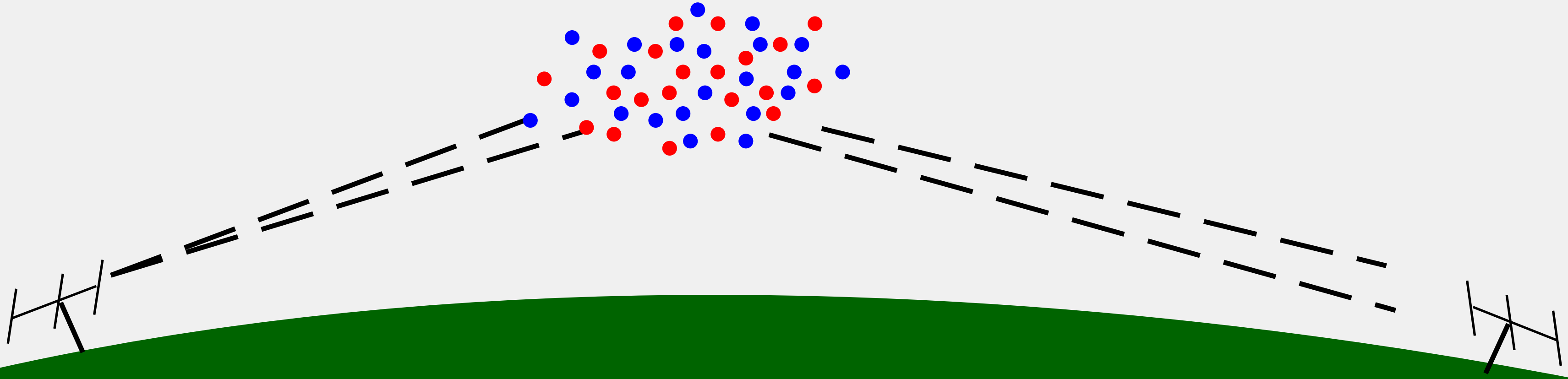
We Communicate by Ionospheric Reflection ...
… not Refraction



Mike Hasselbeck WB2FKO

Central States VHF Conference July 2024

This talk deals exclusively with ionosphere

No tropospheric ducting, rain scatter, etc

Refraction vs Reflection (Optics and RF are E-M waves)

Intuitive model of the ionosphere

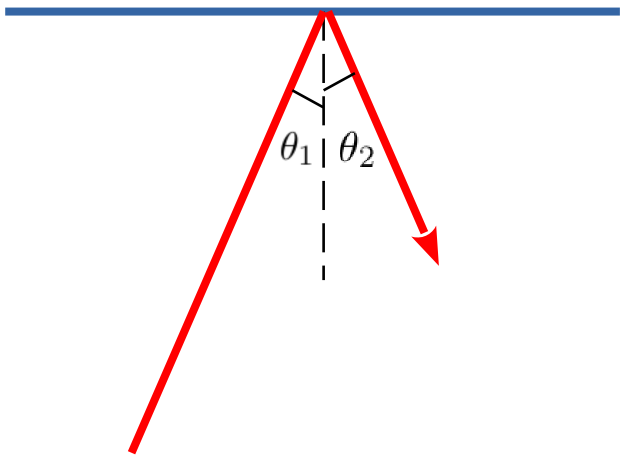
Ignore secondary magnetic field effects

Analysis: 50 MHz vs 144 MHz

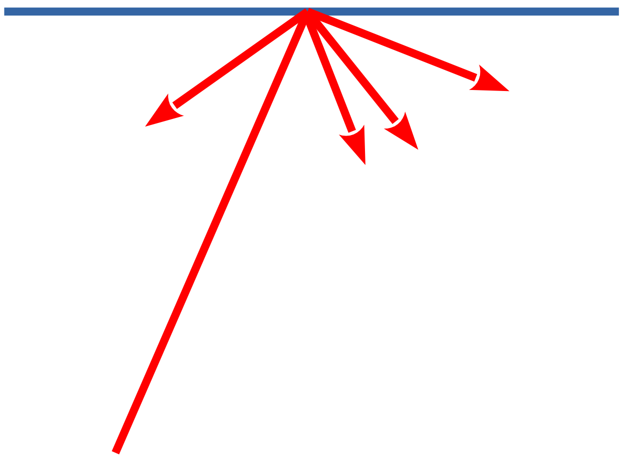
REFLECTION

REFLECTION RAY TRACING

Specular Reflection: $\theta_1 = \theta_2$



Diffuse Reflection



REFRACTION: Deflection in the path of an electromagnetic wave as it passes through different media

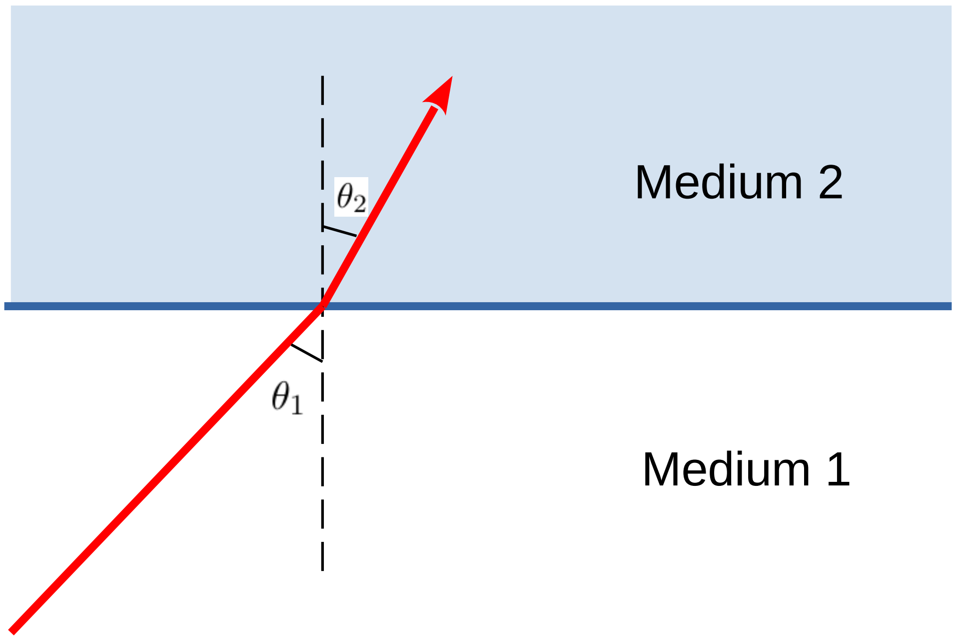
Index of refraction

Air: 1.0

Water: 1.33

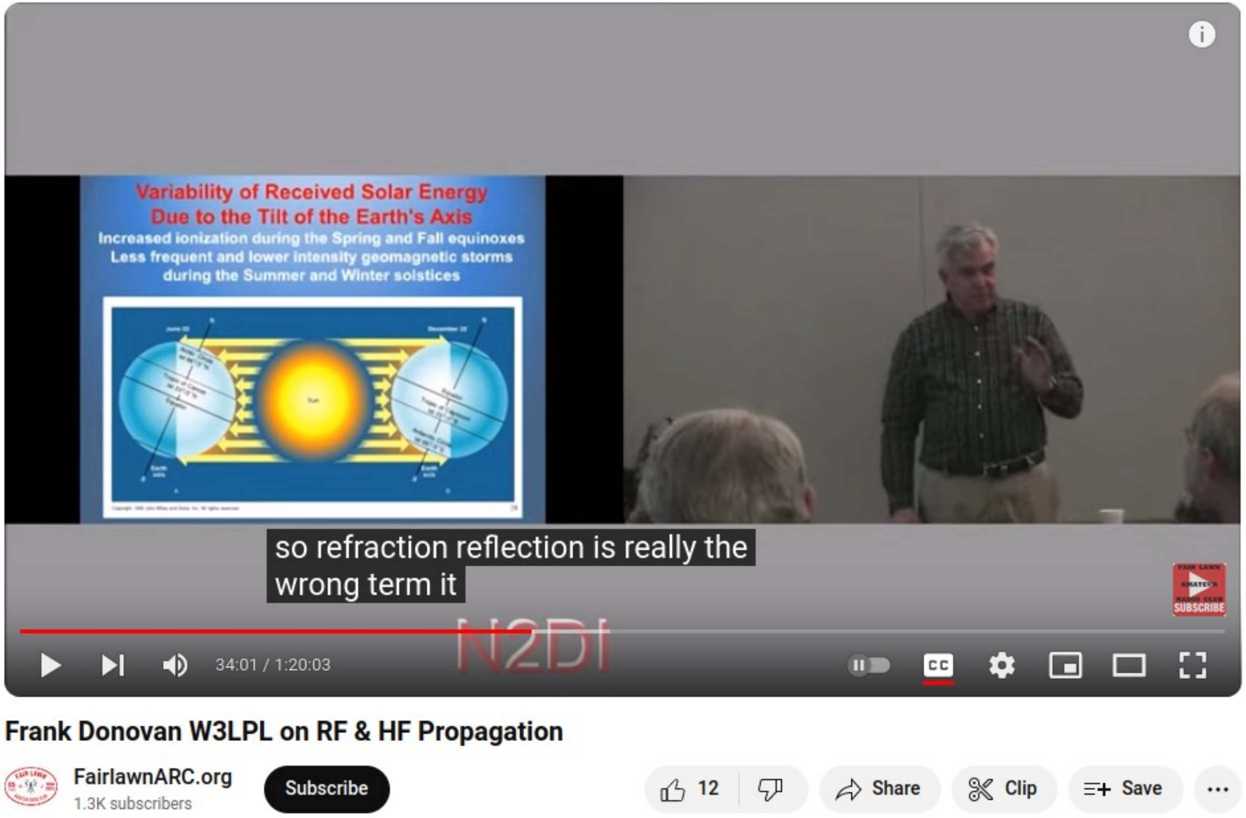
Glass: 1.5

REFRACTION RAY TRACING



“Free electrons cause radio waves to slow down, refract, and bend…

… reflection is really the wrong term.”

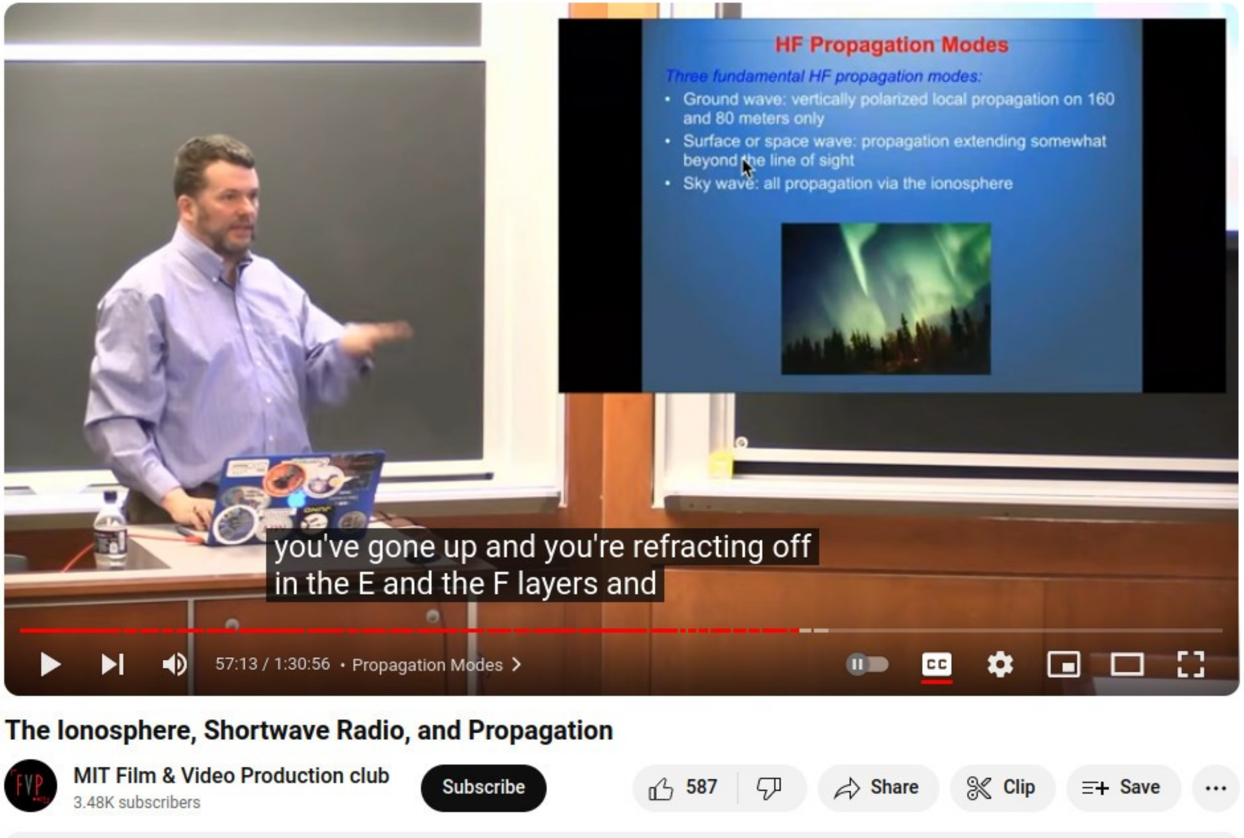


“You’re not bouncing off of anything…

...the signal encounters a different index of refraction...

...refraction bends the signal back down.”

“...the Sky Wave is where you’ve gone up and you’re refracting off the E- and F-layers...”



