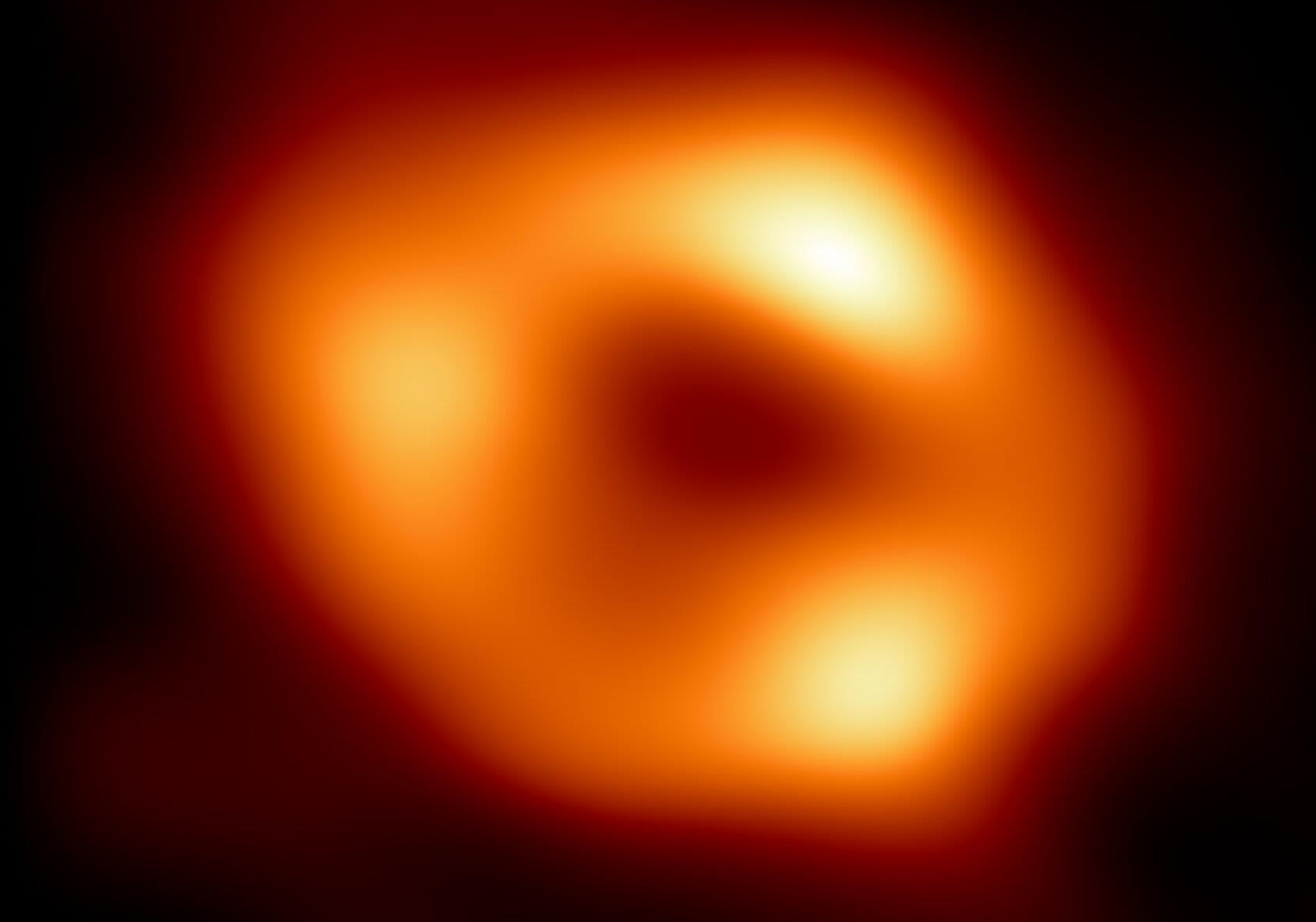
An Introduction to Plasma



David Schaffner, Bryn Mawr College
SULI 2022

An Introduction to Me

17 years ago, I was sitting in the very same place as you

BUT!, my journey to where I am now was very non-linear.

Started in undergrad at UCLA wanting to do particle physics

My first research experience was in plasma physics through NUF/SULI

Continued in grad school at UCLA working with a particle experimentalist

Decided after two years that particle physics wasn't for me—too many people, not enough hands-on projects

Switched to plasma working for the professor who introduced me to SULI

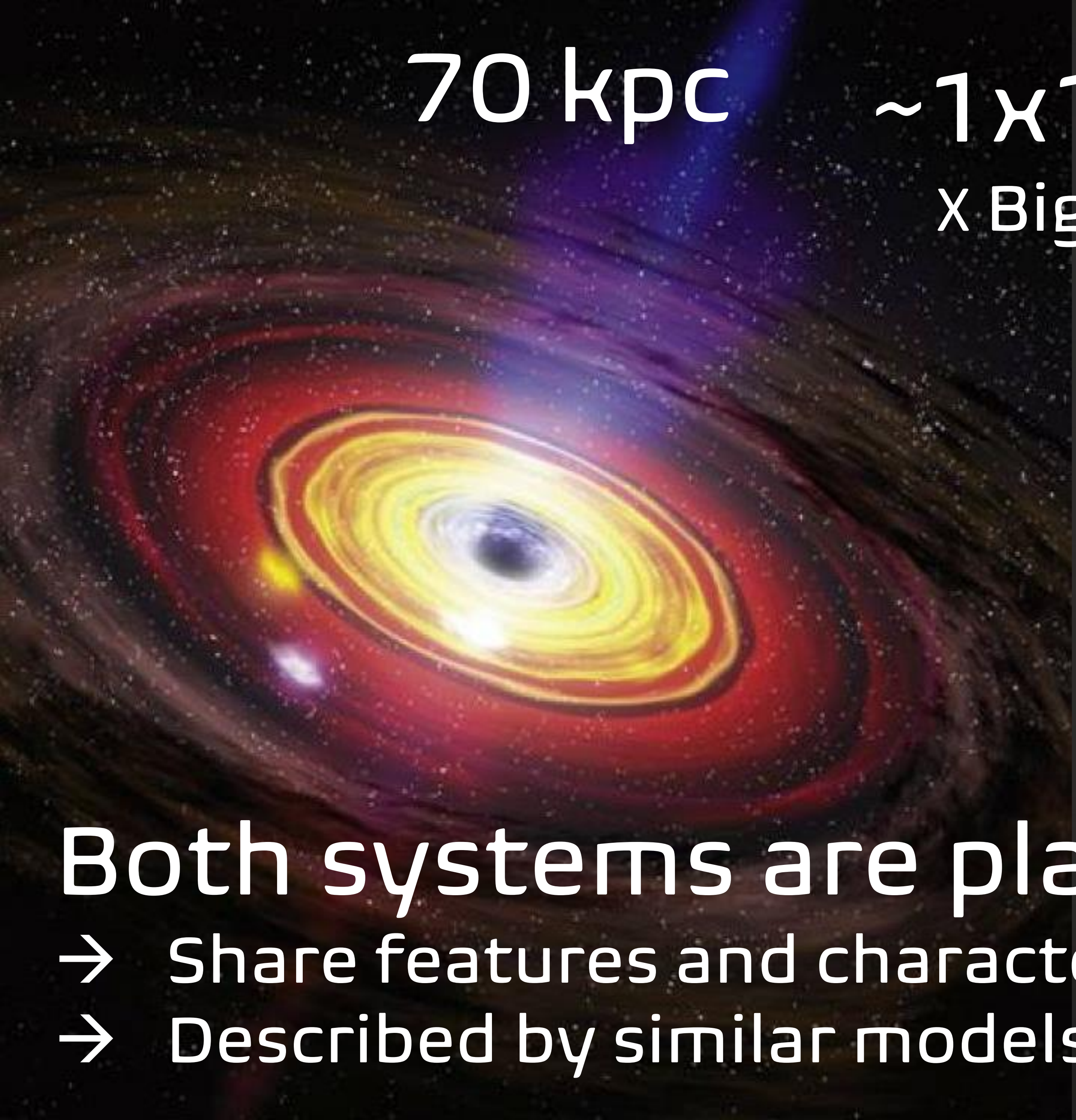
Here I am, talking to you, 17 years later

