Introduction to Incoherent Scatter

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MIT Haystack Observatory

With credit and thanks to **Anja Strømme**, Craig Heinselmann, Phil Erickson, Bill Rideout, Josh Semeter, Juha Vierinen

And my advisor: William E. Gordon

Outline

Distribution of ISRs across the world

Introduction to ISR principles and Incoherent Scatter Spectrum

Global Network of Incoherent Scatter Radars

Can Measure Physical Properties of the Space Environment
<u>as a function of altitude</u>:

electron density, electron temperature, ion temperature, plasma velocity

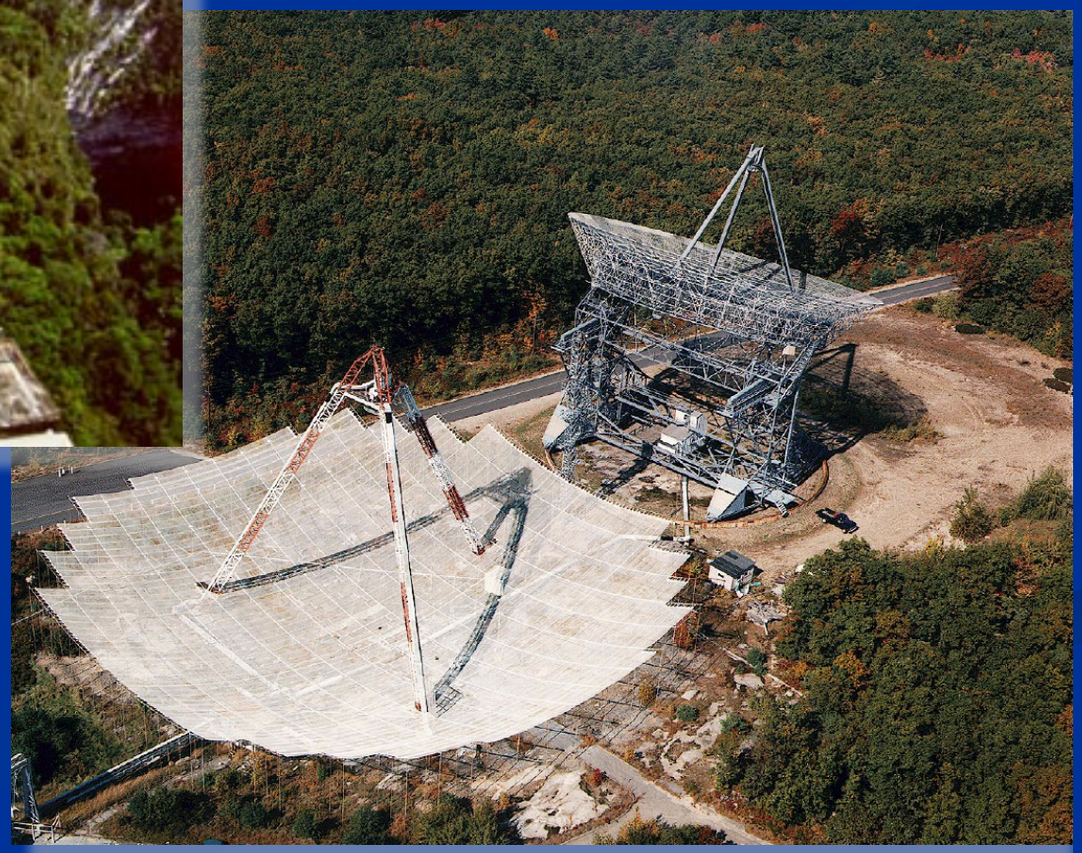
Can Infer:

electric field strength, conductivity, current, neutral air temperature, wind speed

High-Latitude Incoherent Scatter Radars

PFISR (Poker Flat Incoherent Scatter Radar) and RISR-N (Resolute Bay Incoherent Scatter Radar)