ARRL Instructor Resource: General Class License

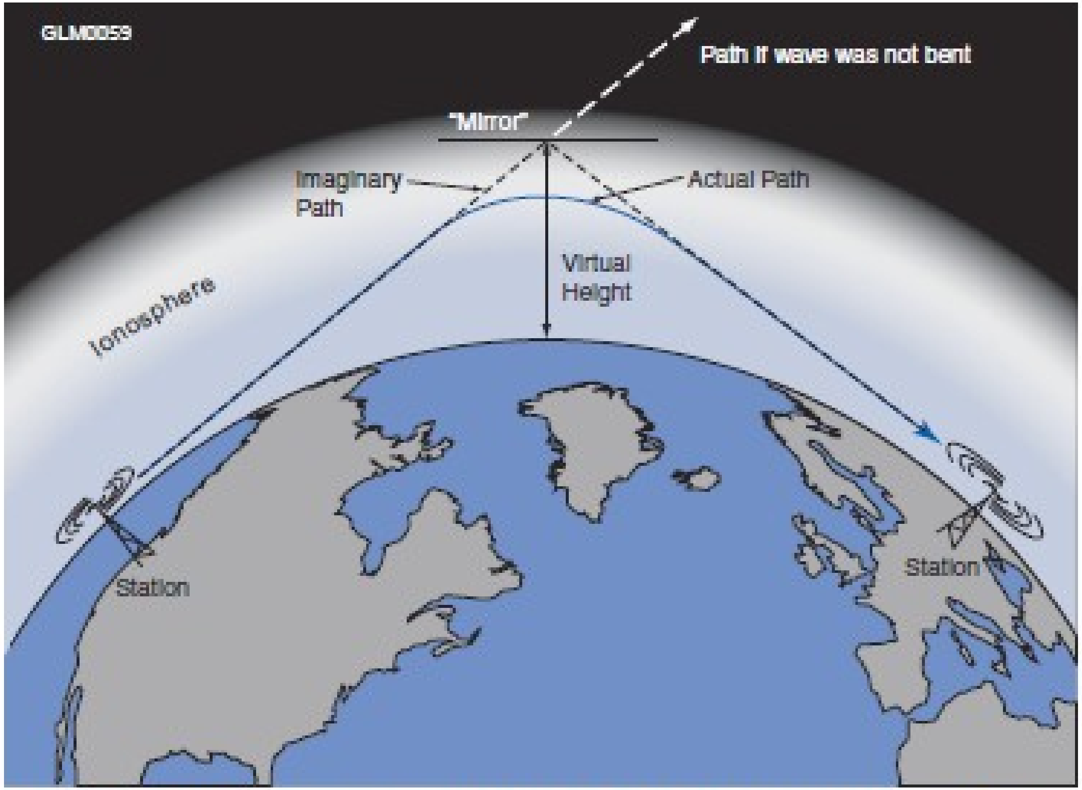


Figure 8.2 — Radio waves are refracted (bent) in the ionosphere, so they return to Earth far from the transmitting station. Without refraction in the ionosphere, radio waves would pass into space. (Not to scale)

From the General Class License Question Pool*:

G3C02 (A)

What is meant by the term “critical frequency” at a given incidence angle?

A. The highest frequency which is refracted back to Earth

B. The lowest frequency which is refracted back to Earth

C. The frequency at which the signal-to-noise ratio approaches unity

D. The frequency at which the signal-to-noise ratio is 6 dB

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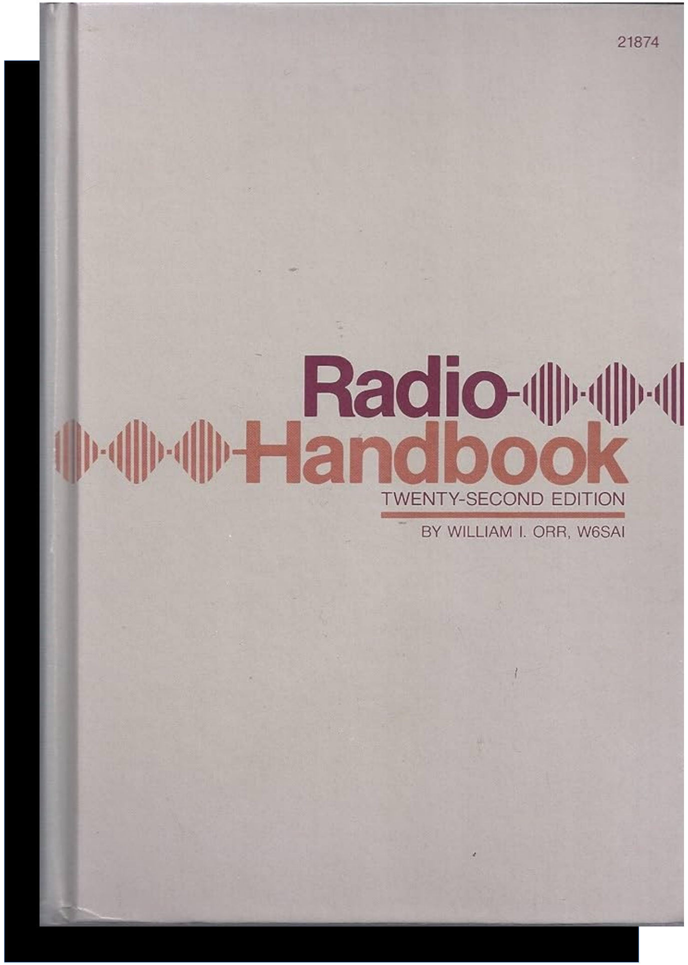
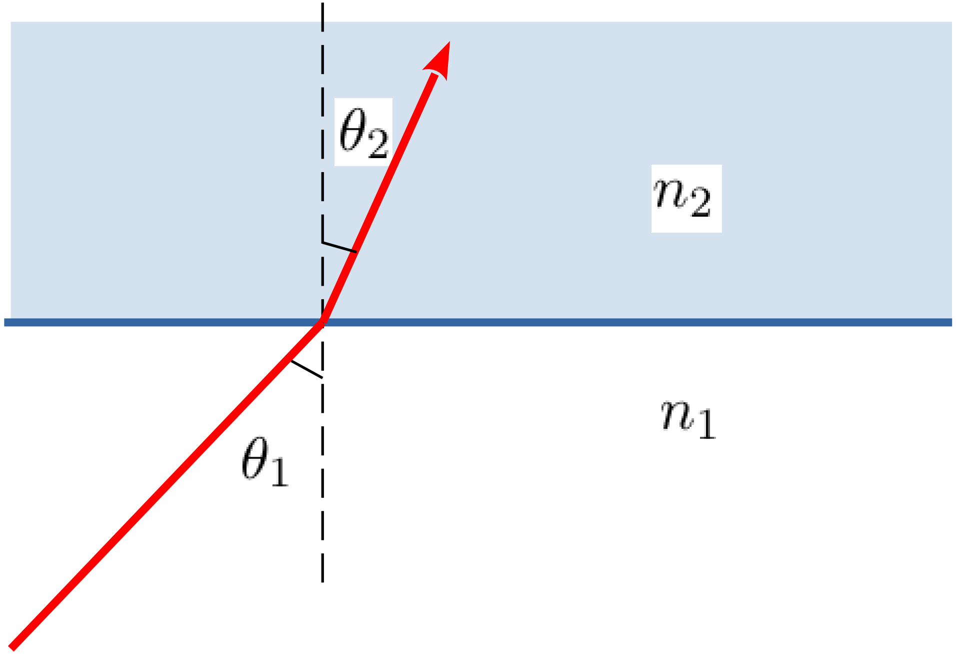
*http://www.arrl.org/general-question-pool



William Orr, W6SAI:

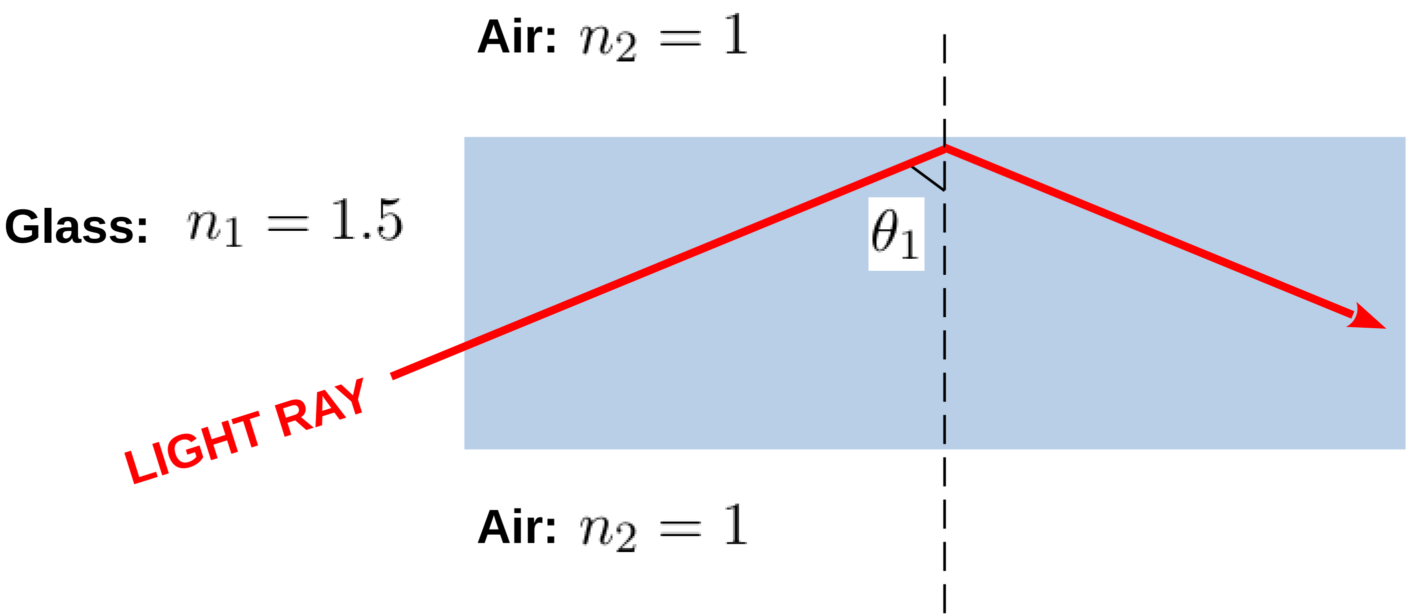
"Propagation ... is primarily by *ionospheric reflection*."



Willebrord Snellius:
1580--1626

Snell's Law of Refraction: $n_1 \sin\theta_1 = n_2 \sin\theta_2$

Total Internal Reflection in Glass Fiber

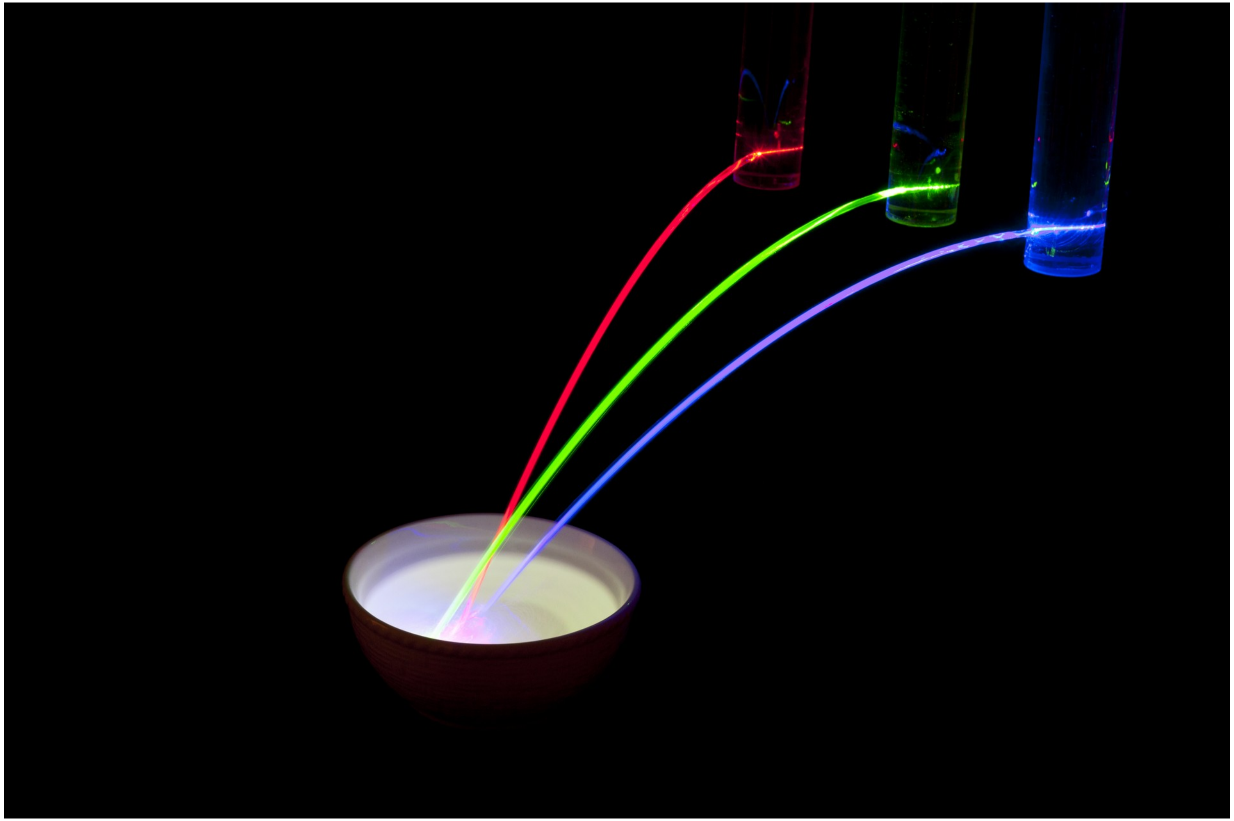


For $\theta_1 > 41^o$ Snell's Law has no solution!