70 kpc

$\sim 1 \times 10^{23}$

X Bigger

2.5cm



Both systems are plasmas!

→ Share features and characteristics

→ Described by similar models

Part 1: Plasma Concepts
Part 2: Basic Plasma Parameters
Part 3: Models of Plasma

Part 1: Plasma Concepts

Part 2: Basic Plasma Parameters

Part 3: Models of Plasma

- ❑ What is a plasma?
- ❑ Why are plasmas important?
- ❑ What tools do you need to study plasma?

- ❑ What is a plasma?
- ❑ **<u>Why are plasmas important?</u>**
- ❑ What tools do you need to study plasma?

Questions that can only be answered when considering plasma:

How does material fall into a black hole?
How is light affected as it travels throughout the universe?
How can fusion reactions be maintained long enough to generate fusion power?
How do turbulent collisionless systems dissipate energy?
How does the sun accelerate matter into the solar wind?
What happens on the inside of planets and stars?
How can magnetic field lines "break" and reconnect?
Why does the Sun exhibit an 11-year cycle of active and quiet phases?
What generates the most energetic particles in the universe?

The study of plasma spans an enormous range in physical scales

Intergalatic scales
to
inter atomic scales

Cosmological
to
Quantum

The state of matter for 99.9% of visible matter

The study of plasma can be of use in every known STEM field

- Physics
- Space
- Astronomy
- Engineering
- Biology
- Chemistry
- Computing

Physics →

- Turbulence
- Reconnection
- Instabilities and Waves
- Resonances

The study of plasma can be of use in every known STEM field

Physics
Space
Astronomy
Engineering
Biology
Chemistry
Computing

Space →
- Solar Wind
- Solar Cycles
- Flares
- Coronal Mass Ejections

The study of plasma can be of use in every known STEM field

- Physics
- Space
- Astronomy
  - Stars
  - Accretion Disks
  - Jets and Shocks
  - Extreme Matter
- Engineering
- Biology
- Chemistry
- Computing

The study of plasma can be of use in every known STEM field

- Physics
- Space
- Astronomy
- Engineering
- Biology
- Chemistry
- Computing

Engineering →

- Controlled Fusion
- Ultra-Fast Lasers
- Material Science
- Particle Accelerators

The study of plasma can be of use in every known STEM field

- Physics
- Space
- Astronomy
- Engineering
- Biology
  - Sterilization
  - Wound Healing
  - Plant Growth
  - Soil Remediation
- Chemistry
- Computing

The study of plasma can be of use in every known STEM field

Physics
Space
Astronomy
Engineering
Biology
Chemistry
Computing

Catalysis

Surface Etching

Carbon Capture

The study of plasma can be of use in every known STEM field

Physics
Space
Astronomy
Engineering
Biology
Chemistry
Computing

High Performance Computing

Machine Learning

A.I.

What makes these plasma systems so ubiquitous?

The answer is the very *special* nature of plasma itself.

- ❑ What is a plasma?
- ✓ Why are plasmas important?
- ❑ What tools do you need to study plasma?

❑ What is a plasma?

My favorite definition:

"Plasma is in some sense the natural, untamed state of matter…"

– Hazeltine and Waelbroeck, The Framework of Plasma Physics

❑ What is a plasma?

One Definition:

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

– NSF Basic Plasma Science and Engineering Website

❑ What is a plasma?

One Definition:

”physical systems whose intrinsic properties are governed by **collective interactions** of **large ensembles** of **free charged particles**.”

Charged particles
Large Ensembles
Free
Collective Interactions

Charged particles →Electromagnetism

Electromagnetism involves "long-range" interactions

- Two charged particles in a finite system ALWAYS have a non-zero level of interaction—no matter the size
- E&M interactions bestows plasma with the ability to exist at almost ANY scale
- Fields (particular magnetic) can span interatomic to intergalactic distances

BUT! Just having charged particles does not explain why plasmas are so ubiquitous throughout the universe

Charged particles
Large Ensembles

- → Most systems in the universe consist of large ensembles of particles (solid, liquid, gas)
- → Adding charge means every particle interacts at some level with EVERY other particle in the system
- → Interactions with local neighbors of similar importance to interactions with the global population

Sure, but… large ensembles of charged particles can technically describe most matter

Charged particles
Large Ensembles
Free

- Free means "not bound"
- Free *also* means, able to easily gain or lose energy, both as individual particles AND as an entire system
- EM forces provide easy mechanisms for energy exchange

Charged particles
Large Ensembles
Free

Collective Interactions

Charged particles
Large Ensembles
Free
Collective
Interactions

Systems that can grow or shrink to any scale and can absorb AND retain enormous amounts of energy (high temperature)

Charged particles
Large Ensembles
Free
Collective
Interactions

Systems that can grow or shrink to any scale and can absorb AND retain enormous amounts of energy (high temperature)

<u>THIS</u> is what makes plasmas prevalent and so useful!

But wait, if plasma is so ubiquitous, why don’t we see it all the time in our everyday lives?

The problem is that Earth is in an unfortunate parameter space: too little energy, too much stuff

~~Charged particles~~
Large Ensembles
~~Free~~
~~Collective~~
~~Interactions~~

To have plasmas on Earth, need:

- Low density (vacuum systems or upper atmosphere)
- High energy (lightning)

- ✓ What is a plasma?
- ✓ Why are plasmas important?
- ❑ What tools do you need to study plasma?