Mid-Latitude Incoherent Scatter Radars



Low-Latitude Incoherent Scatter Radars

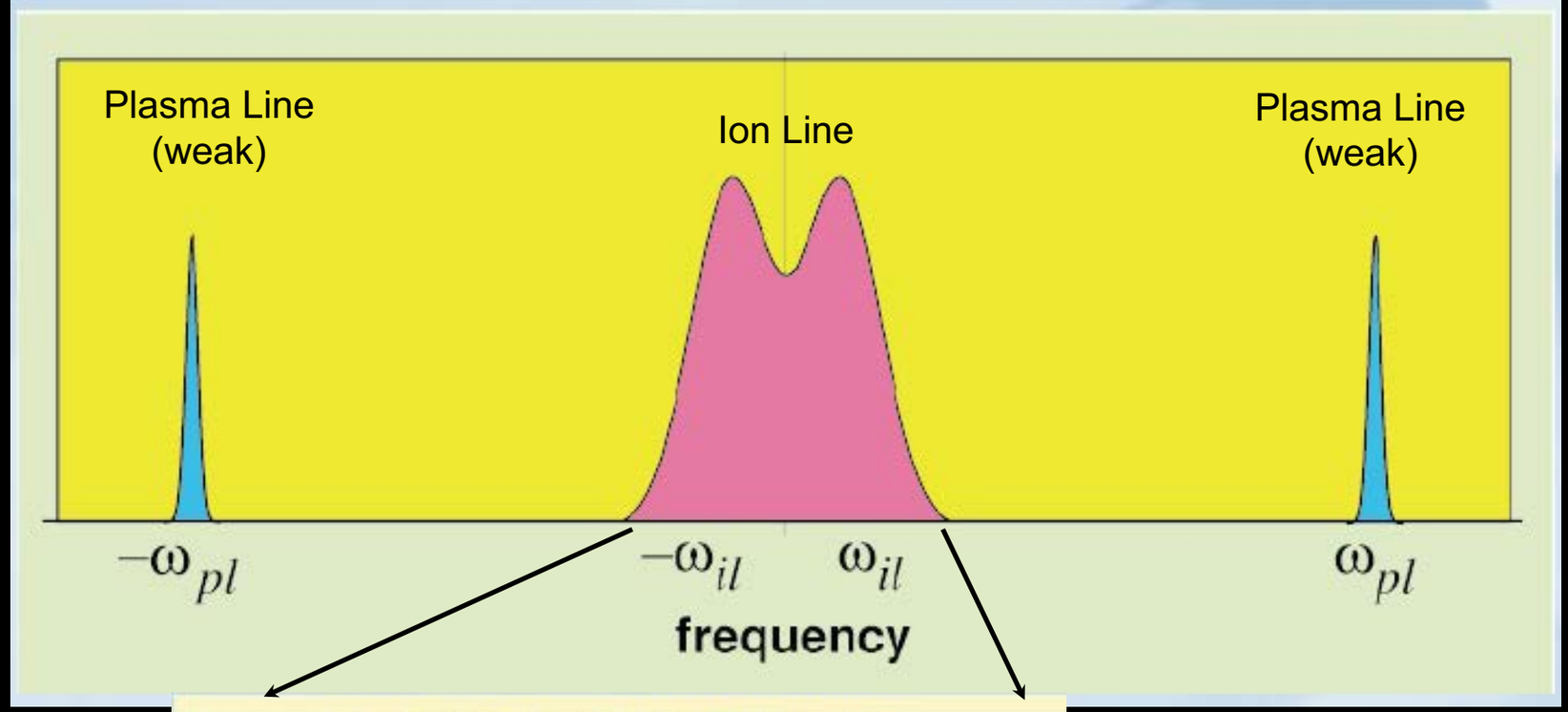
IS Radar Remote Sensing Capabilities