These rays are completely reflected – there is no refraction

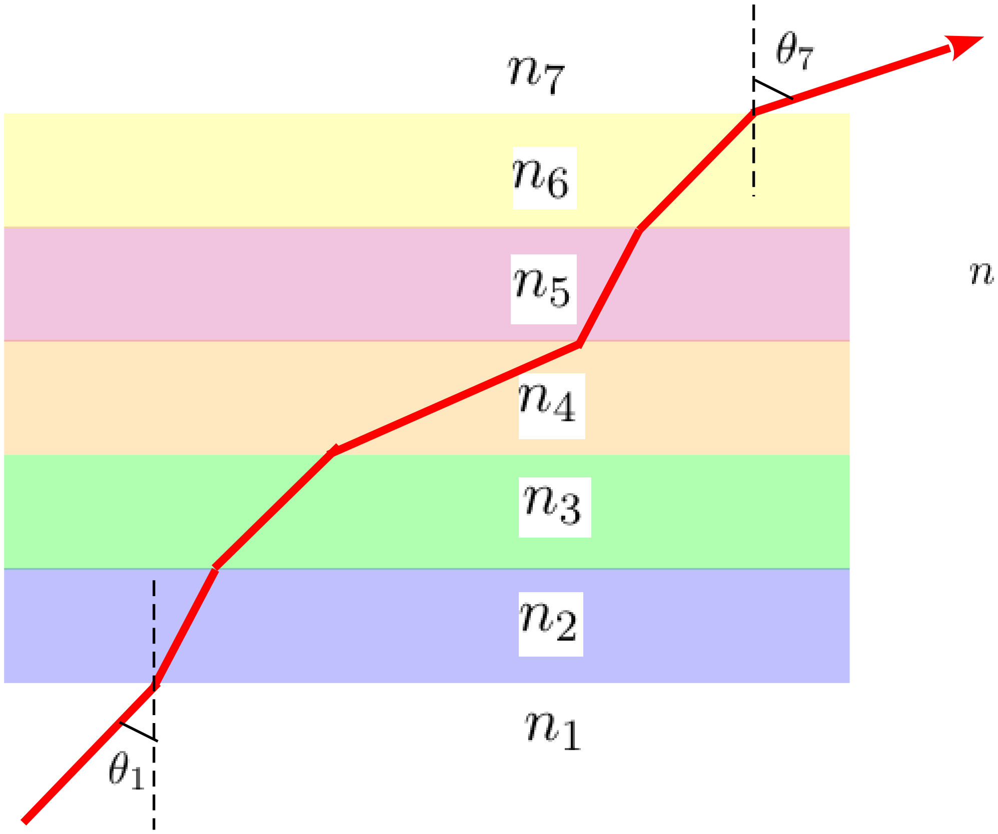
TOTAL INTERNAL REFLECTION:

Laser light launched into liquid Laminar flow streams



Courtesy of Dr Alexander Albrecht, UNM Physics & Astronomy

Propagation through stratified layers of ionosphere

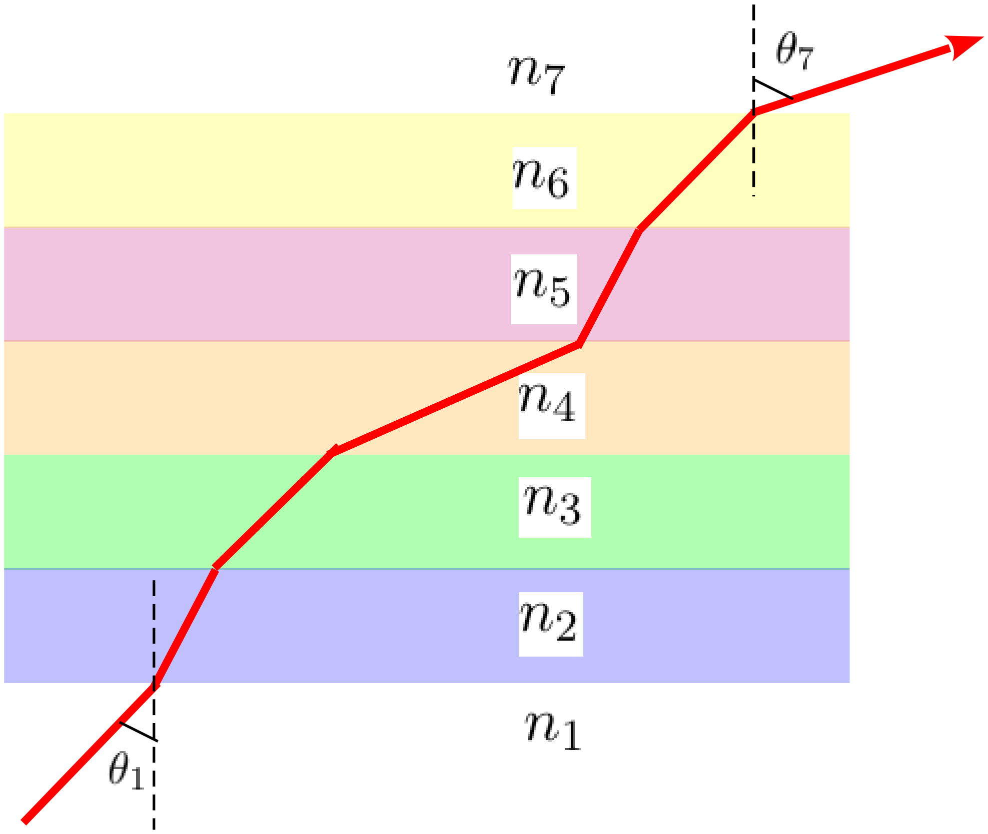


$$n_1 \sin\theta_1 = n_2 \sin\theta_2 = n_3 \sin\theta_3 = \ldots = n_7 \sin\theta_7$$

$$n_1 \sin\theta_1 = n_7 \sin\theta_7$$

$$\theta_7 < 90^{\text{o}}$$

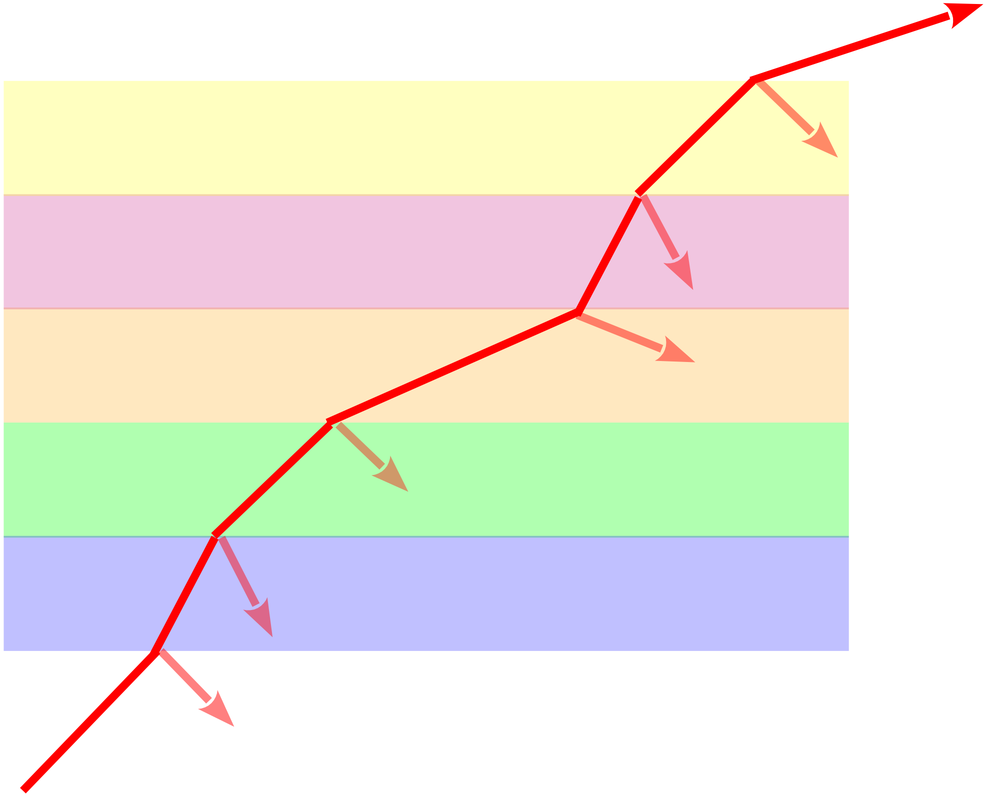
Refraction alone cannot return a radio wave back to the earth's surface



In vertically stratified layers like the **ionosphere**, no amount of refraction can bend an electromagnetic wave beyond 90 degrees.

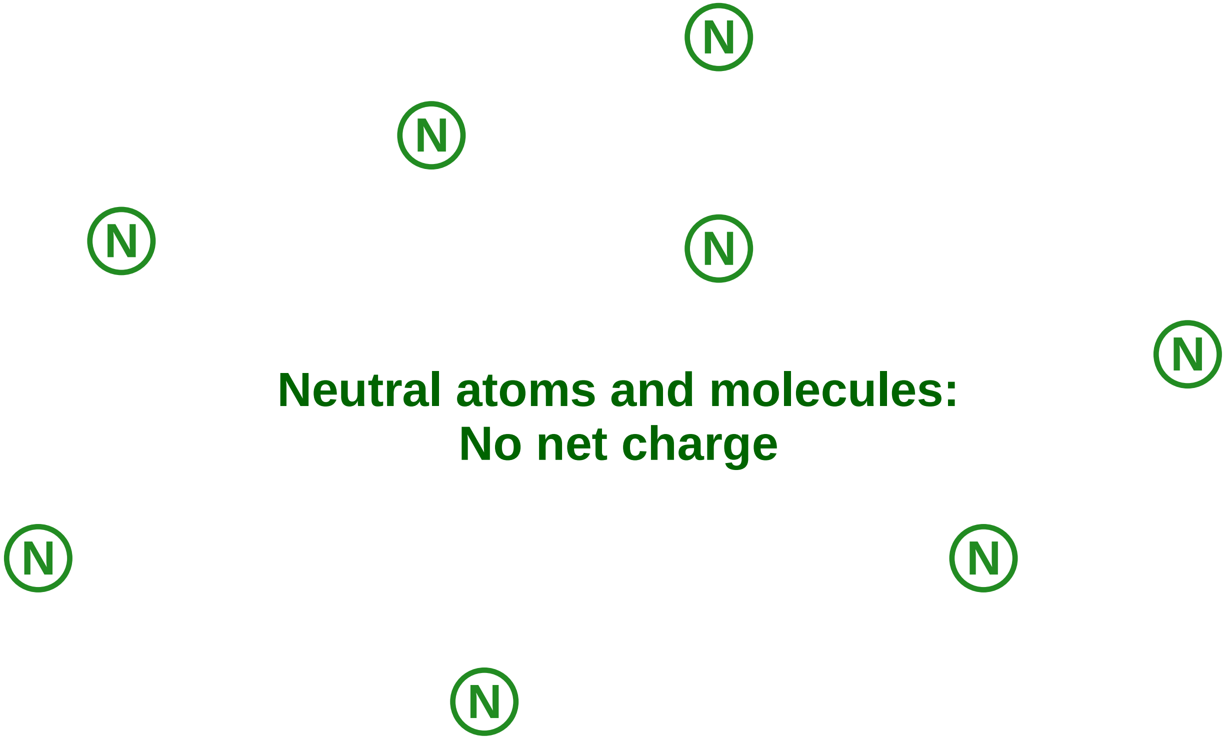
Partial reflections will occur at each interface where there is an index mismatch

Augustin-Jean Fresnel
1788-1827

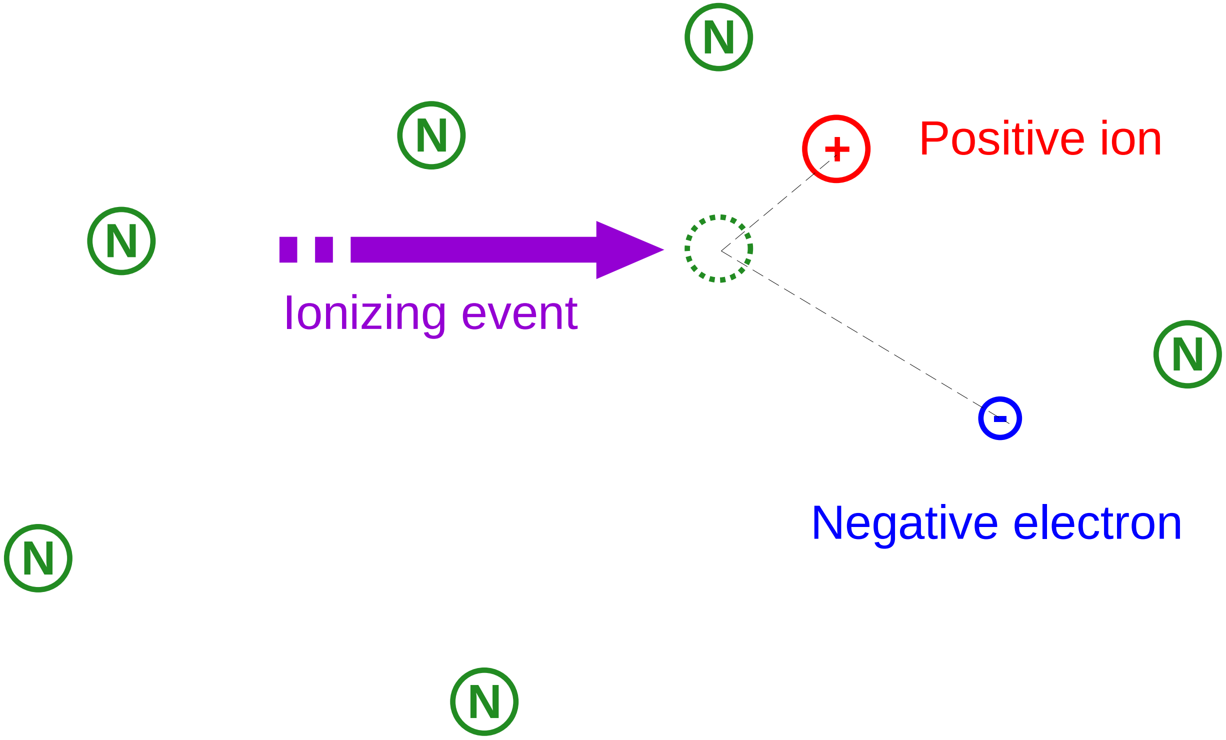


… but Fresnel **reflection** is not the same thing as **refraction**.