Types of Tools Need to Study Plasma

- Experimental/Observational
- Theoretical/Mathematical/Modeling
- Computational

Types of Tools: Experimental

1) Vacuum System
2) Gas
3) Energy Sources
   - Electrical sources
   - Inertial sources
4) Methods of measurement
   - Touch the plasma
   - Detect the fields
   - Detect the light

Types of Tools: Observational

1) Space
2) Rockets/Satellites/Telescopes
3) Energy Sources
   - Sun
   - Solar Wind
4) Methods of measurement
   - Touch the plasma
   - Detect the fields
   - Detect the light

Types of Tools: Mathematical/Modeling

Charged particles
Large Ensembles
Free
Collective
Interactions

Vector Calculus

(tracking the motion of single particles)

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

$$\vec{F} = m\vec{a} = q\vec{E} + q(\vec{v} \times \vec{B})$$

$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t}$$

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

Types of Tools: Mathematical/Modeling

Charged particles
Large Ensembles
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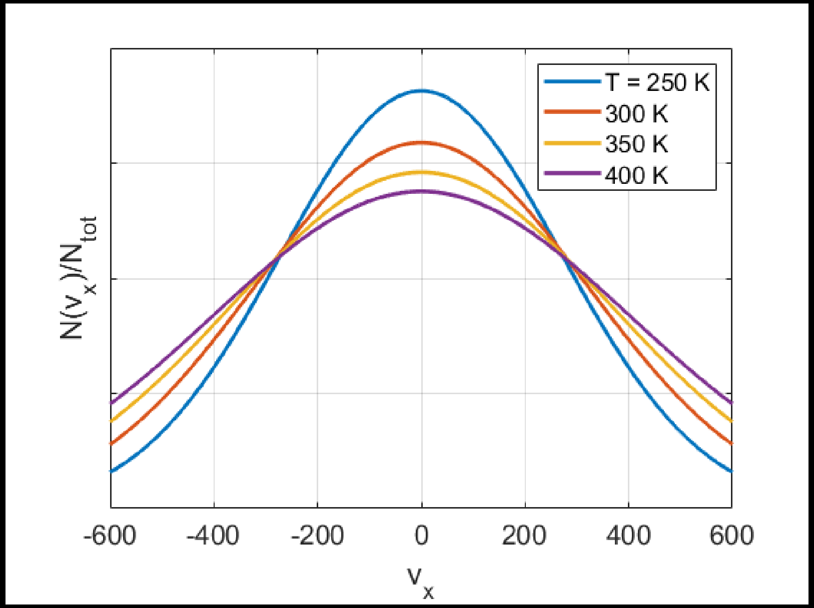
Collective
Interactions

Statistical Mechanics

(group behavior of enormous #'s of particles)

$$f_s(\bar{v}) = n_s \left(\frac{m_s}{2\pi k T_s} \right)^{3/2} e^{-\frac{m_s v^2}{2kT_s}}$$



Types of Tools: Mathematical/Modeling

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Statistical Mechanics

(group behavior of enormous #'s of particles)

$$f_s(\bar{v}) = n_s \left(\frac{m_s}{2\pi k T_s}\right)^{3/2} \mathrm{e}^{-\frac{m_s v^2}{2kT_s}}$$

Moments:

$$\mu^n = \int v^n f(v)$$

$$\mu^0 = n = \int v^0 f(v)$$

~Density

Types of Tools: Mathematical/Modeling

Charged particles
Large Ensembles
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Statistical Mechanics

(group behavior of enormous #'s of particles)

$$f_s(\bar{v}) = n_s \left(\frac{m_s}{2\pi k T_s} \right)^{3/2} \mathrm{e}^{-\frac{m_s v^2}{2kT_s}}$$

Moments:

$$\mu^n = \int v^n f(v)$$

$$\mu^2 = E = \int v^2 f(v)$$ ~Energy

Types of Tools: Mathematical/Modeling

Charged particles
Large Ensembles
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Fluid Mechanics

(tracking the group behavior of enormous #'s of particles)

$n\vec{u}$ (fluid element)

$$m\vec{a} = q\vec{E} + q(\vec{v} \times \vec{B})$$

$$m\frac{d\vec{v}}{dt} = q\vec{E} + q(\vec{v} \times \vec{B})$$

$$mn\frac{\partial\vec{u}}{\partial t} + mn(\vec{u} \cdot \nabla)\vec{u} = qmn\vec{E} + qmn\left(\vec{u} \times \vec{B}\right) - \nabla P$$

Types of Tools: *Mathematical/Modeling*

Charged particles
Large Ensembles
Free
Collective
Interactions

Differential Equations

(tracking the energy evolution of systems)
(waves and instabilities)

DE's for:

Single Particles

$$m\frac{d\vec{v}}{dt} = q\vec{E} + q(\vec{v} \times \vec{B})$$

Types of Tools: *Mathematical/Modeling*

Charged particles
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Differential Equations

(tracking the energy evolution of systems)
(waves and instabilities)

DE's for:

- Single Particles
- Fluid Elements

$$mn\frac{\partial\vec{u}}{\partial t} + mn(\vec{u}\cdot\nabla)\vec{u} = qmn\vec{E} + qmn\left(\vec{u}\times\vec{B}\right) - \nabla P$$

Types of Tools: *Mathematical/Modeling*

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Differential Equations

(tracking the energy evolution of systems)
(waves and instabilities)

DE's for:

- Single Particles
- Fluid Elements
- Distribution Functions

$$\frac{\partial f}{\partial t} + \vec{v} \cdot \nabla f = \frac{q}{m}\left(\vec{E} + \vec{v} \times \vec{B}\right) \cdot \frac{\partial f}{\partial v} = 0$$

Types of Tools: Mathematical/Modeling

Charged particles
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Differential Equations

(tracking the energy evolution of systems)
(waves and instabilities)

Common Techniques for DE's:

- Linearization
- Special Functions
- Transforms (FFT)
- Complex Analysis

Types of Tools: Mathematical/Modeling

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Differential Equations

(tracking the energy evolution of systems)
(waves and instabilities)

Boundary Conditions
→ Initial State of system
→ Size/Shape of System

Real Boundaries can make a model extremely difficult to solve

Types of Tools: Computational

Numerical Integration
Transforms (Fast Fourier, etc)
Differential Equation Solvers
High Performance Computing

