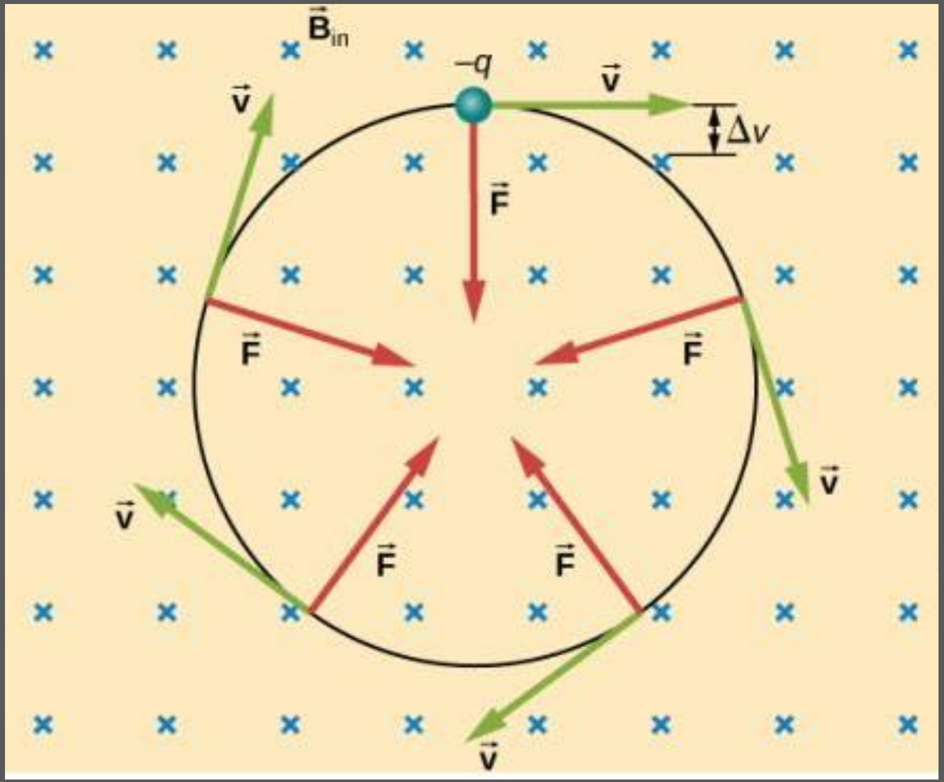
Influence of Magnetic Field

$$F_m = q\vec{v} \times \vec{B}$$

$$F_m = qv_{\perp}B$$



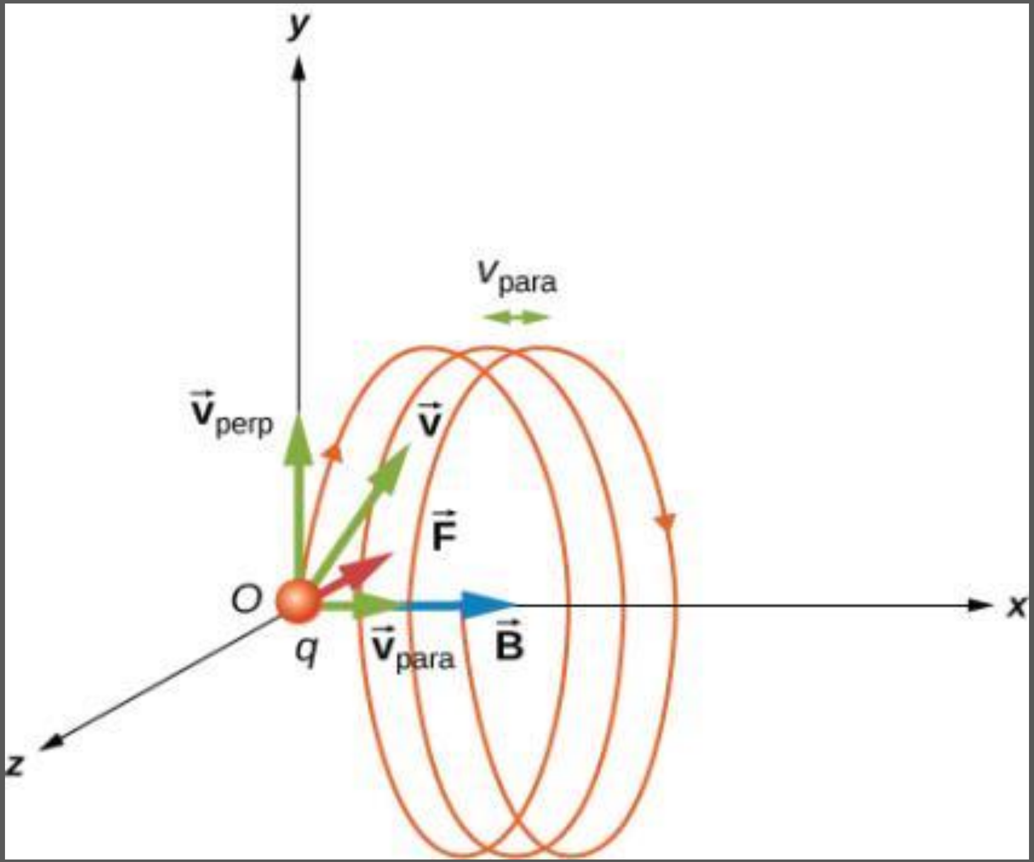
$$w_c = \frac{qB}{m}$$



Influence of Magnetic Field

Charge particles are greatly influenced by magnetic field lines.

- Fields lines effectively restrict plasma particles.
- Provide anisotropic properties to the plasma.



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Plasmas are systems that comprise of large ensembles of free charged particles that exhibit collective motions.

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4^{th} State of Matter:

Comprises 99% of the known universe

Described with thermodynamic variables: n, T, B

Plasmas are systems that comprise of large ensembles of free charged particles that exhibit collective motions.

Span multiple fields of study, for example, but not limited to:

- Biology
- Physics
- Chemistry
- Engineering

Plasmas are systems that comprise of large ensembles of free charged particles that exhibit collective motions.

Criteria

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$$\lambda_D = \left(\frac{\epsilon_o k_B T_e}{e^2 n_e}\right)^{1/2} \qquad w_{pe} \equiv \left(\frac{e^2 n_e}{\varepsilon_o m_e}\right)^{1/2} \qquad w_c = \frac{qB}{m}$$