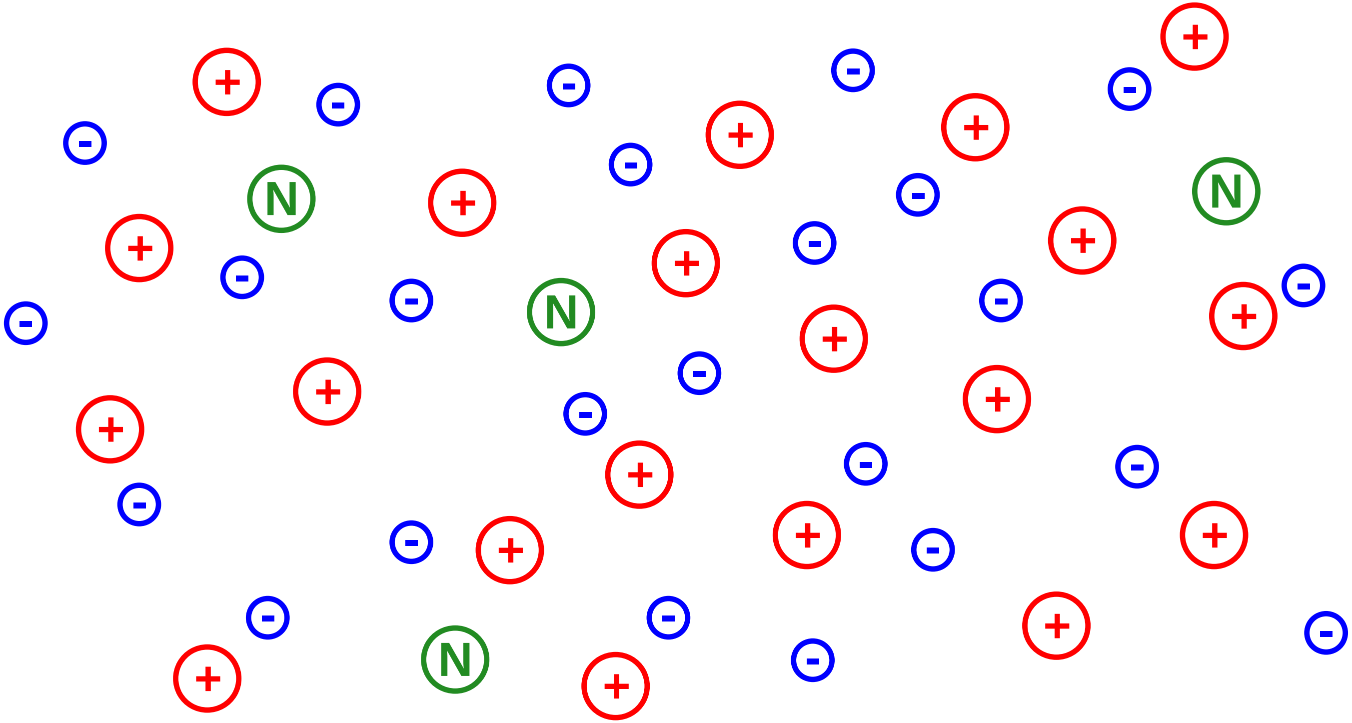
SIMPLE MODEL OF IONOSPHERE



SIMPLE MODEL OF IONOSPHERE

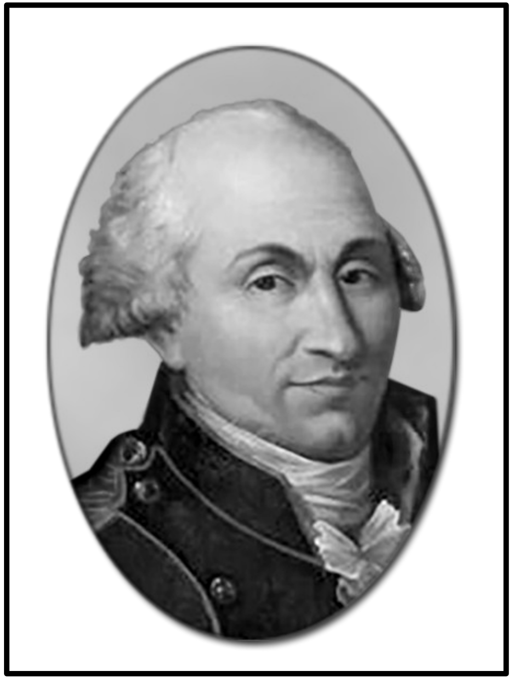


Equal density of IONS and ELECTRONS

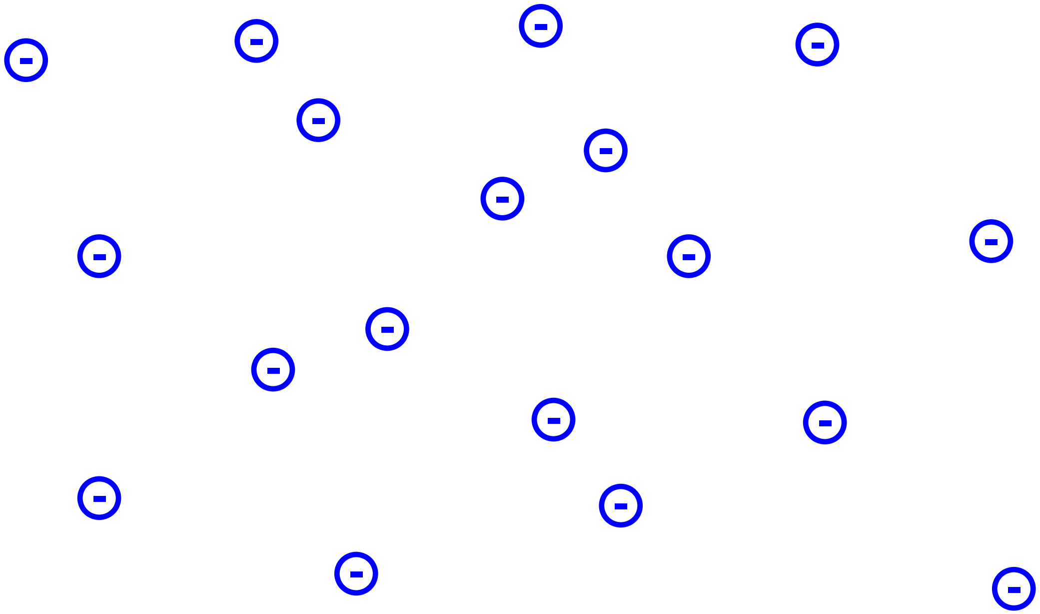


The ensemble is electrostatically neutral: *PLASMA*

It’s not just the Electrons – The Crucial Role of Ions



Charles-Augustin de Coulomb
1736--1806

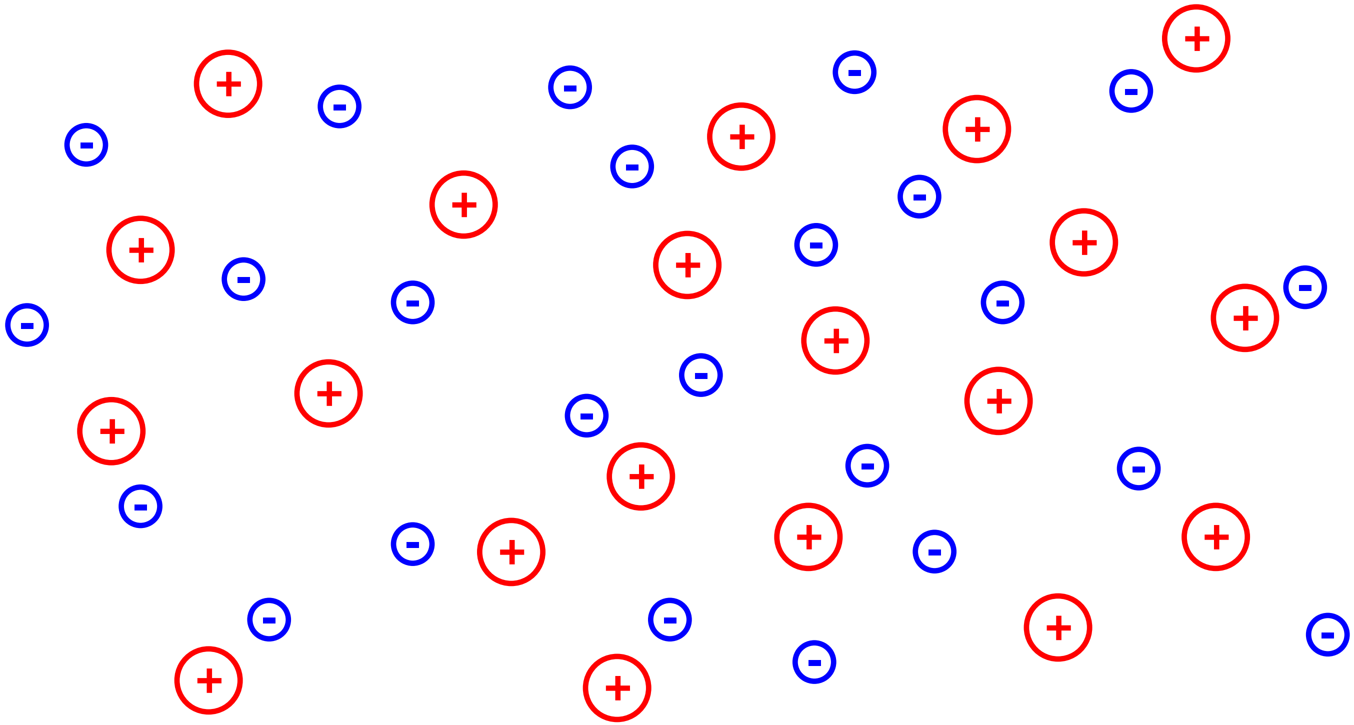


Coulomb’s Law: Like-Charges Repel

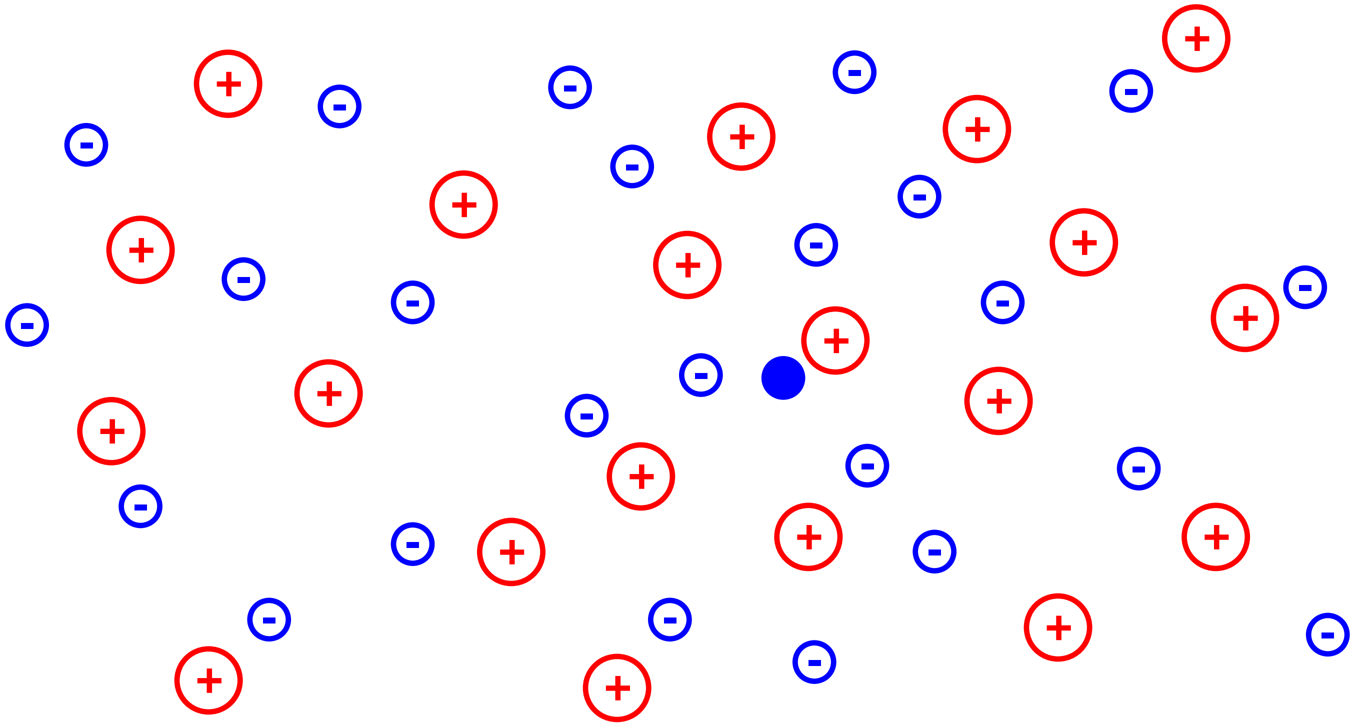
In the absence of positive ions...