Part 1: Plasma Concepts

Part 2: Basic Plasma Parameters

Part 3: Models of Plasma

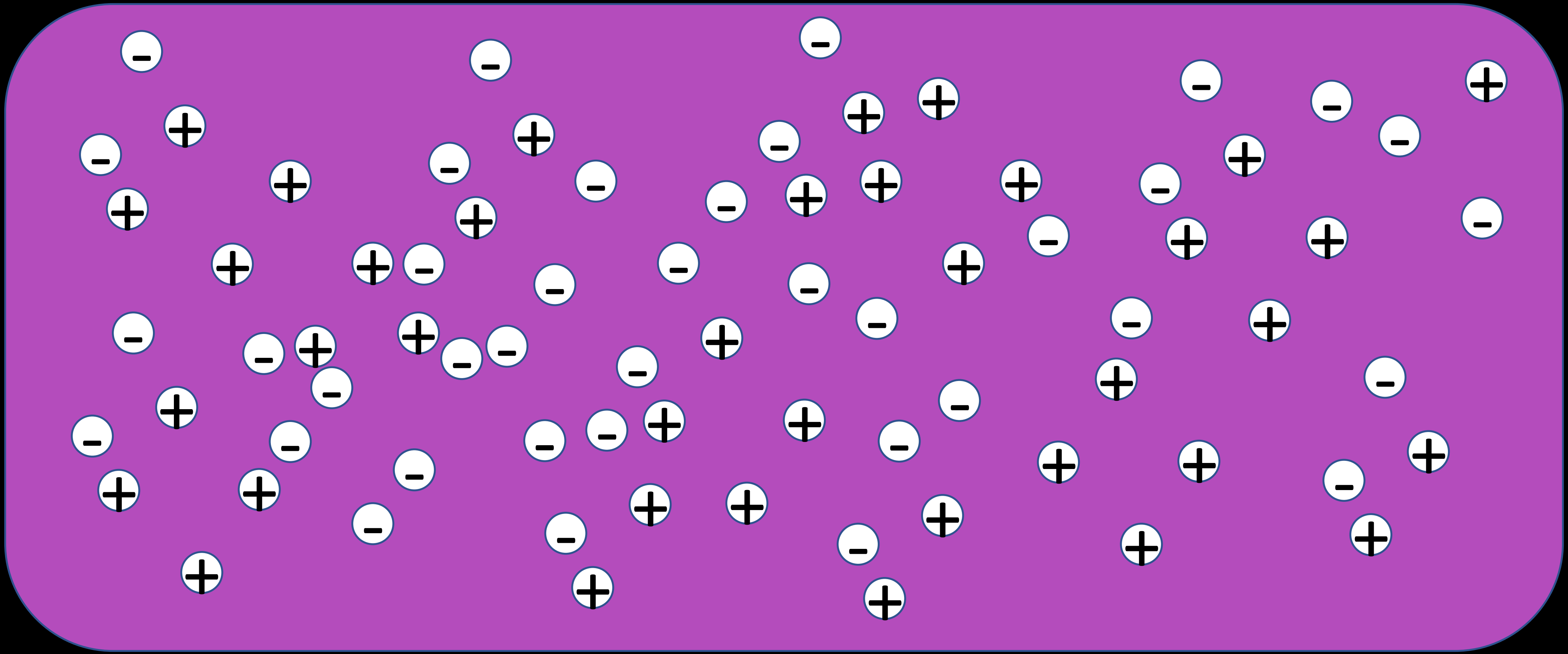
Using our tools to extract some basic quantitative information about plasmas

Qualitatively demonstrate how charged particles, free, large ensembles and collective behavior manifests into quantitative characteristics

Case Study: Debye Length, λ_D

Consider a container of plasma

Consider a container of plasma



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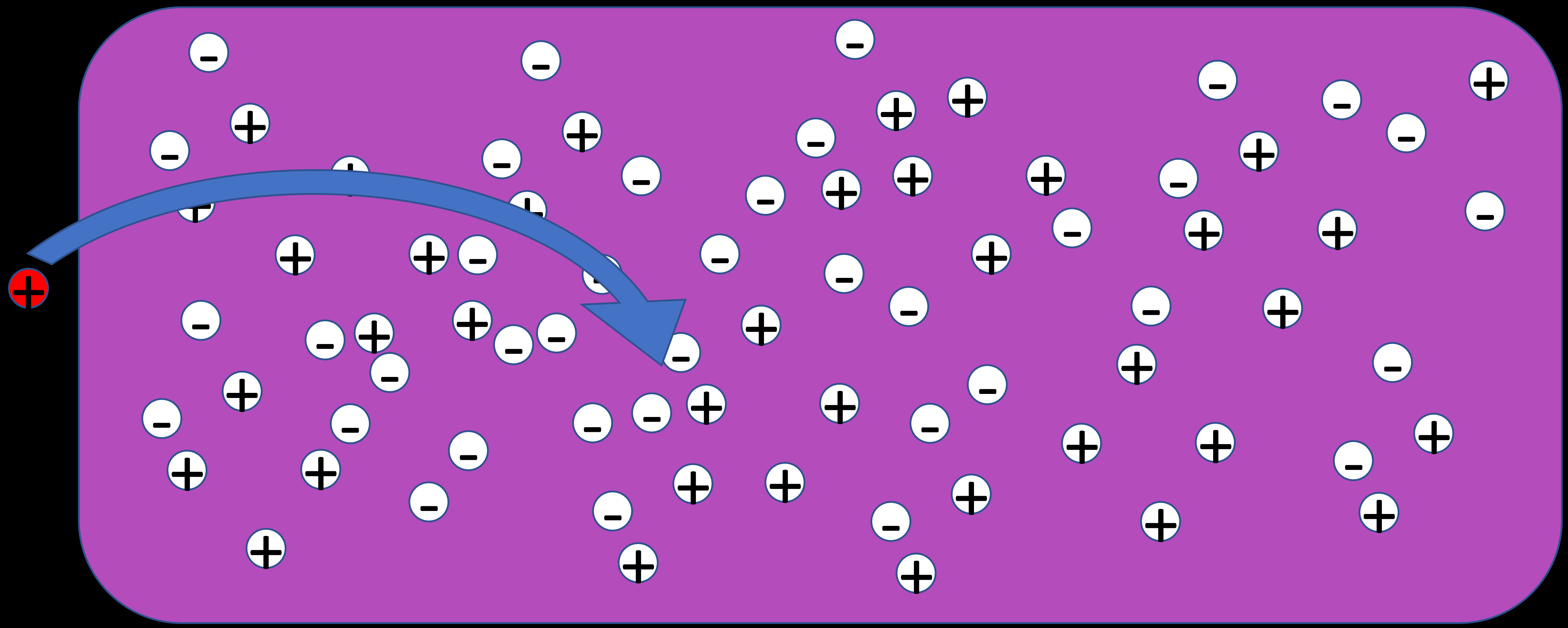