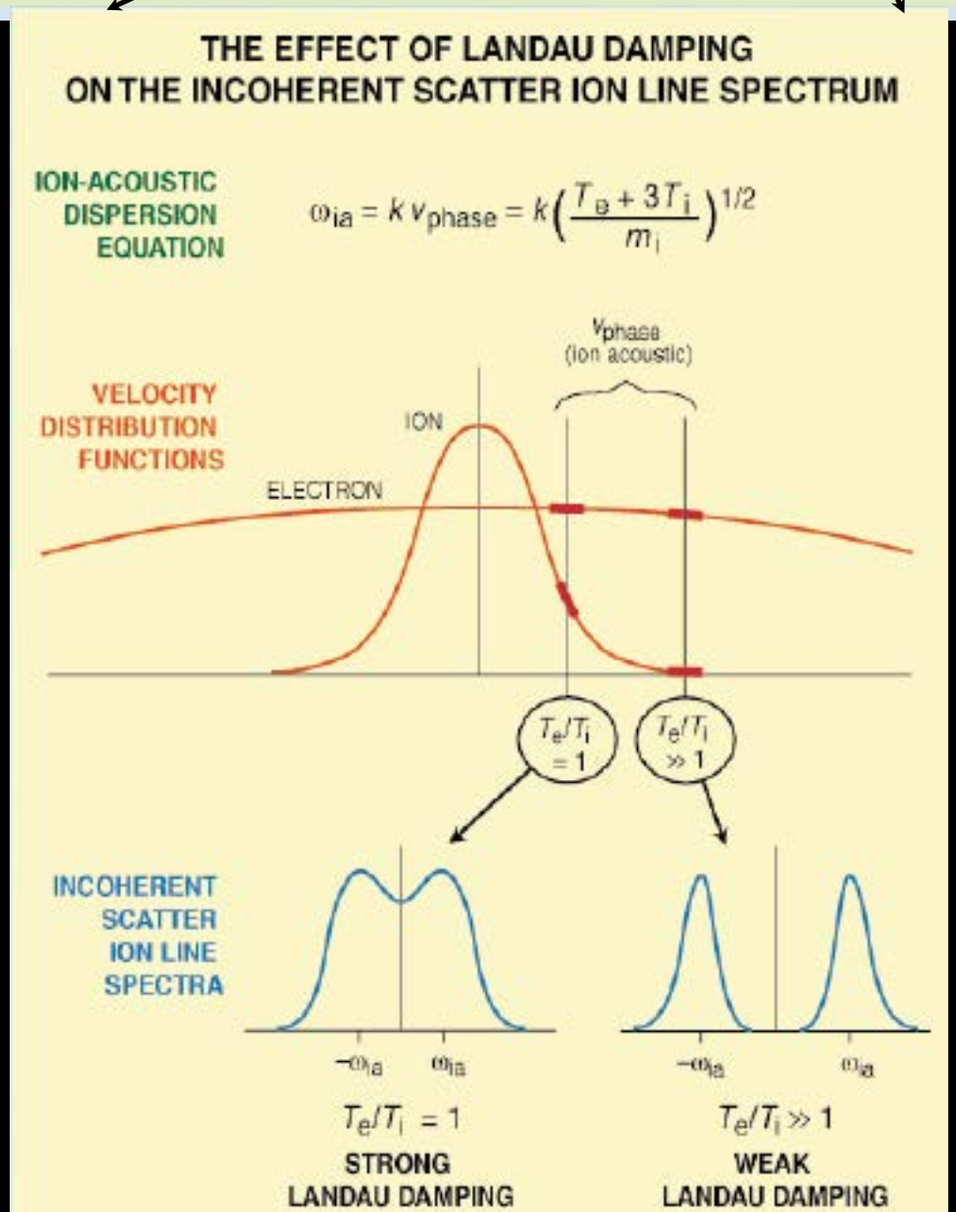
Parameters sensed:

Basic
- Electron density
- Electron temperature
- Ion temperature
- Ion composition
- LOS Velocity