...electrostatic repulsive force blows apart the electron ensemble

IONS: Heavy, fixed positions
ELECTRONS: Light and mobile
PLASMA: No net charge; + and – exactly balance

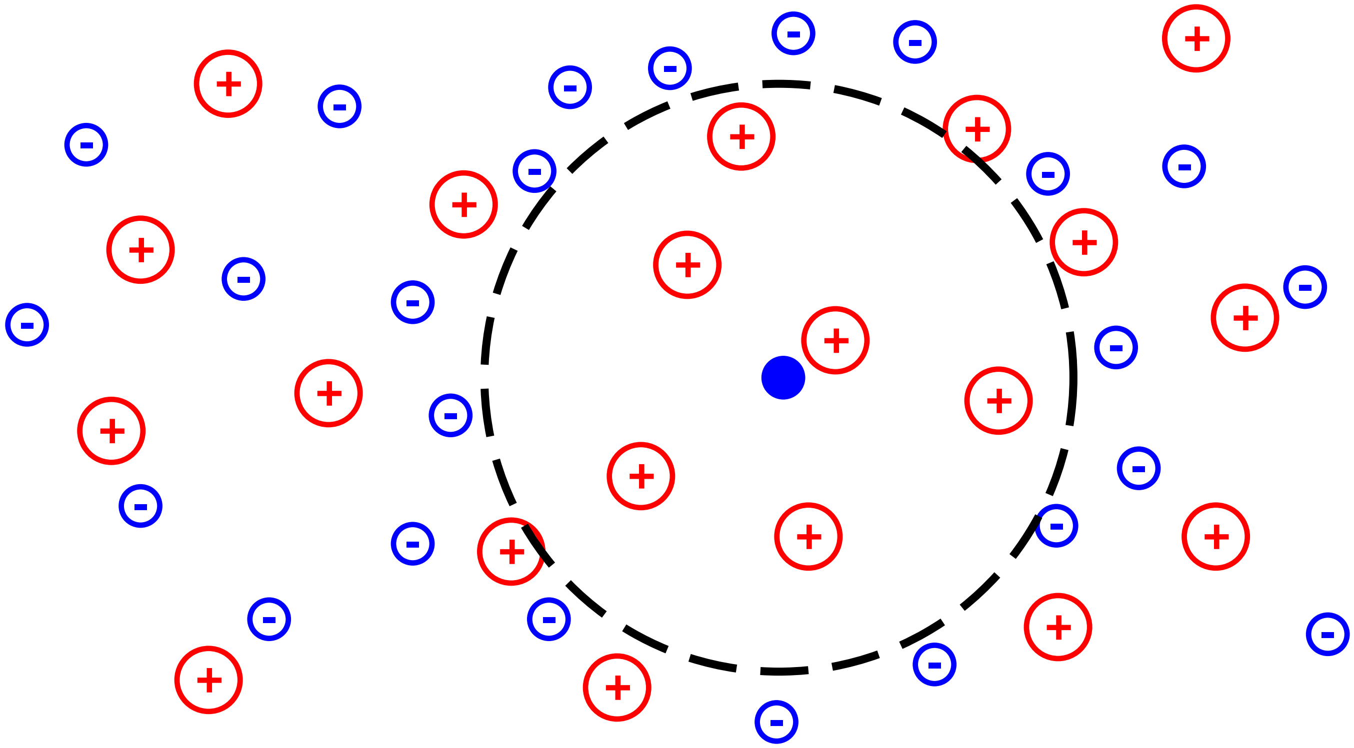


Upset the charge balance by introducing an ***extra negative charge***



Plasma does not fly apart

Mobile electrons re-arrange to ***screen*** electric field of the extra charge

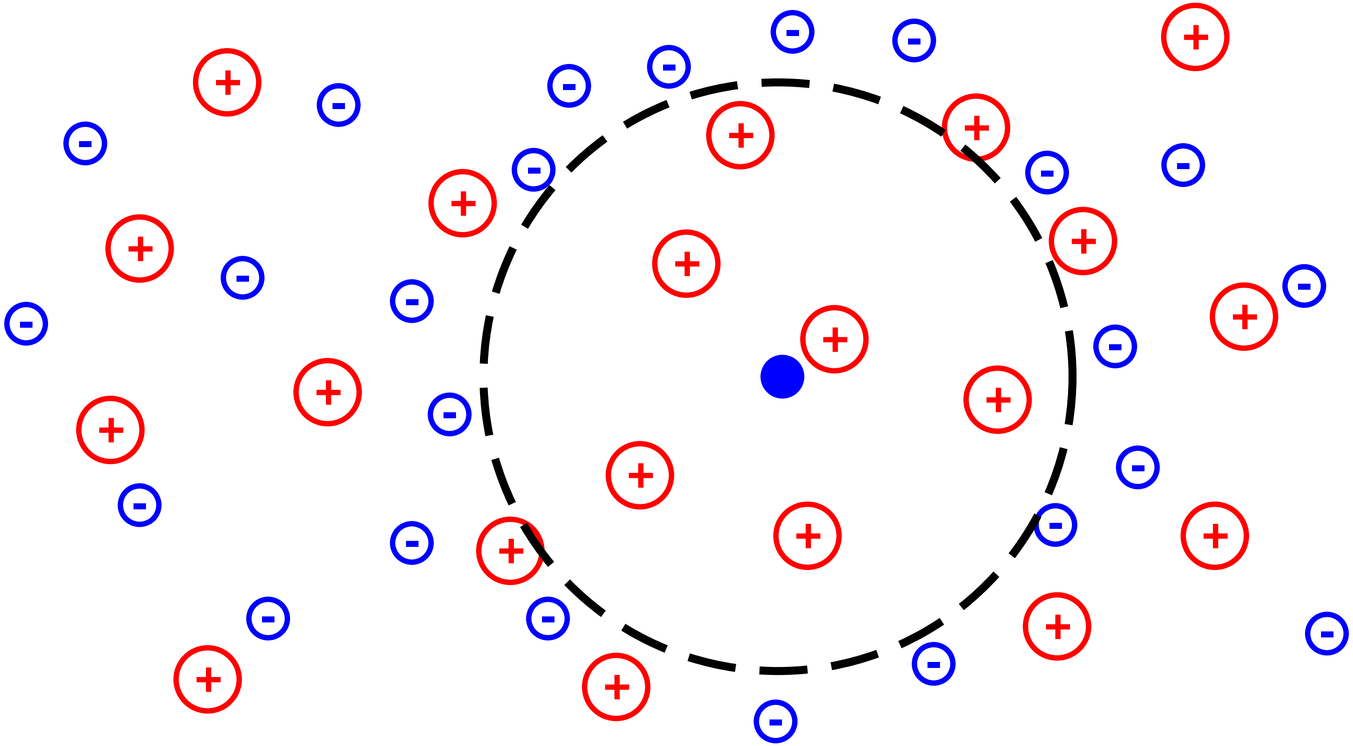


Debye Screening Radius

Outside the radius, plasma remains electrically neutral

The extra charge is “invisible”

Peter Debye
1884--1966



Paul Drude
1863--1906

Charge screening cannot happen instantly!

What are the dynamics, i.e. time response?

The Drude Model

Drude's Model of Plasma Oscillations: Interplay of Two Forces

● Electric Field (Coulomb, Gauss)

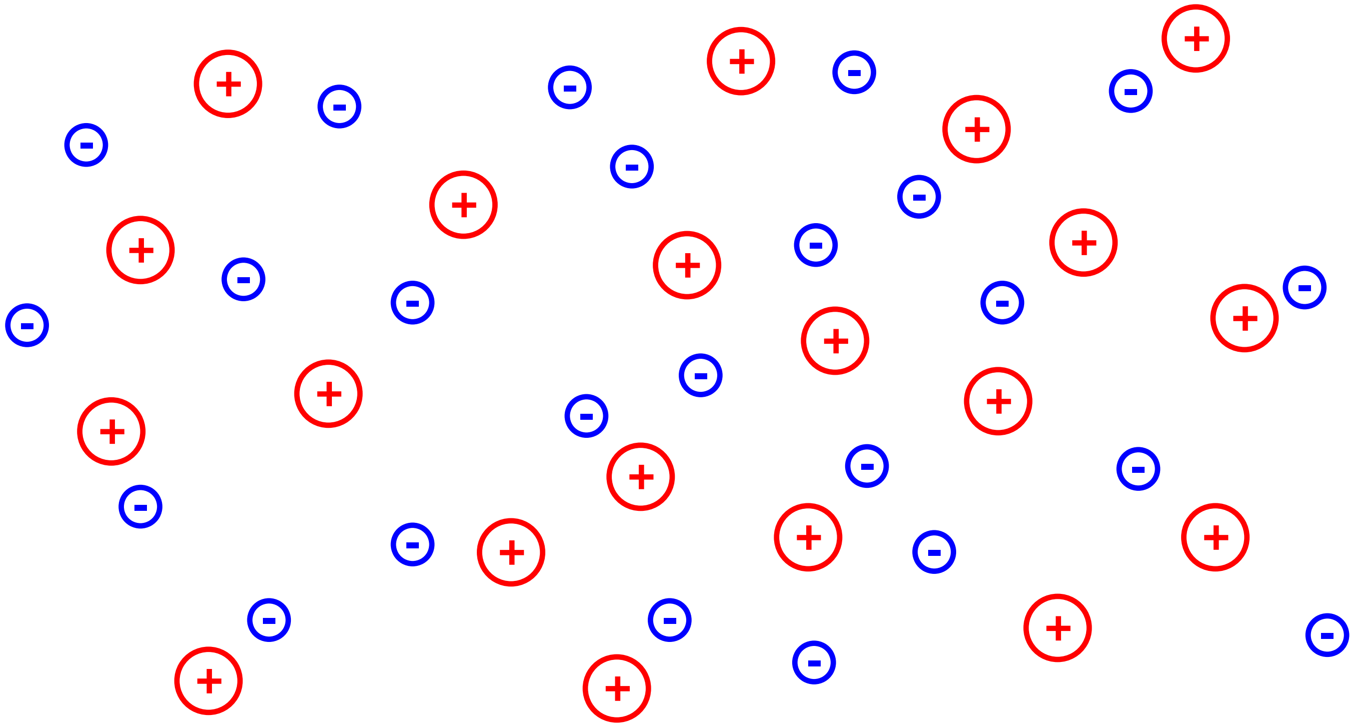
● Newton's Second Law of Motion ($F = ma$)