- Introduction to Plasma Physics and Controlled Fusion,

F.F. Chen

- Fundamentals of Plasma Physics

Paul M. Bellan

- Fundamentals of Plasma Physics,

J. A. Bittencourt

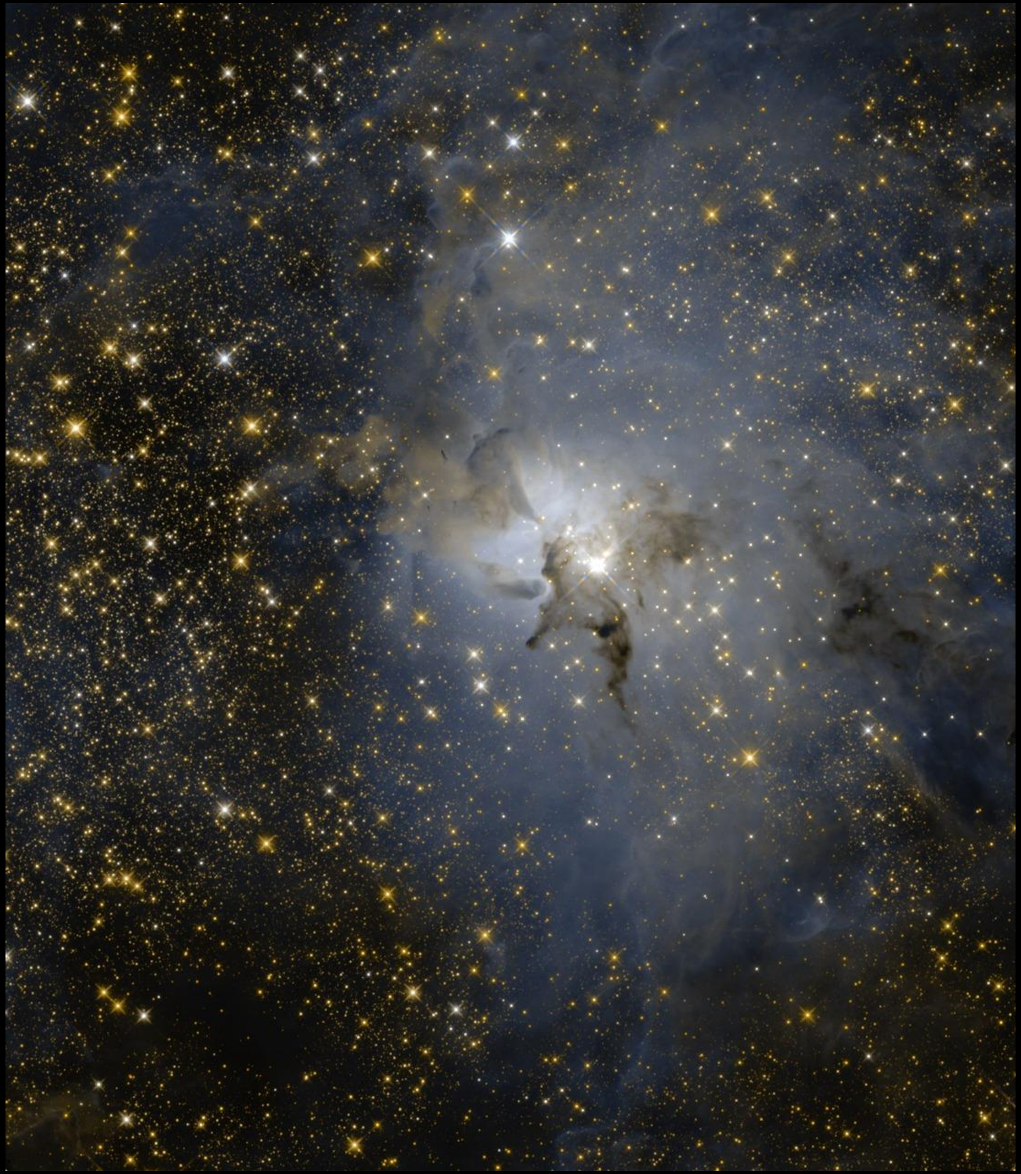
- National Academies of Sciences, Engineering, and Medicine. 