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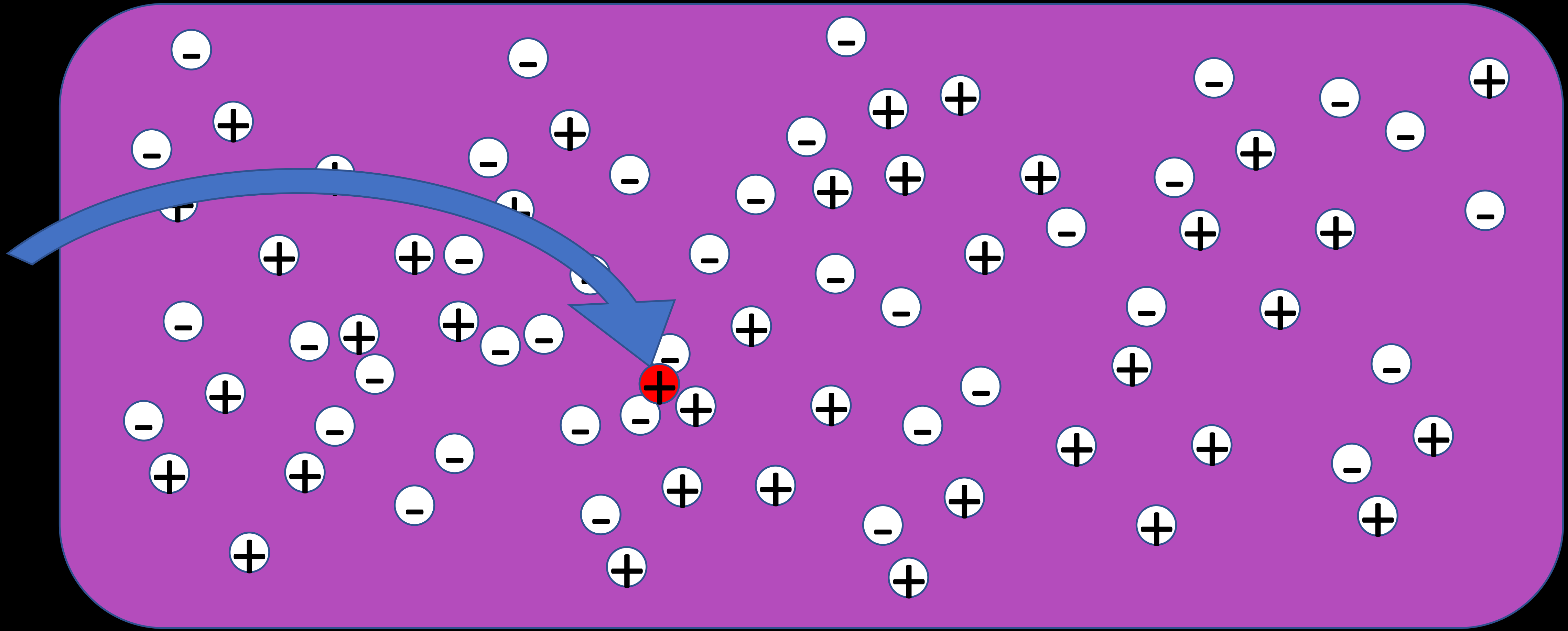

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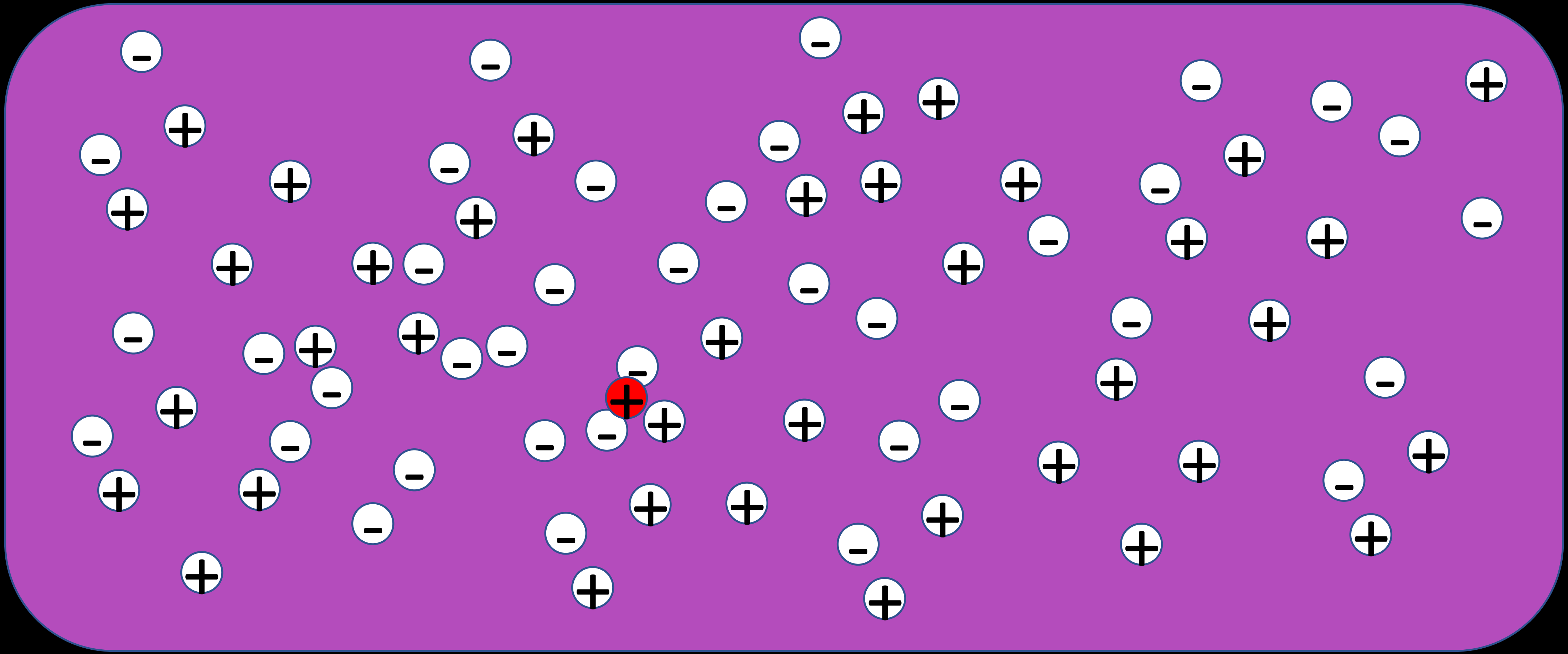