C.A. de Coulomb

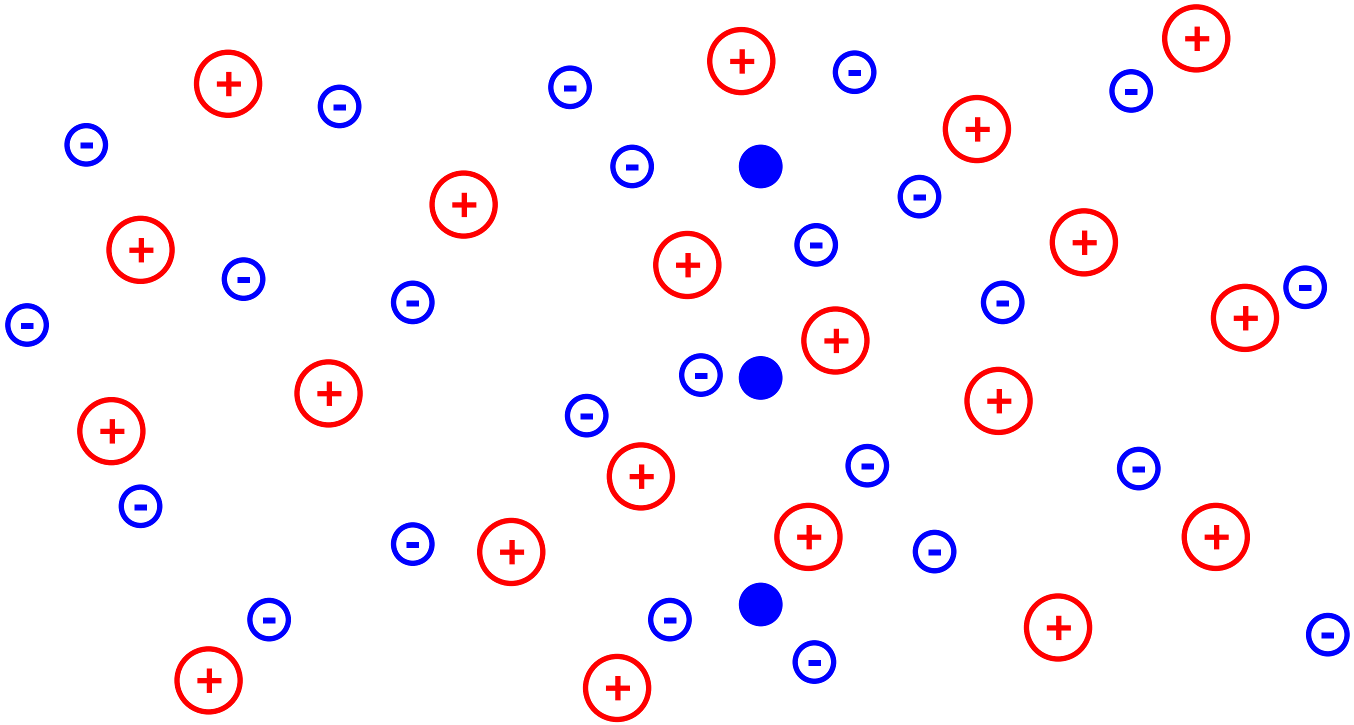
F. Gauss

I. Newton

Upset the charge balance by introducing a line of ***negative charge***

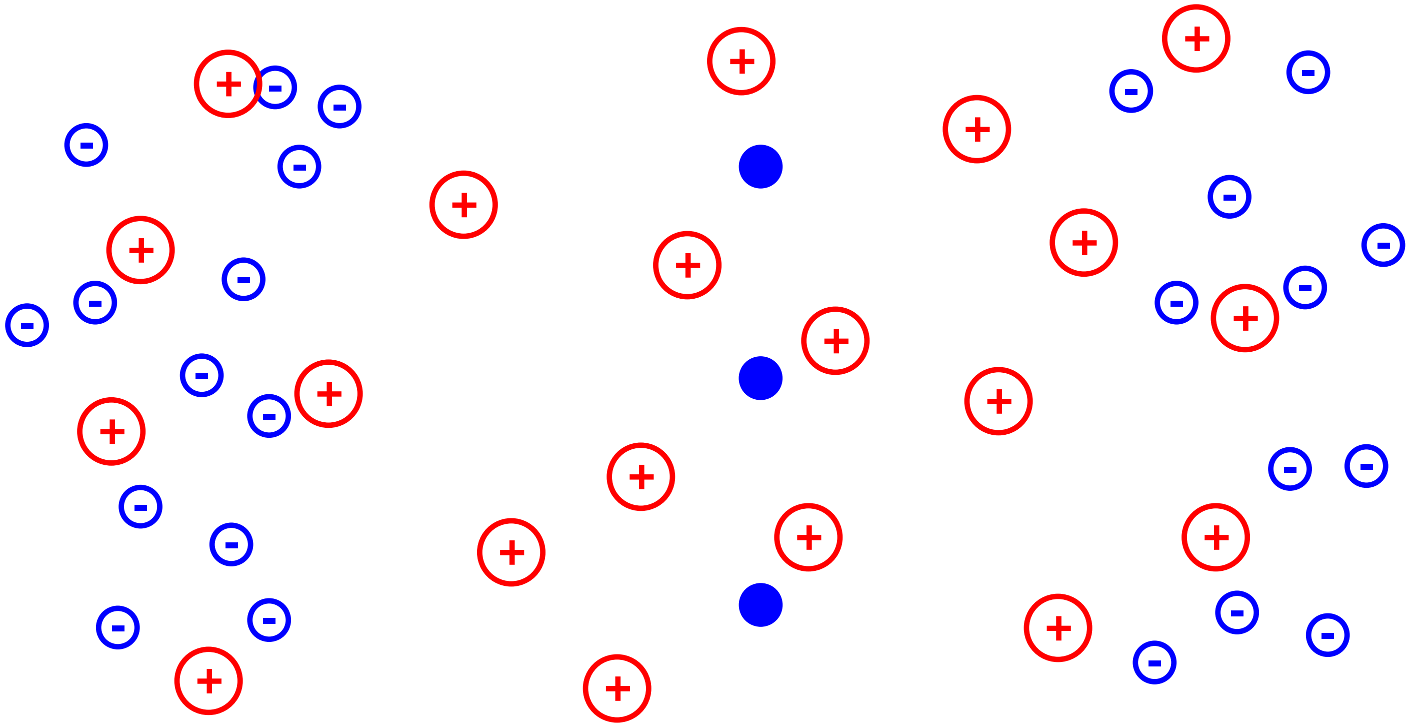


Upset the charge balance by introducing a line of ***negative charge***



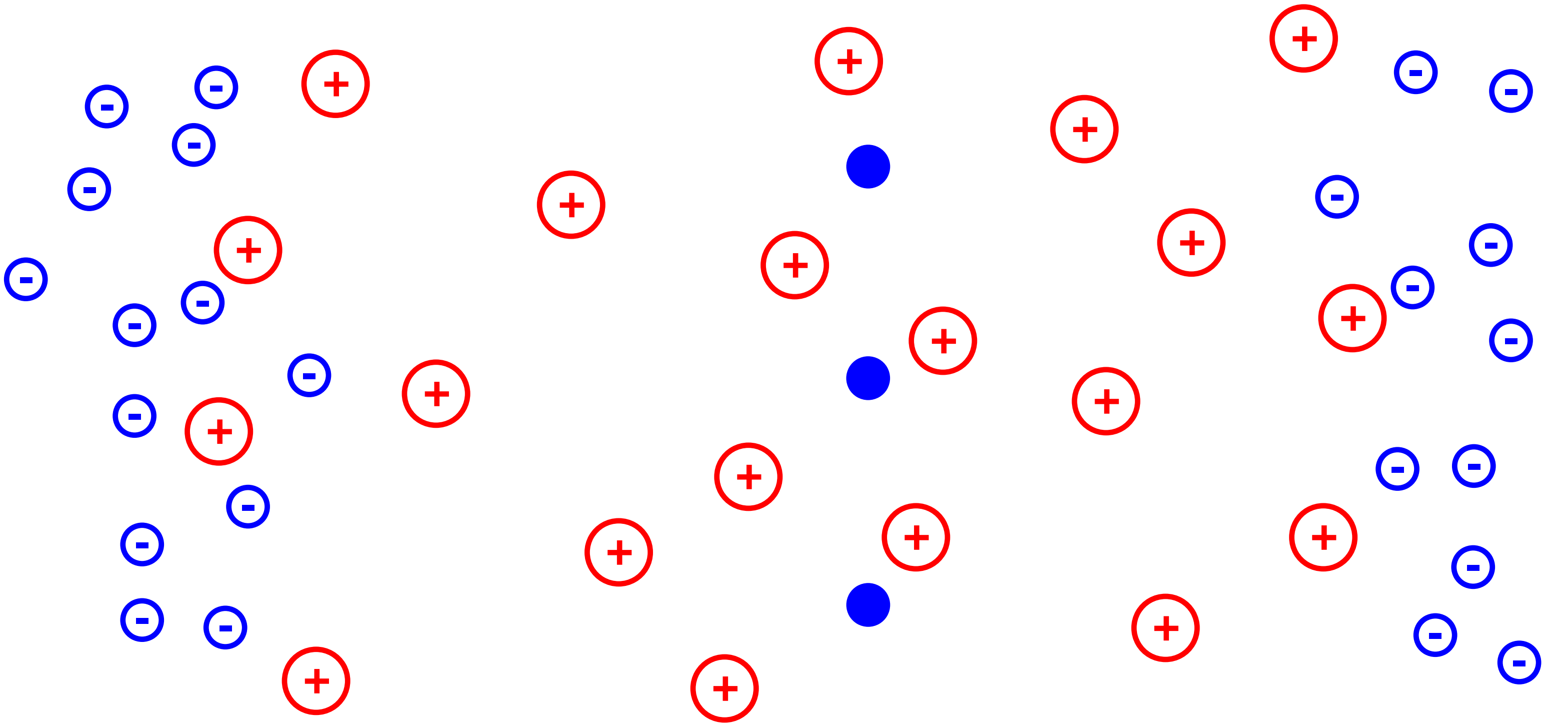
Highly mobile negative electrons are quickly repulsed

Heavy positive ions remain stationary

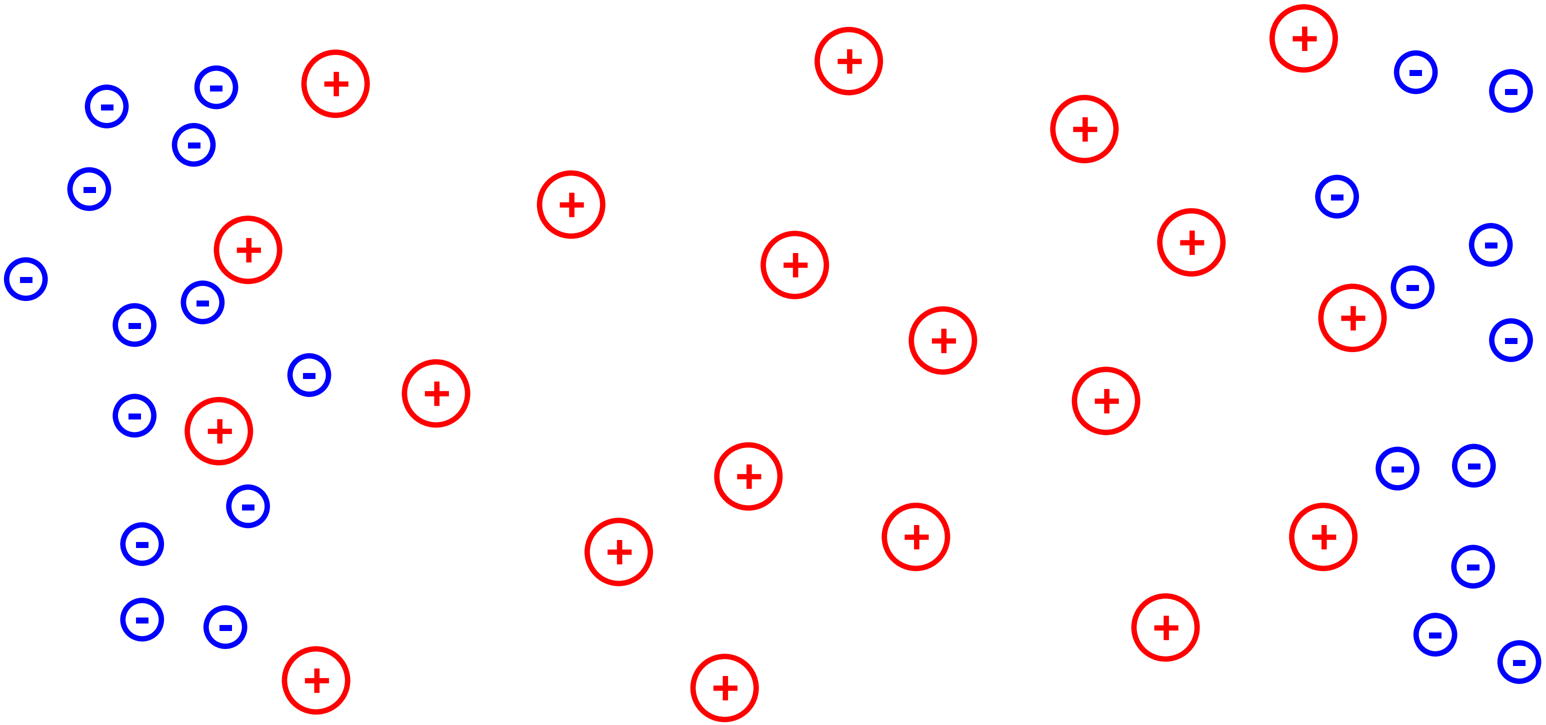


Because electrons are so light,

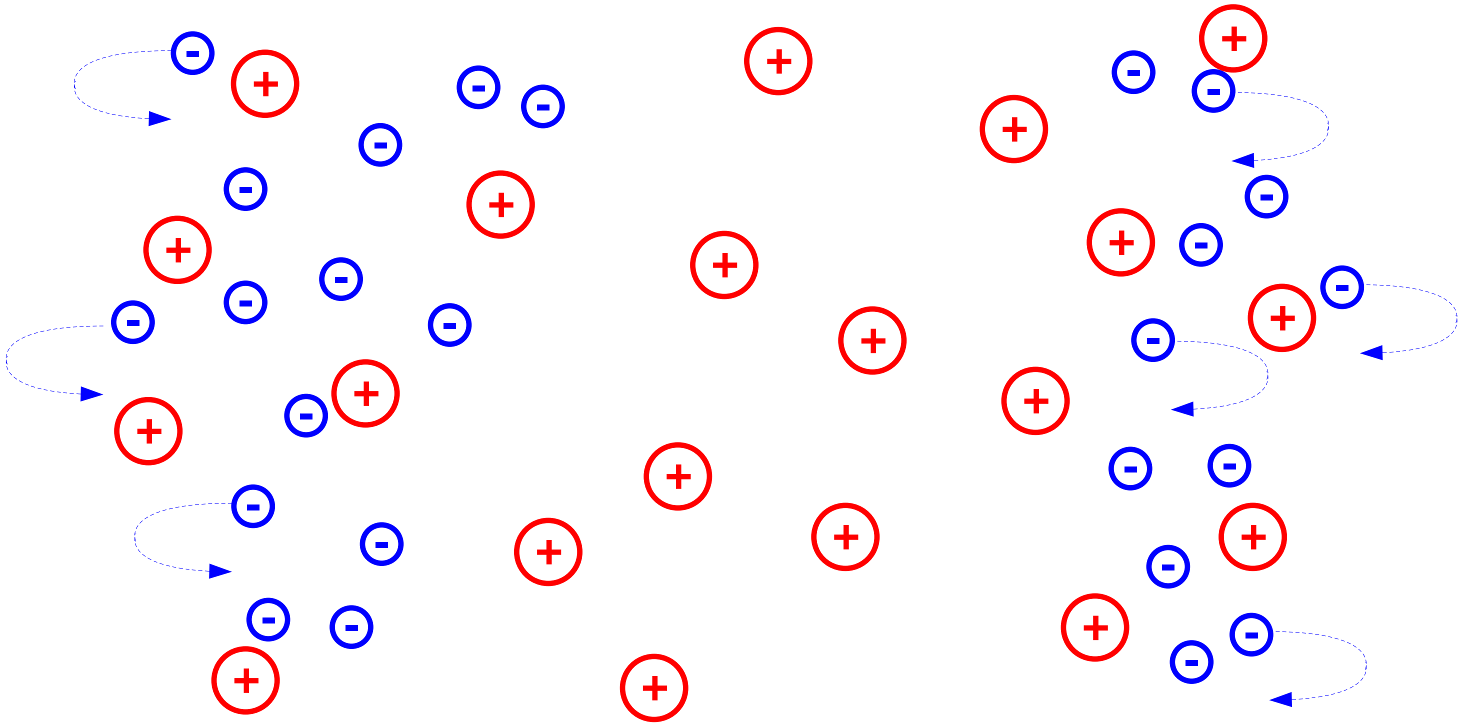
they *OVERSHOOT* the static screening distance



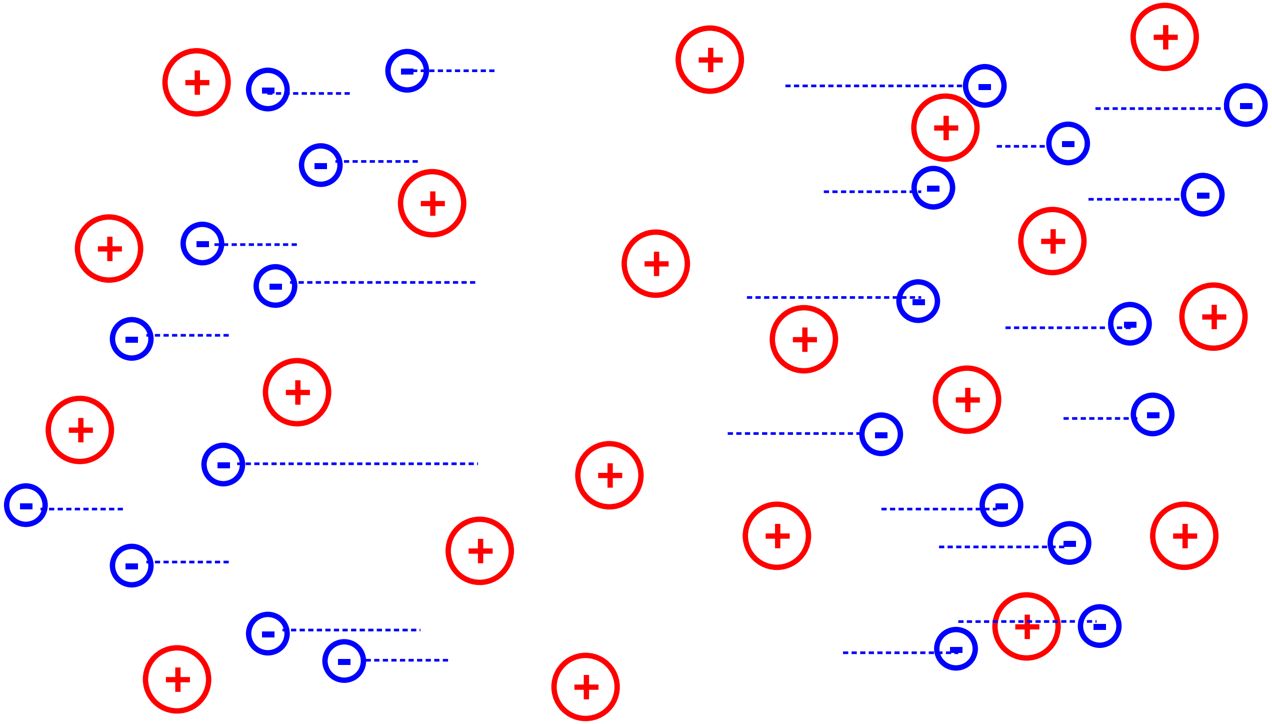
Unscreened positive ions exert attractive electric force on the electrons