2021. *Plasma Science: Enabling Technology, Sustainability, Security, and Exploration*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25802.

- https://arxiv.org/pdf/2007.04783v1

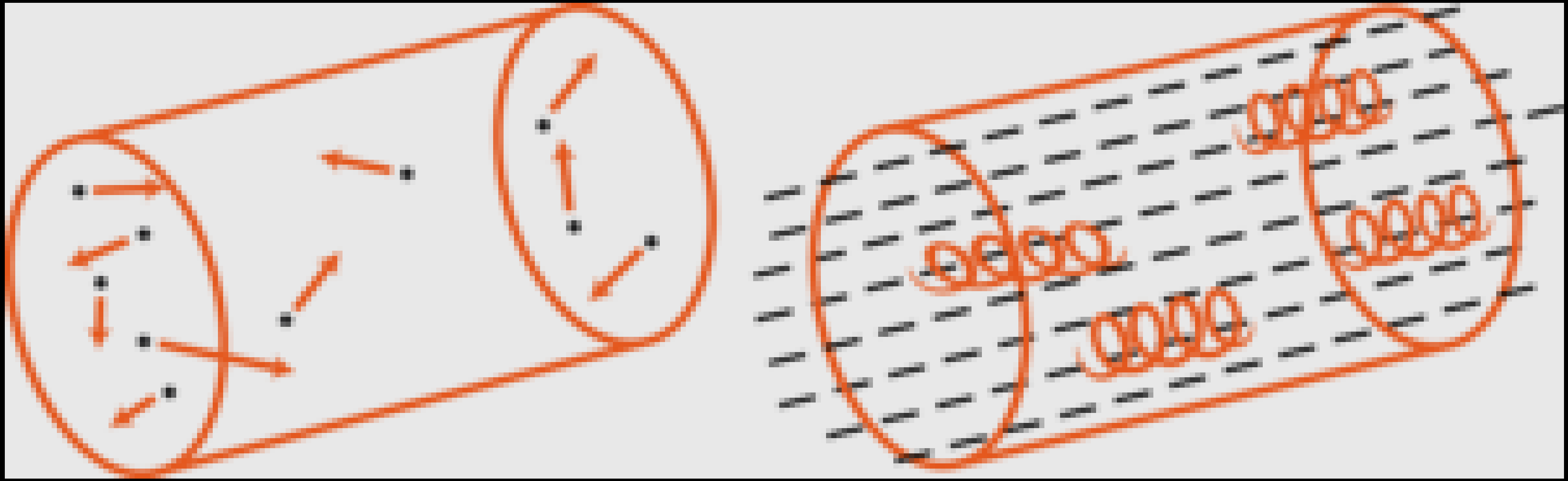
Problem:

Suppose you have two stationary identical rigid bodies both charged to $+e$. How massive would the two objects need to be such that they stay in equilibrium?

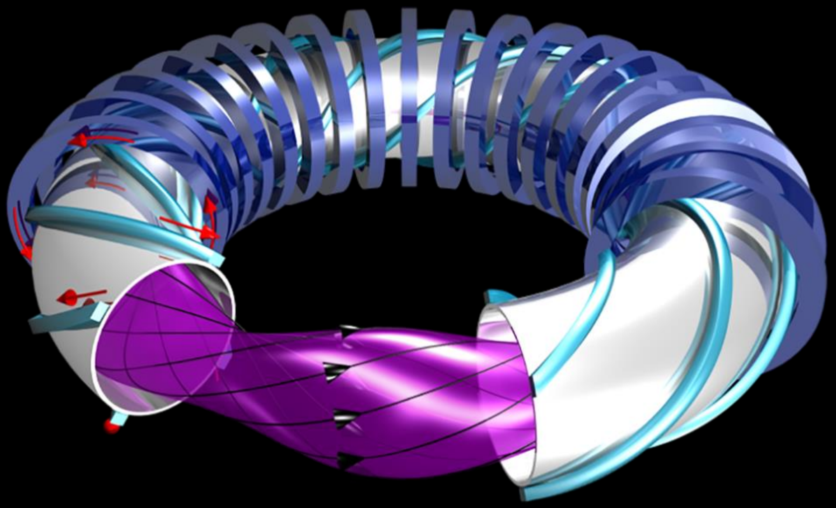
$L \sim kpc$

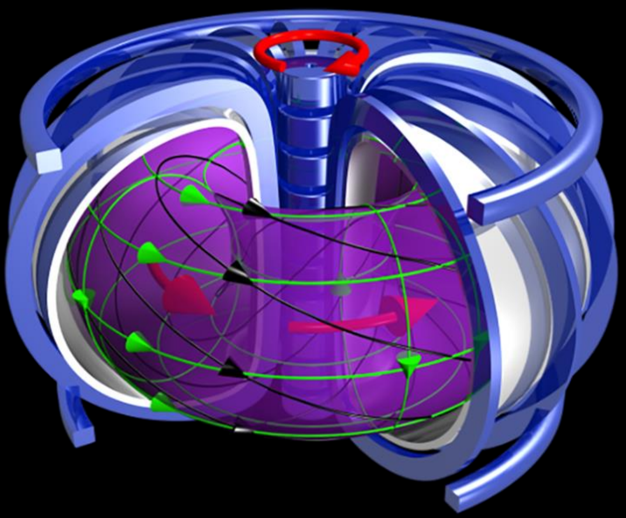


$L \sim cm$



Creator: James Ginsberg, http://large.stanford.edu/courses/2016/ph240/ginsberg1/





Images: Max Planck Institute for Plasma Physics, Germany

Plasma Response to Electromagnetic Wave

$$w_{rad}^2 = \frac{\lambda^2}{4\pi^2 c^2}$$

$$w_{pe}^2 = \frac{e^2 n_e}{\varepsilon_o m_e}$$

$\lambda > \lambda_{crit}$ EM wave is reflected

$$\frac{w_{pe}^2}{w_{rad}^2} = \frac{e^2 n_e}{\varepsilon_o m_e} \frac{4\pi^2 c^2}{\lambda^2}$$

$\lambda < \lambda_{crit}$ EM wave is transmitted

$$n_e[cm^{-3}] \sim 10^{21} \lambda_{crit}^{-2}$$