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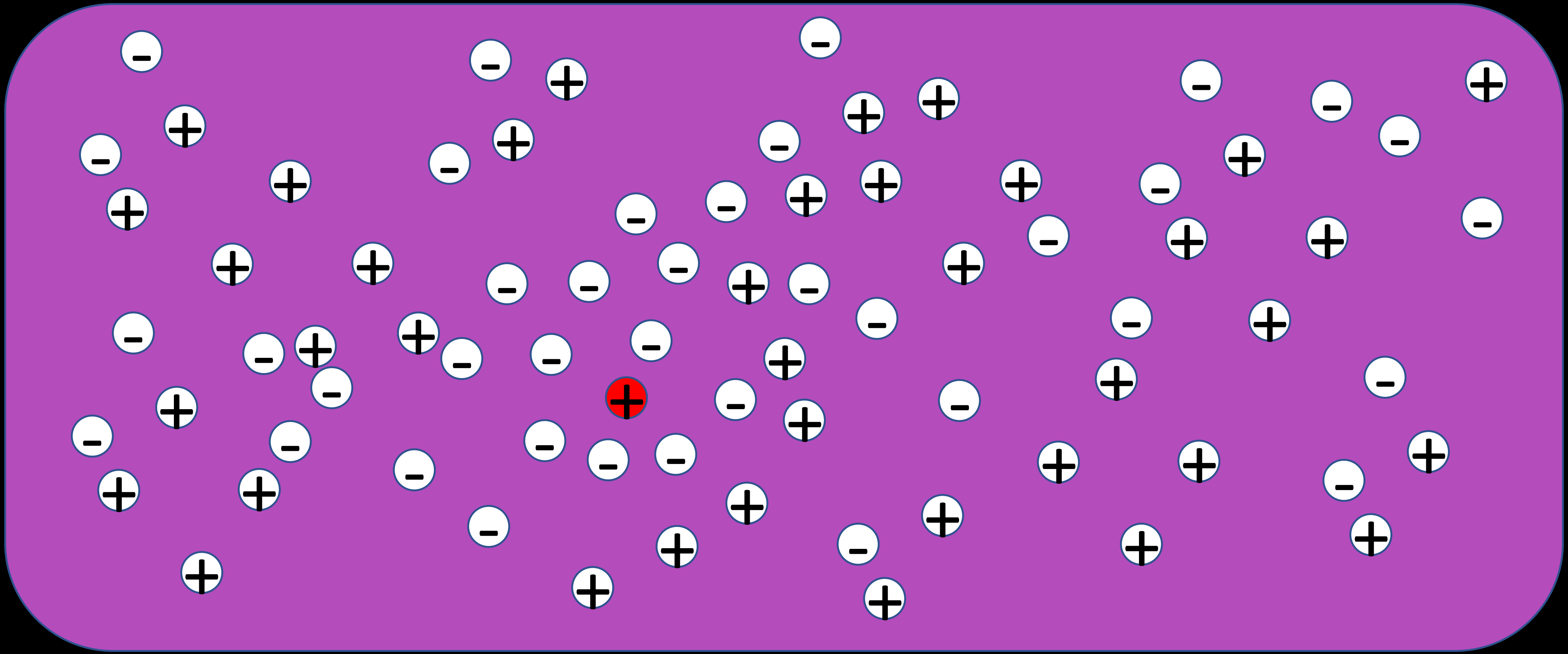

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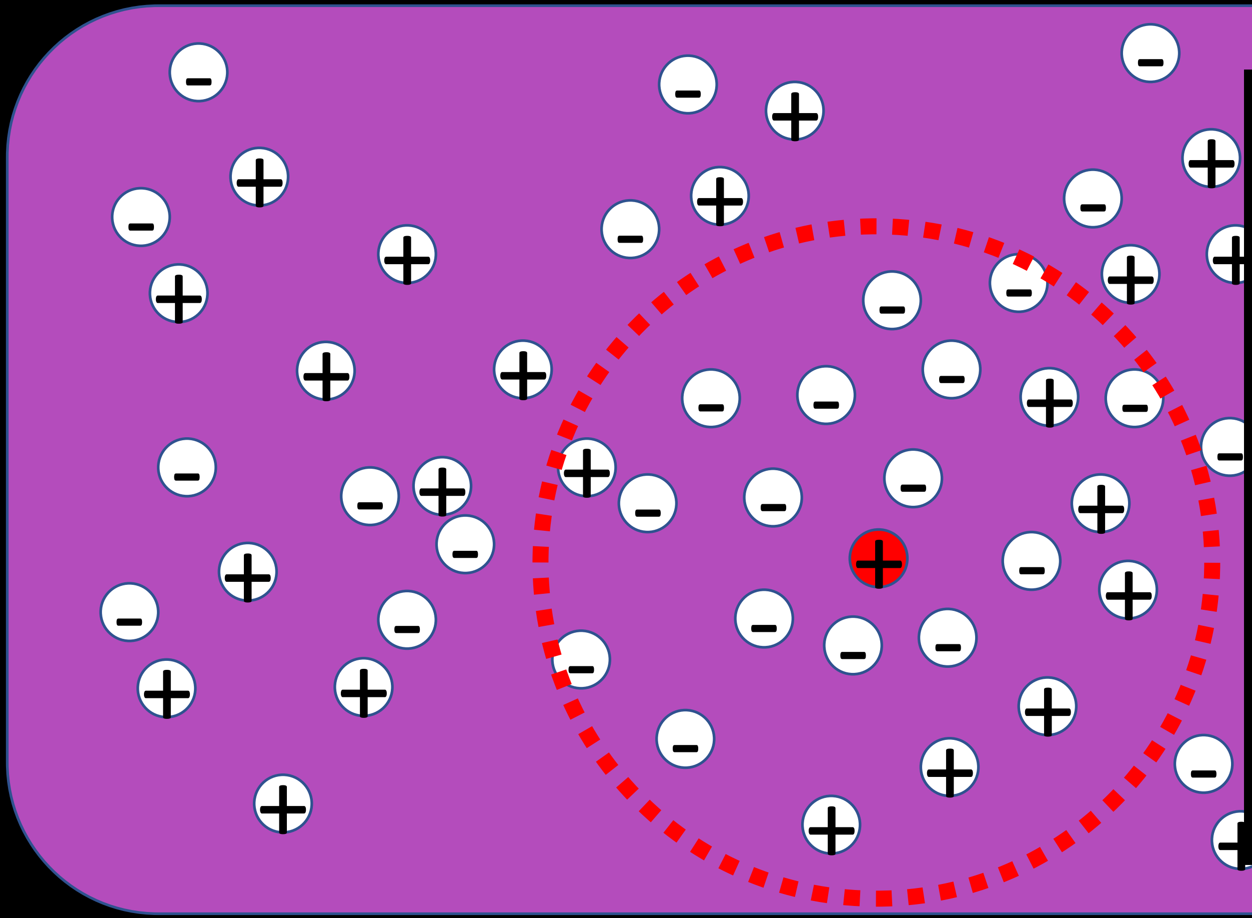

Key Question:

What is the radius of the sphere of influence of this extra charge?

Or

How far away do you have to be for the extra charge to be completely "shielded" by the plasma?