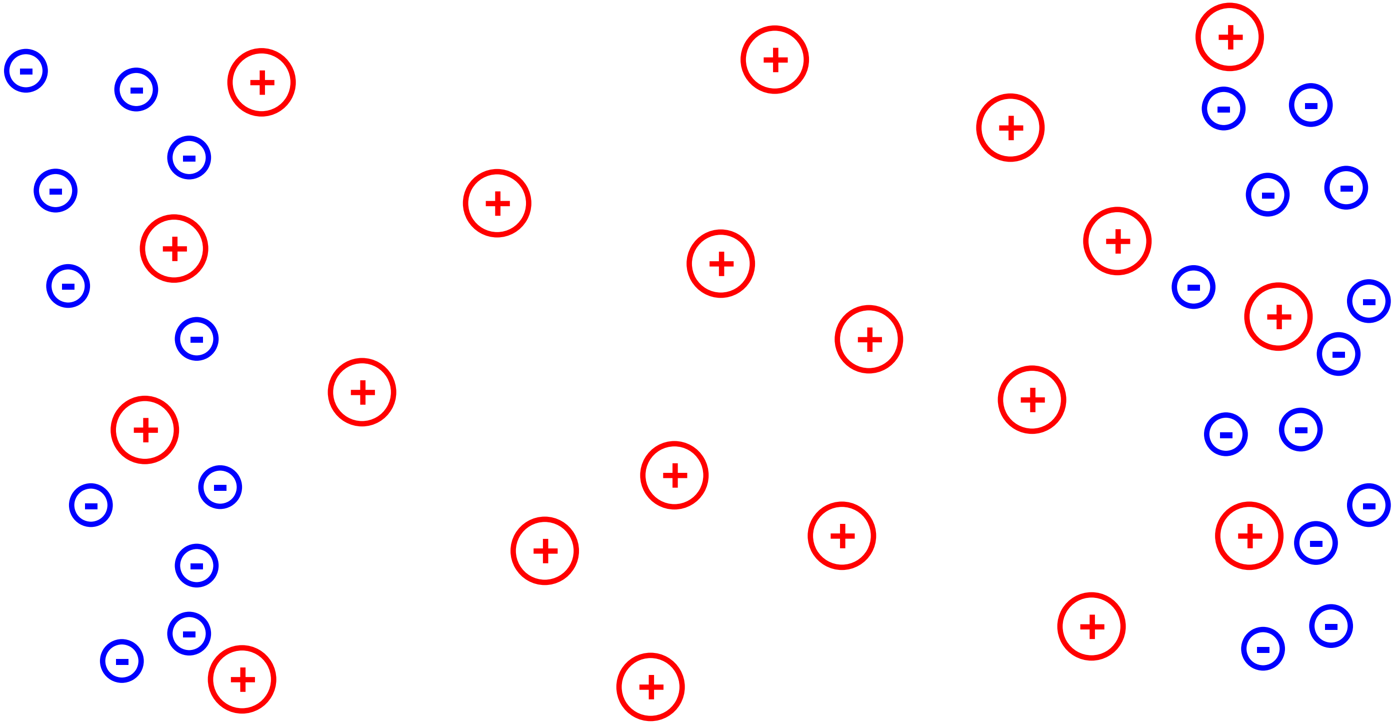
Electrons stop and get pulled back by the ions



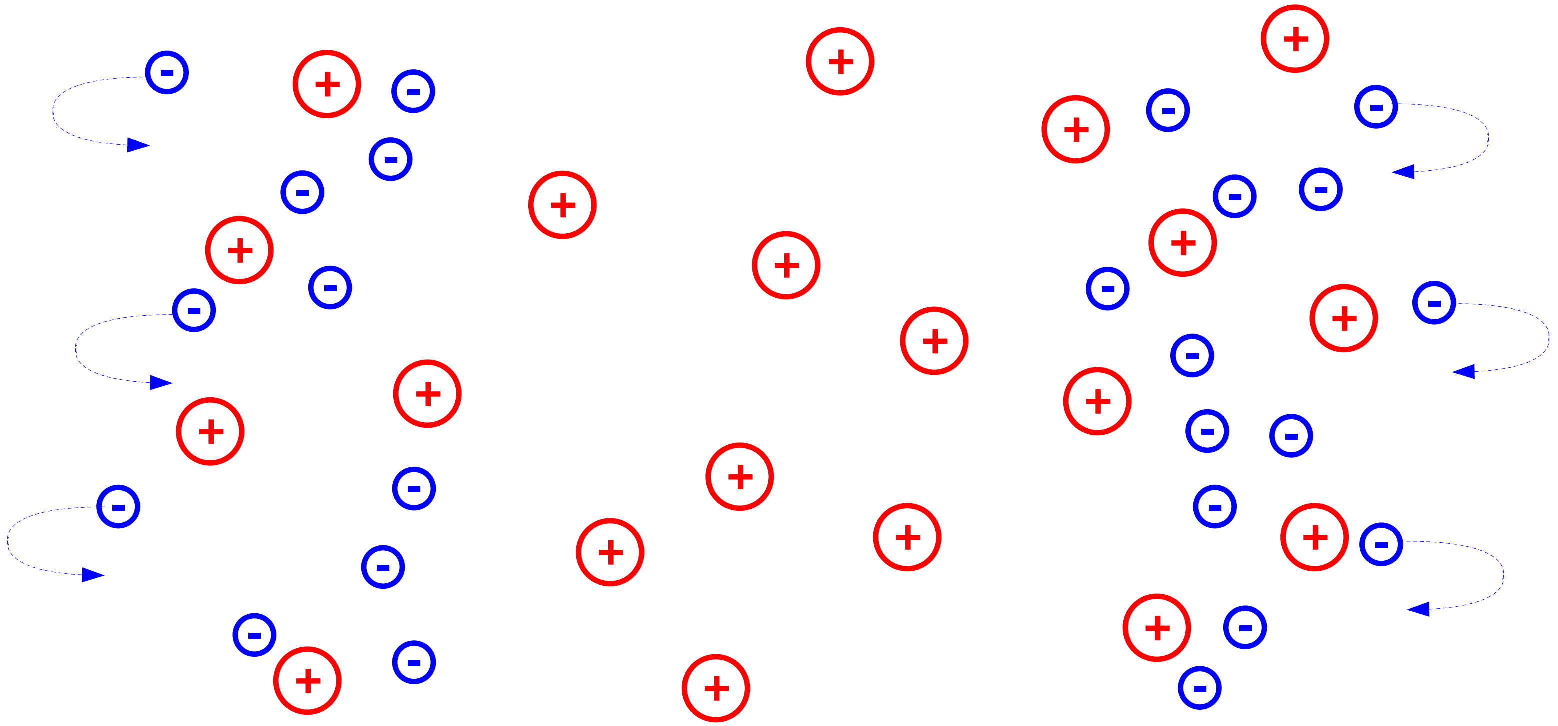
But electrons have inertia and overshoot the equilibrium position ...



… until they are stopped again by attractive Coulomb force of the positive ions

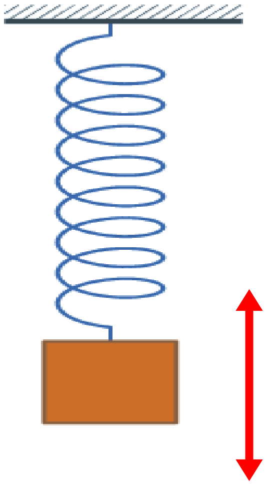


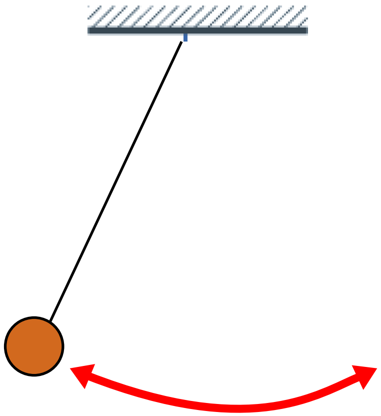
And the process repeats. This is collective charge oscillation



Classical picture of plasma oscillations

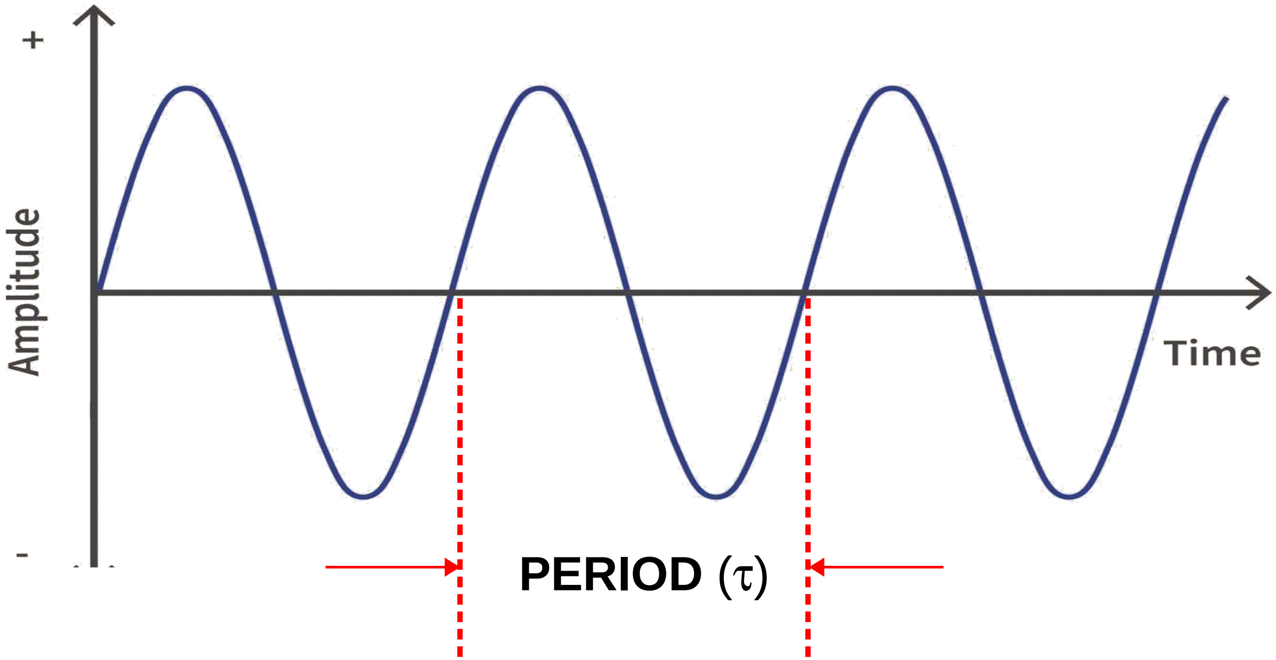
Modeled similar to a vibrating spring or swinging pendulum





HARMONIC OSCILLATOR

HARMONIC OSCILLATOR:
Sinusoidal motion with a characteristic frequency



$$\text{FREQUENCY} = \frac{1}{2 \pi \tau}$$

Natural (resonant) frequency of plasma oscillations (f_p)*

$$f_p = \frac{1}{2\pi}\sqrt{\frac{Nq^2}{m\epsilon_0}}$$

N: Density of electrons (or ions)

q : Charge on the electron

m : Mass of the electron

ϵ_0 : Physical constant

* Also known as the critical frequency

REFRACTIVE INDEX OF PLASMA (IONOSPHERE)

$$\sqrt{1-\left(\frac{f_p}{f}\right)^2} = \sqrt{1-\kappa\frac{N}{f^2}}$$

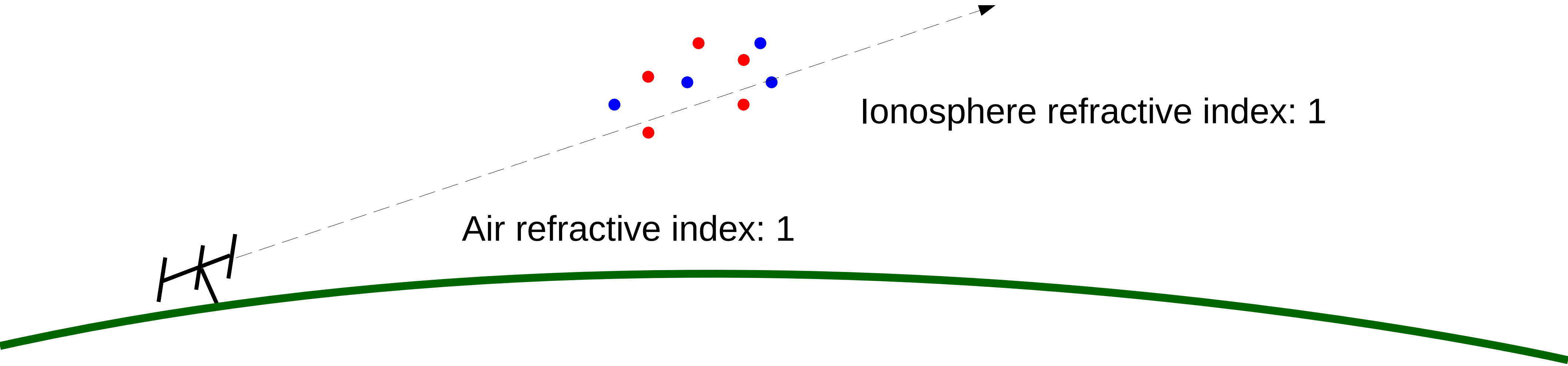
N: Density of electrons (or ions)