Derived
- Neutral winds
- Neutral temperature
- Vector velocity

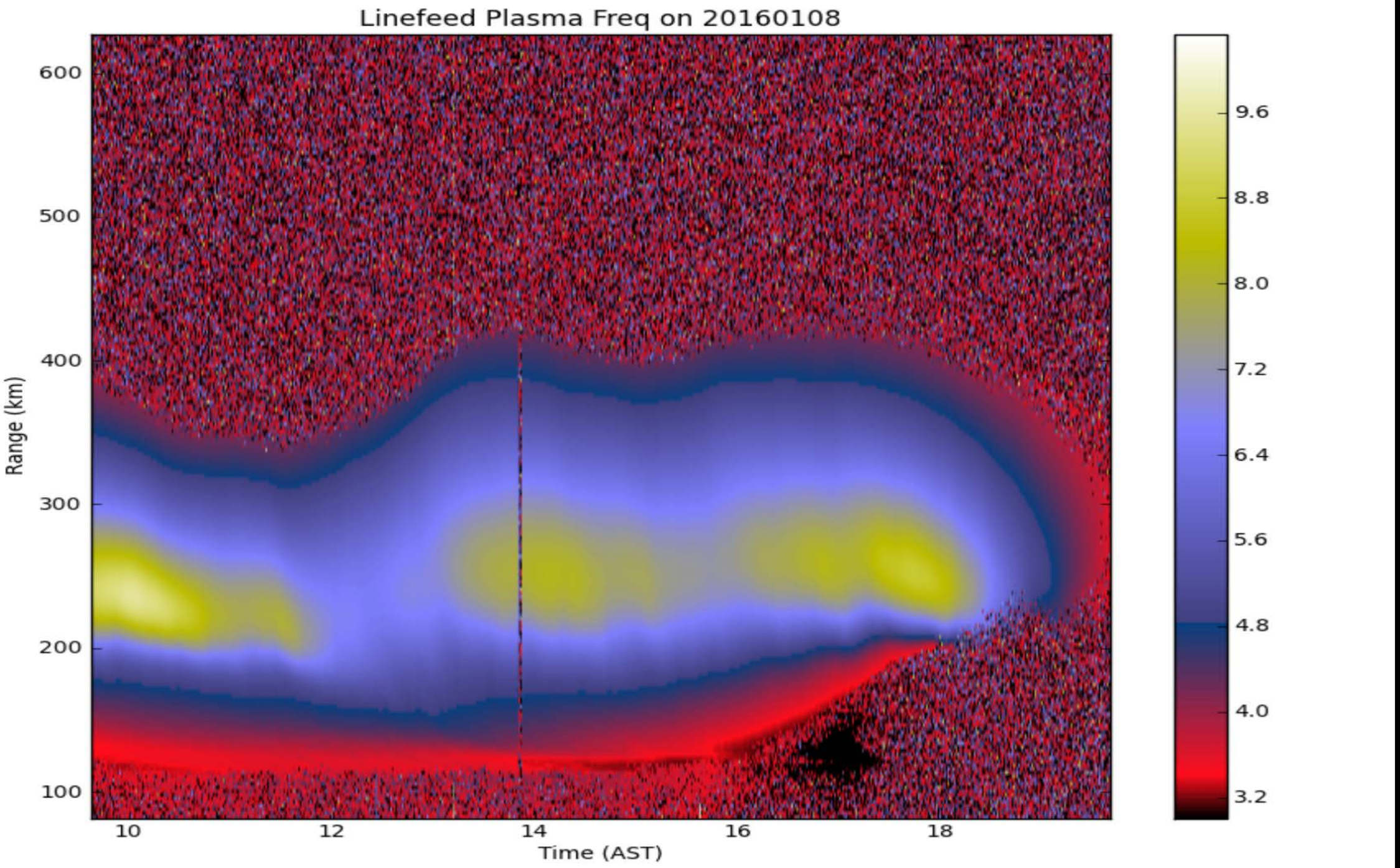
More limited
- Ion-neutral collisions (E region)
- Background mag field (equator)
- Regularized binned/gridded data
- Etc....