Use plasma concepts and tools

Charged particles
Large Ensembles
Free
Collective
Interactions

Can write down
Boltzmann distribution

$$f_e(\bar{v}) \propto \mathrm{e}^{-\left(\frac{Energy}{kT}\right)}$$

Use plasma concepts and tools

Charged particles
Large Ensembles
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Can write down Boltzmann distribution

$$f_e(\bar{v}) \propto \mathrm{e}^{-(\frac{Energy}{kT})}$$

$$f_e(\bar{v}) \propto \mathrm{e}^{-(\frac{mv^2+qV}{2kT})}$$

Take zeroth moment: $\mu^0 = n = \int v^0 f(v)$

$$n = n_0 \mathrm{e}^{-(\frac{qV}{kT})}$$

Use plasma concepts and tools

Charged particles
Large Ensembles
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Use this density to solve a *Maxwell* Equation

$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$

Poisson's Equation

$$\nabla \cdot \overrightarrow{\nabla V} = \frac{-qn}{\varepsilon_0}$$

$$\nabla^2 V = -\frac{qn}{\varepsilon_0}$$

$$\nabla^2 V = -\frac{q}{\varepsilon_0} n_0 \mathrm{e}^{-\left(\frac{qV}{kT}\right)}$$

Use plasma concepts and tools

Charged particles
Large Ensembles
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Reduce to 1D, Linearize DE by expanding and taking first order term

$$\nabla^2 V = -\frac{q}{\varepsilon_0} n_0 \mathrm{e}^{-(\frac{qV}{kT})}$$

$$\frac{d^2V}{dx^2} = -\frac{q}{\varepsilon_0} n_0 \left[\frac{qV}{kT} + \frac{1}{2}\left(\frac{qV}{kT}\right)^2 + \cdots\right]$$

$$\frac{d^2V}{dx^2} \approx -\frac{q}{\varepsilon_0} n_0 \frac{qV}{kT}$$

Use plasma concepts and tools

Charged particles
Large Ensembles
Free
Collective
Interactions

We can solve this differential equation!

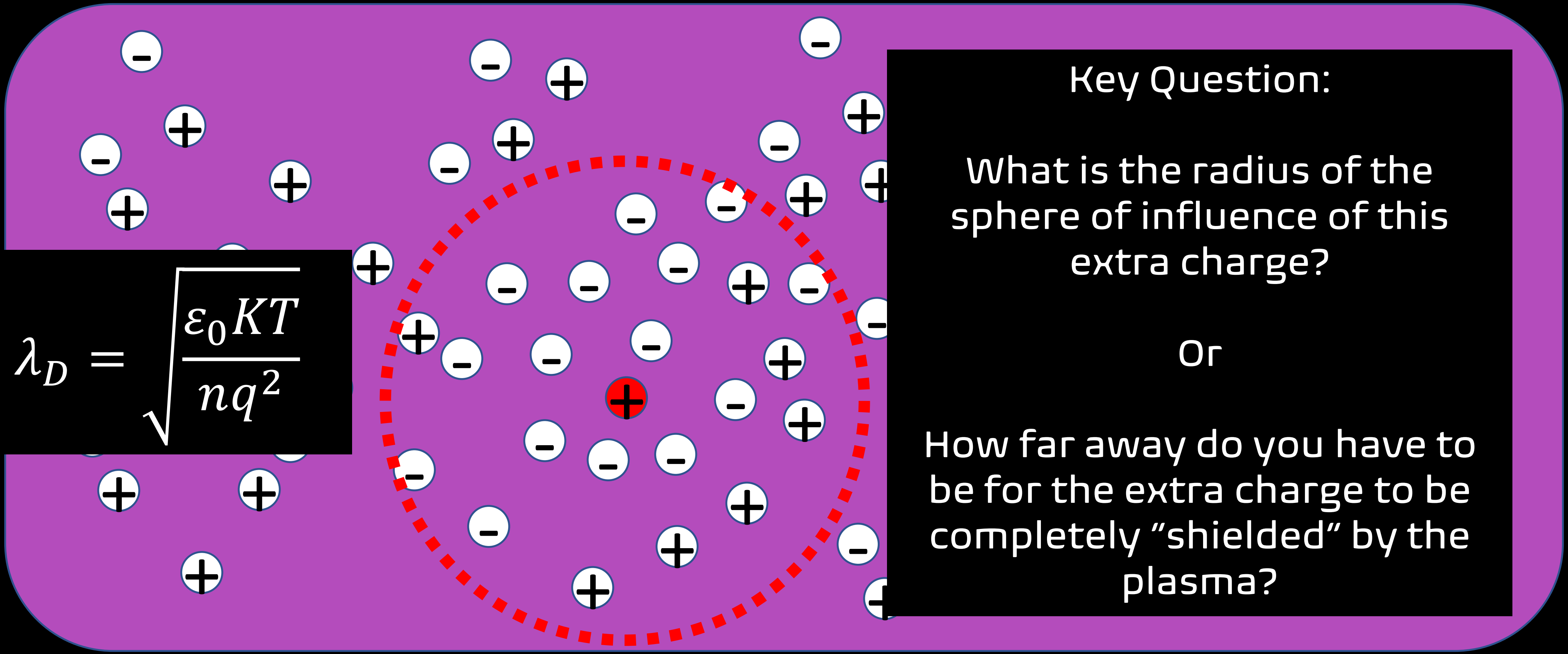
$$\frac{d^2V}{dx^2} \approx -\frac{q}{\varepsilon_0} n_0 \frac{qV}{kT}$$

$$V(x) = V_0 e^{-|x|/\lambda_D}$$

$$\lambda_D = \sqrt{\frac{\varepsilon_0 KT}{nq^2}}$$

Debye Length

Consider a container of plasma



$$\lambda_D = \sqrt{\frac{\varepsilon_0 KT}{nq^2}}$$

Key Question:

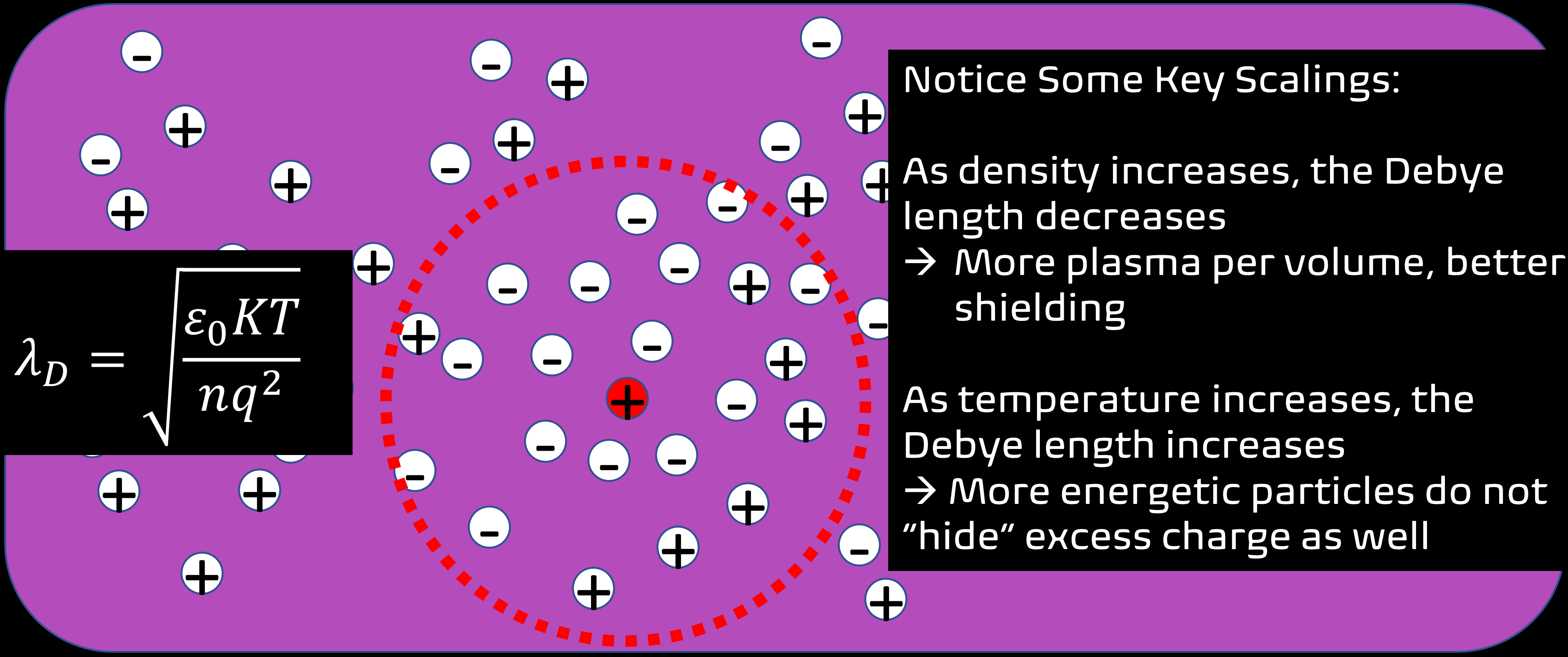
What is the radius of the sphere of influence of this extra charge?

Or

How far away do you have to be for the extra charge to be completely "shielded" by the plasma?

Answer: A few Debye Lengths

Consider a container of plasma



$$\lambda_D = \sqrt{\frac{\varepsilon_0 KT}{nq^2}}$$

Notice Some Key Scalings:

As density increases, the Debye length decreases
→ More plasma per volume, better shielding

As temperature increases, the Debye length increases
→ More energetic particles do not "hide" excess charge as well

Answer: A few Debye Lengths

The Debye Length can be used to quantitatively define a plasma!

A system of free charged particles can be a PLASMA if at least:

1) The number of particles in a Debye Sphere is very, very, very large
2) The Debye Length is much smaller than the system size

Part 1: Plasma Concepts

Part 2: Basic Plasma Parameters

Part 3: Models of Plasma

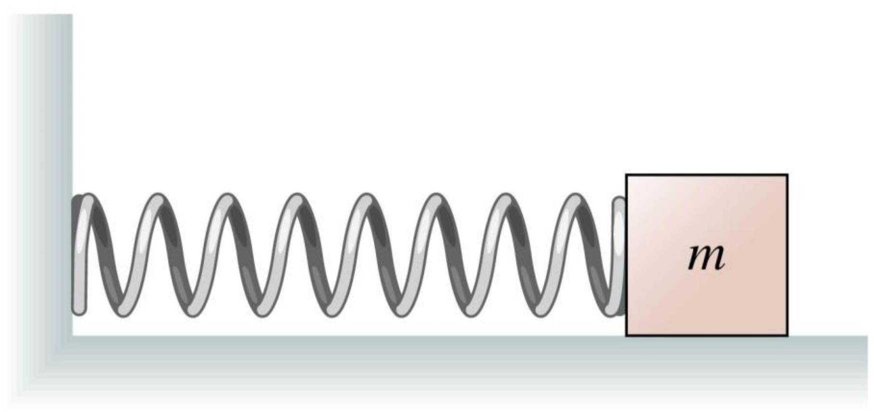
What is a model?

Personal Definition:

"A set of relationships between measurable quantities that follow certain rules of logic and can often be described using mathematical equations, all of which is then used to predict the behavior of a natural system given initial or boundary conditions to some pre-determined level of accuracy."

A simple model

Consider a Mass on a Spring



Given a mass, m, and a spring constant, k, the mass will oscillate with amplitude A according to the equation

$$x = A\cos(2\pi f t)$$

where the frequency of oscillation depends on the mass and the spring constant as $f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$

Simple because: one degree of freedom, few parameters

Plasma, is not, simple

So how do we model it?

Answer: We can only model PART of the system at any given time

There are too many components, degrees of freedom, too many interactions to tractably model

What part do we model?
→Which ever part (or scope) you care about.

A simple guide to complex models

Most models used in plasma science come down to one question:

<u>How much do I care about individual particles?</u>

Answer 1) I care about ***every single*** particle.
Good luck! This would be the most accurate model if we could track not only upwards of 10^{26} particles, but every binary interaction between each of those particles.

Thus far, this has proven impossible, even with the most sophisticated computers and coding available.

A simple guide to complex models

Most models used in plasma science come down to one question:

How much do I care about individual particles?

Answer 2) I only care about ***one*** particle.
This can work nicely. We can track the behavior of a single particle in the presence of background electric and magnetic fields. Called Single Particle Motion.

This tells us about some behaviors, but not really how a ***plasma*** behaves (i.e. no collective behaviors).

A simple guide to complex models

Most models used in plasma science come down to one question:

<u>How much do I care about individual particles?</u>

Answer 3) I thought this was a plasma class. I don't care about particles ***<u>at all</u>***!

Well then! Rather then model a discrete number of particles, we can pretend the particles blend together into a fluid. In this case, a conducting fluid. This is called Magnethydrodynamics or MHD.

A simple guide to complex models

Most models used in plasma science come down to one question:

<u>How much do I care about individual particles?</u>

Answer 3) I thought this was a plasma class. I don't care about particles ***<u>at all</u>***!

A benefit of MHD is that is can predict many collective behaviors well (like waves), but loses all sense of the true particle-based nature of plasma. A compromise is two-fluid, where the ions and electrons can be treated as separate fluids.

A simple guide to complex models

Most models used in plasma science come down to one question:

How much do I care about individual particles?

Answer 4) I care about as many particles as I can.

This is a common compromise. Rather than tracking every aspect of every particle, we can form distribution functions that summarize behavior of many particles. Called kinetic theory. We can observe how the distribution function evolves and interacts with fields. Mathematically, most intense…

Important Reminder:

In the end,

A plasma model ≠ A real plasma system

A model is our best representation of a real plasma system as we can get. Thus far, there is NO single plasma model that can accurately predict an ENTIRE plasma system at all scales

It takes multiple models/theory, experiments and observation, and computation all working together to figure out what is going on. ***But it's worth it!***

Thank you and enjoy the rest of your plasma adventure!