f : Frequency of electromagnetic wave

κ: Constant

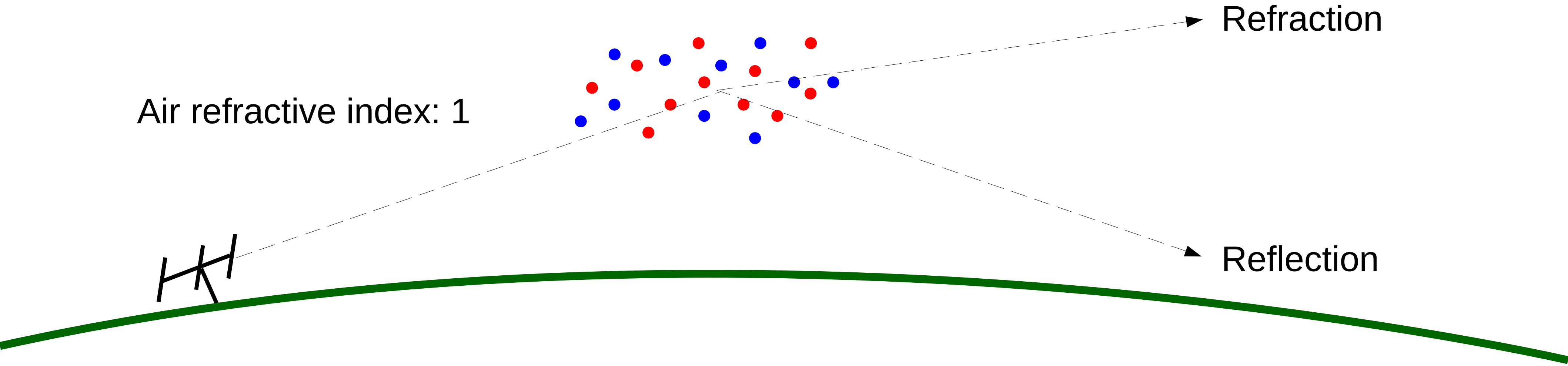
$$\sqrt{1 - \kappa \frac{N}{f^2}}$$

Weak Ionization ⇨ N is small ⇨ Ionosphere Index ≈ 1 ⇨ Transparent



$$\sqrt{1 - \kappa \frac{N}{f^2}}$$

Moderate Ionization: Ionosphere refractive index < 1



Depends on plasma density, radio frequency, incidence angle, polarization

$$\sqrt{1-\kappa\frac{N}{f^2}}$$

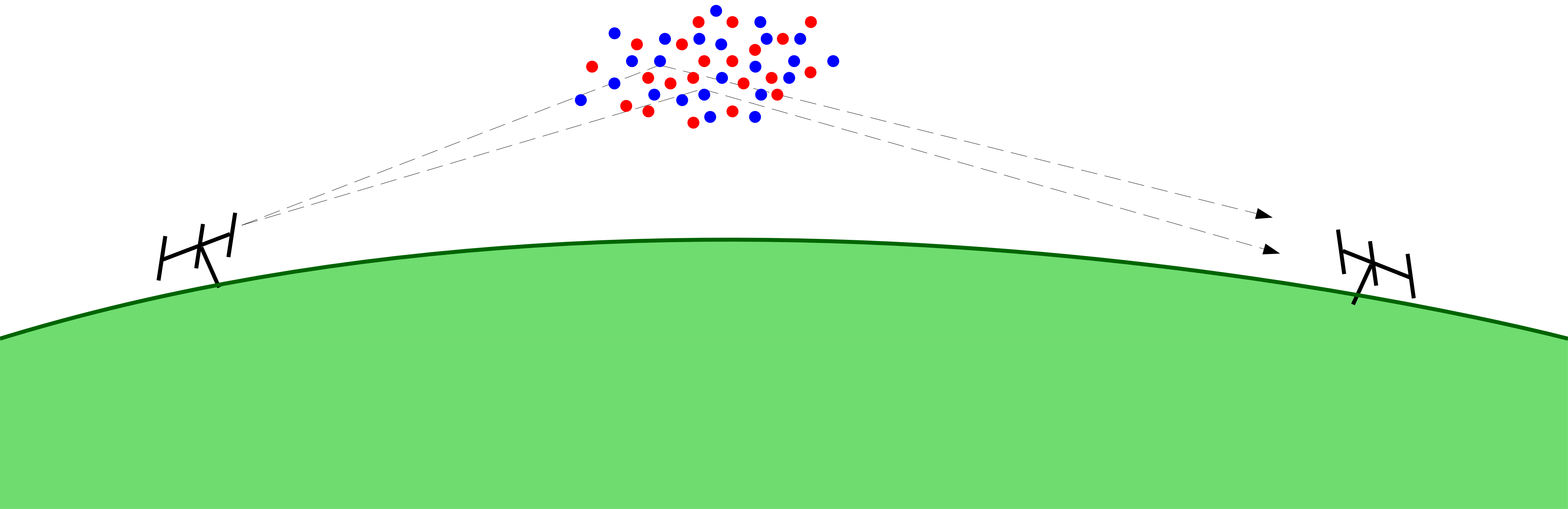
What happens when: $\kappa\frac{N}{f^2} > 1$ **???**

Refractive index of ionosphere becomes imaginary

Ionosphere appears *metallic* to the electromagnetic wave

Metallic ionosphere is opaque

Electromagnetic wave is completely **REFLECTED**

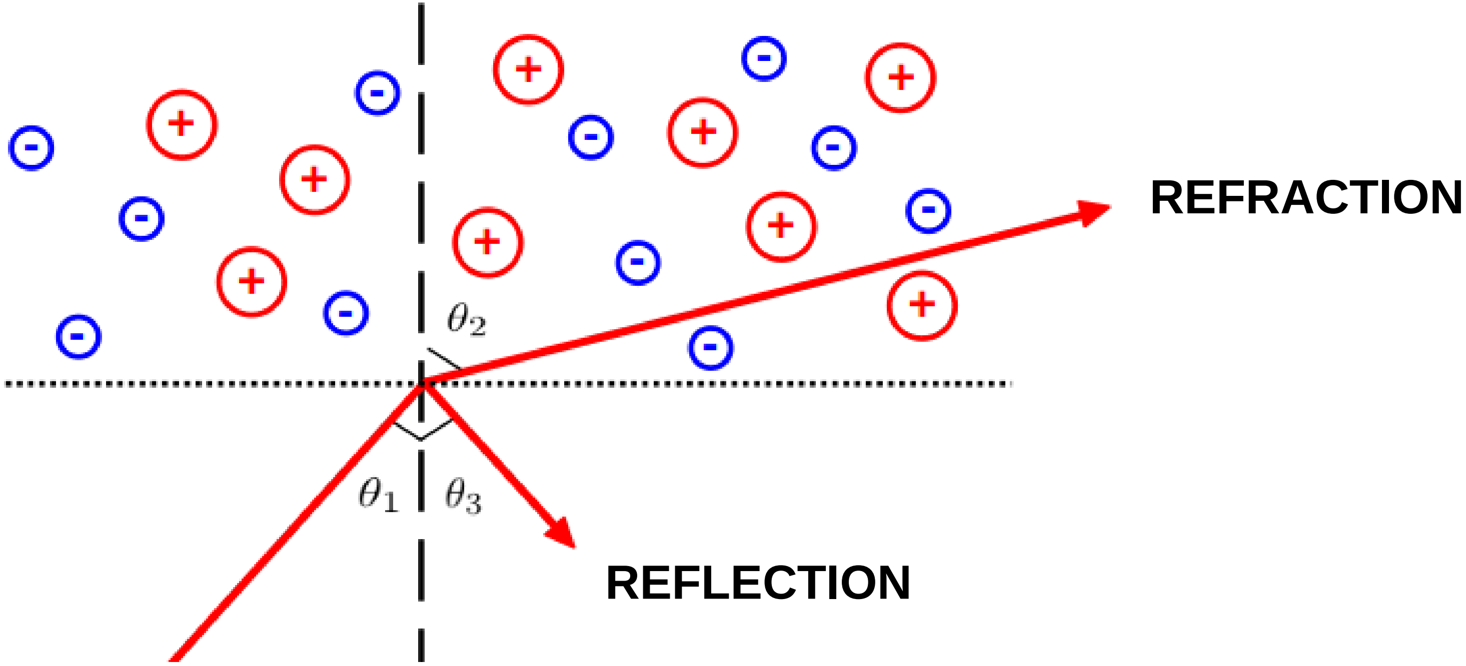


VHF PROPAGATION

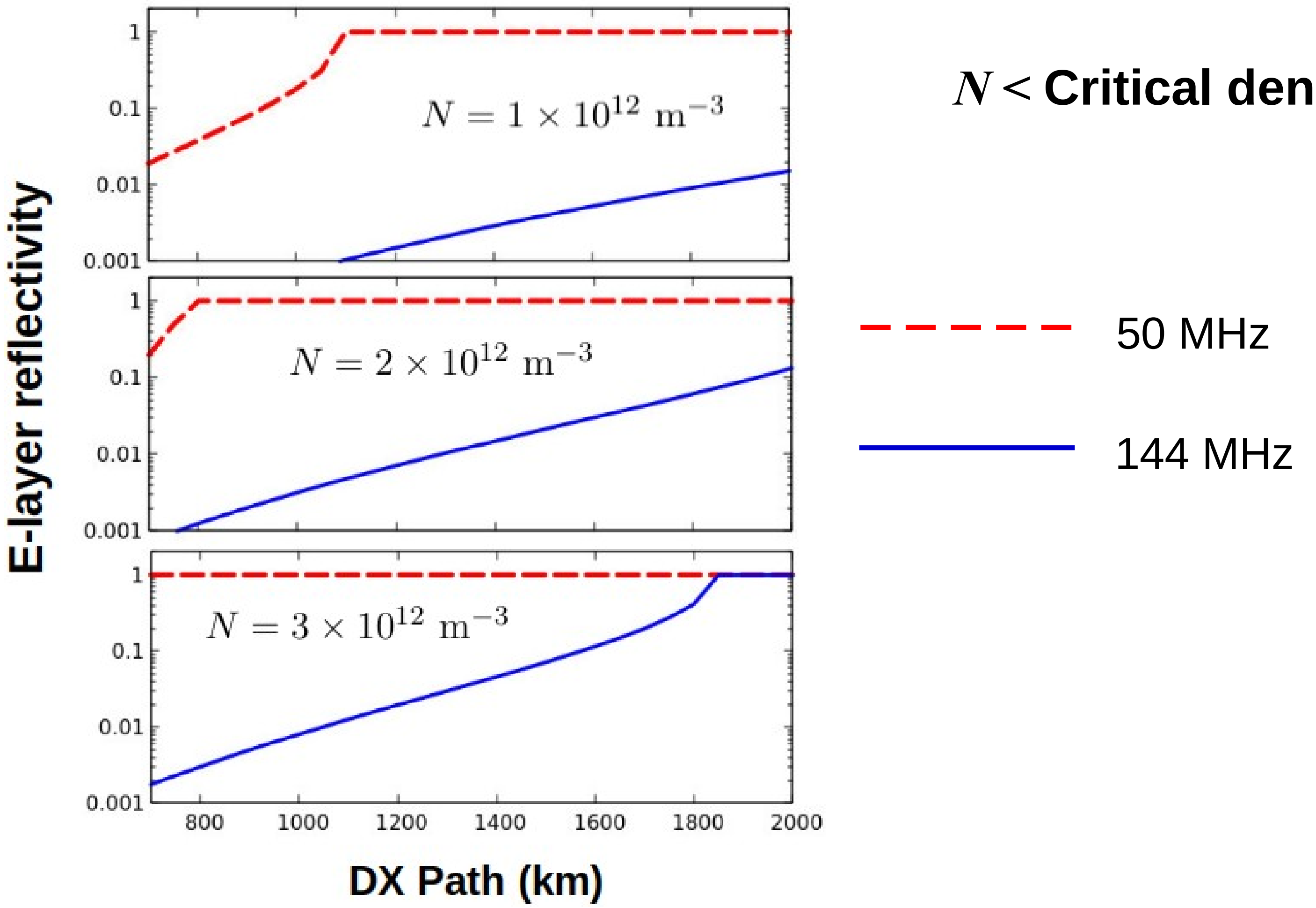
Use classical plasma model to calculate ionosphere reflection at 50 and 144 MHz

$$n_2 = \sqrt{1 - \kappa \frac{N}{f^2}}$$

Air: $n_1 = 1$



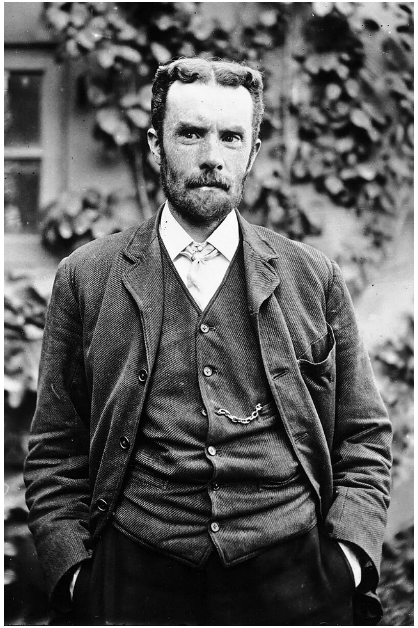
Calculated Fresnel reflectivity of *E*-layer with increasing ionization



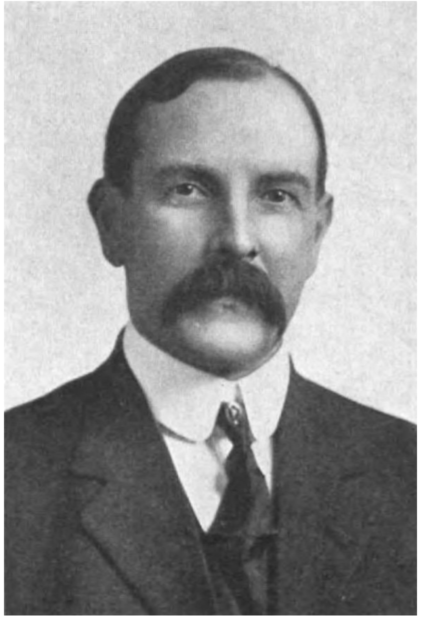
QUESTION: **When you look in the mirror ...**

Are you seeing your reflection or your refraction?

ACKNOWLEDGEMENTS



Oliver Heaviside
1850-1925



Arthur Kennelly
1861-1939

Edward Appleton
1892-1965