Example:
"Ion Line"
Sensitivity to
Plasma
Temperatures

Arecibo's Summary Plasma Line Data



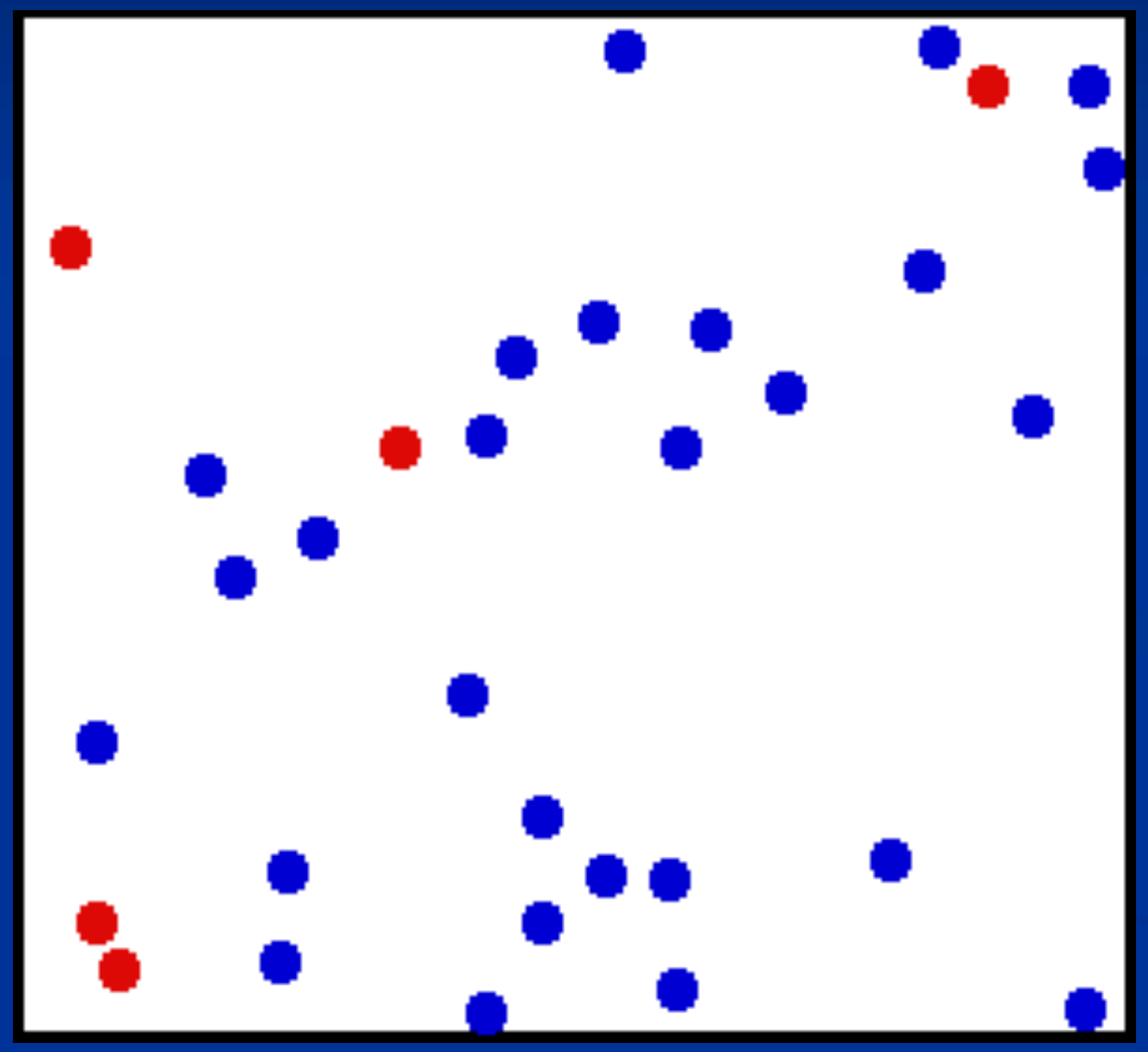
Incoherent Scatter Radar

- Radar
- Scatter
- Incoherent

Radar

- RADAR (RAdio Detection And Ranging)
- A technique for detecting and studying remote targets by transmitting a radio wave in the direction of the target and observing the reflection of the wave.
- **Radar** is an object detection system which uses radio waves to determine the range, altitude, direction, or speed of objects. (Wikipedia)

Thermal fluctuating electrons



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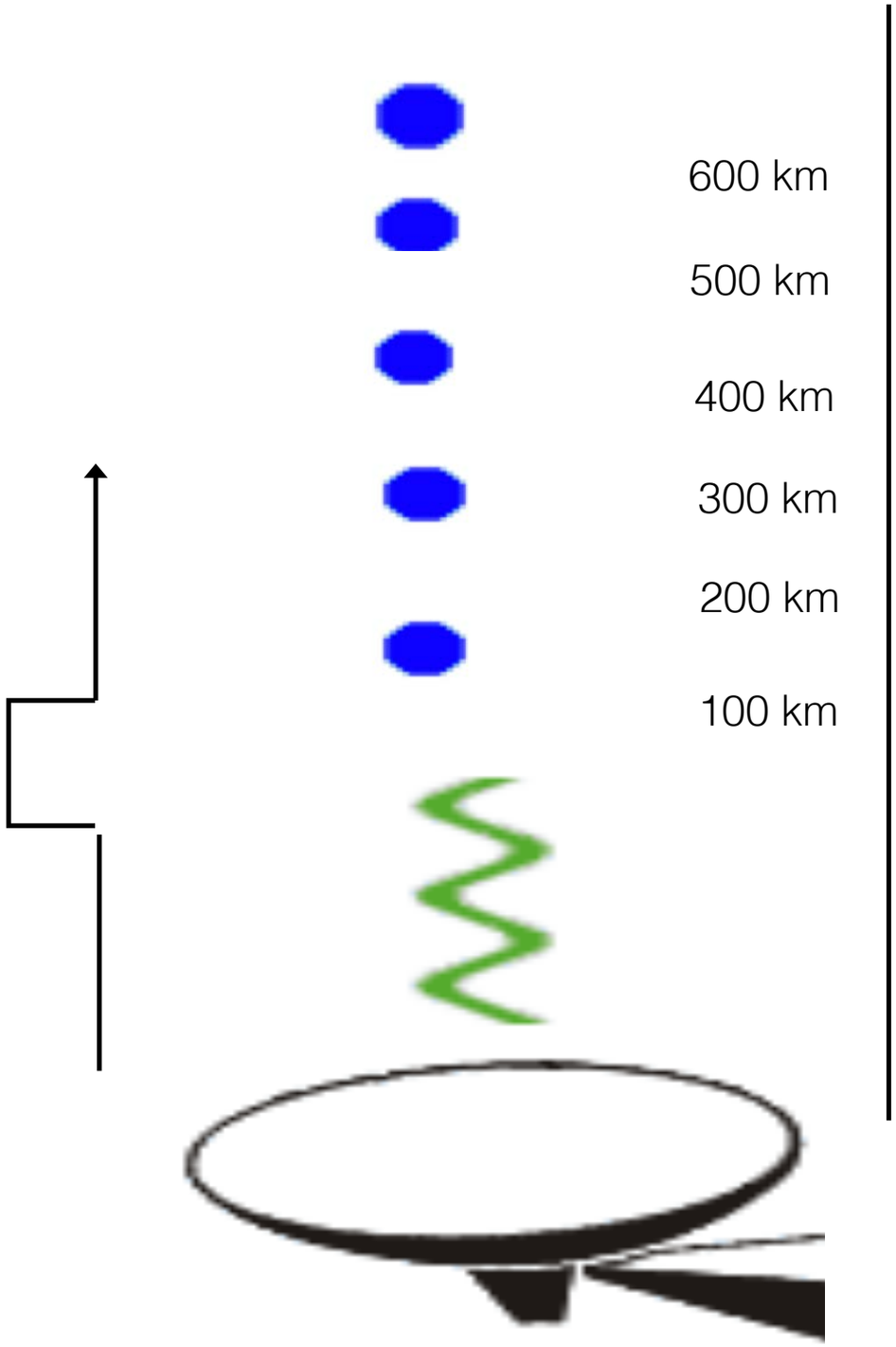
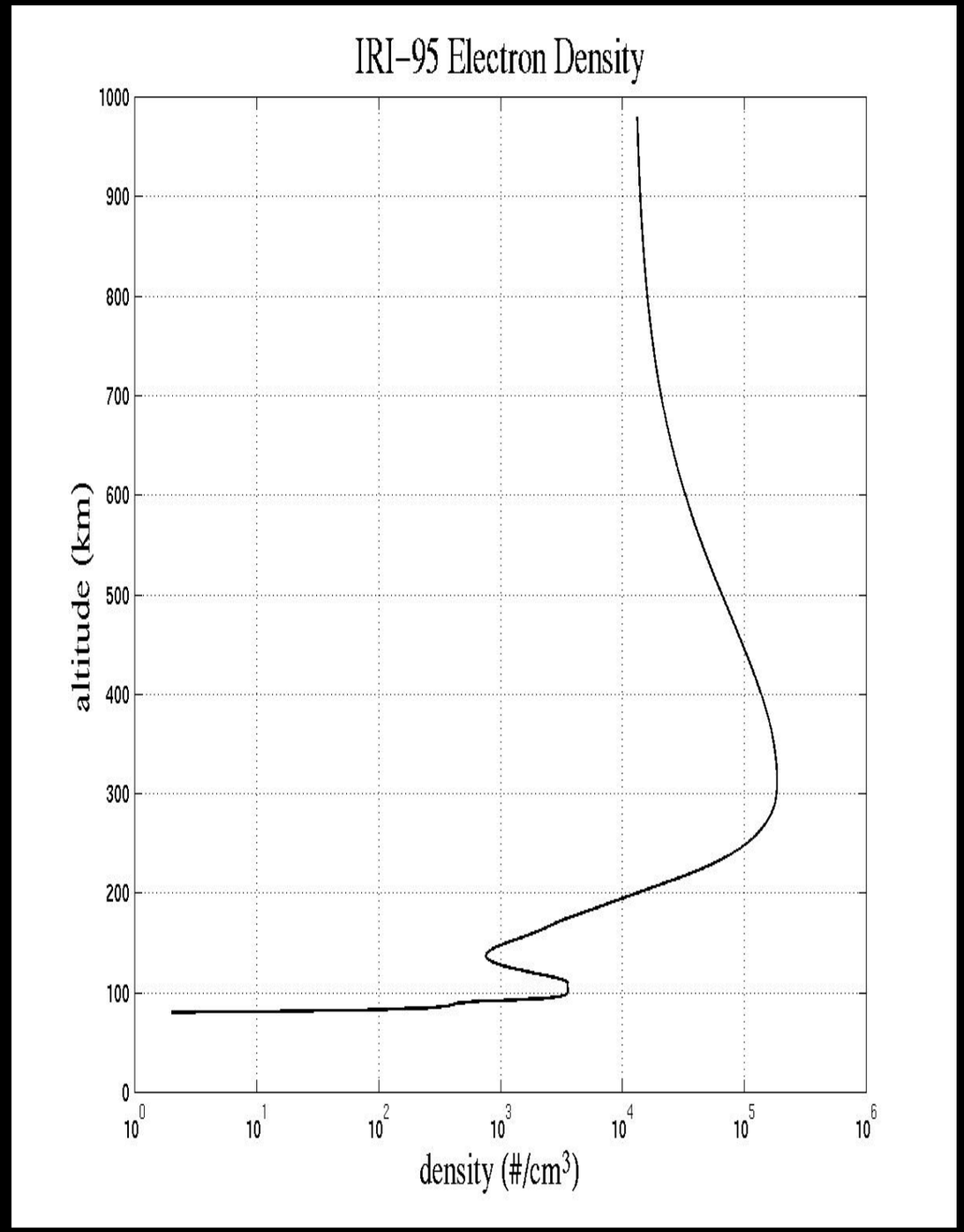
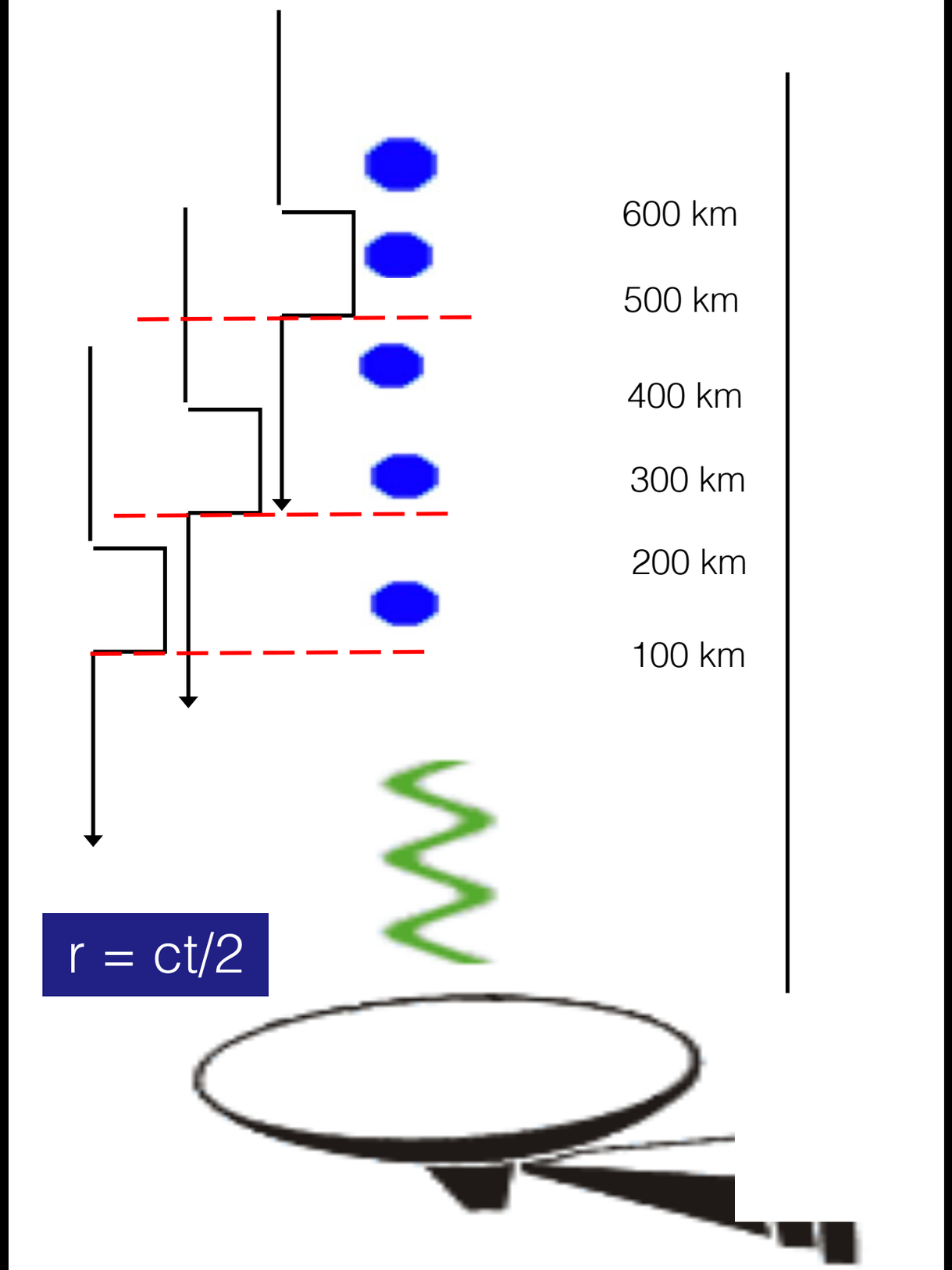
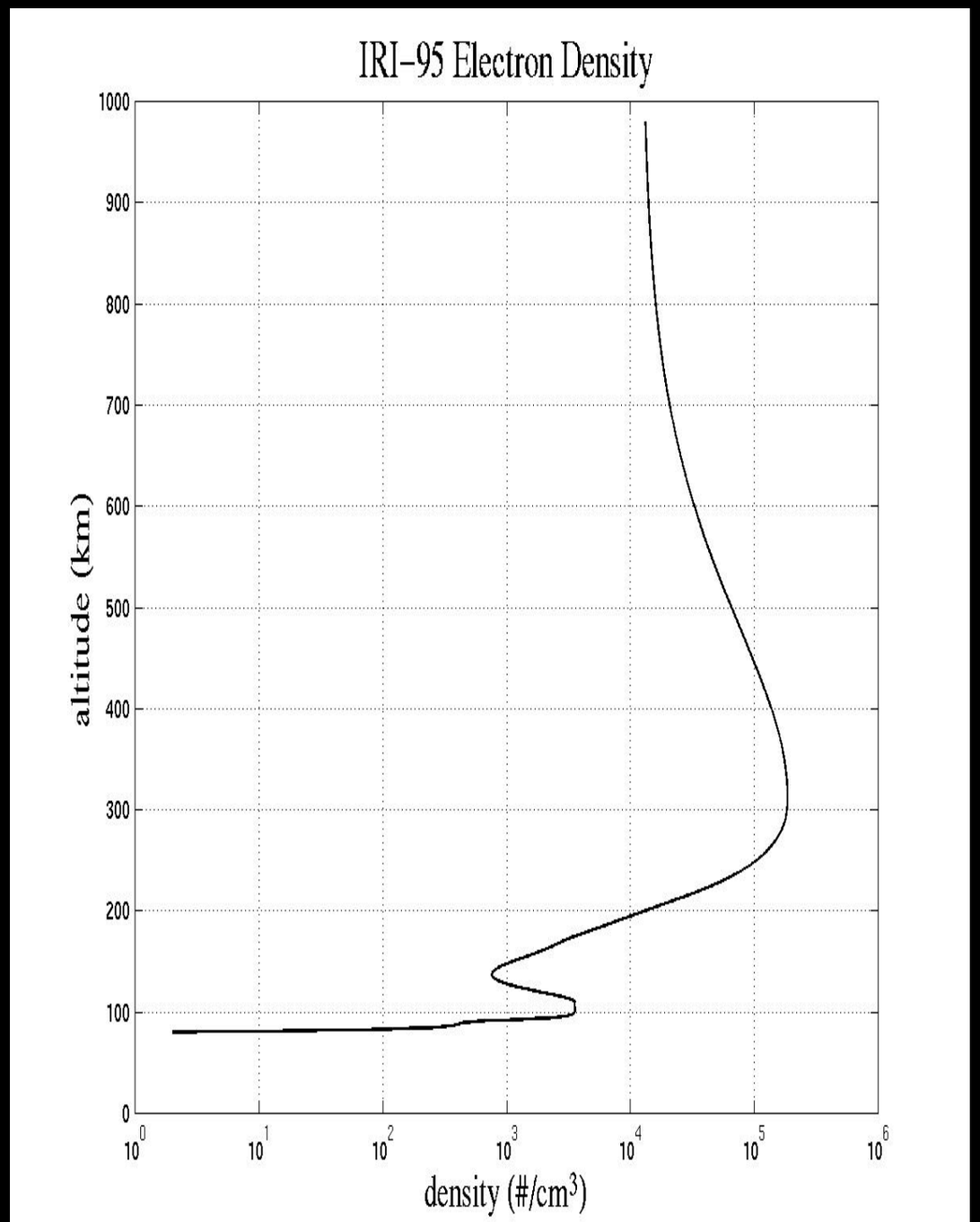

600 km
500 km
400 km
300 km
200 km
100 km


IRI-95 Electron Density
altitude (km)
density (#/cm3)
1000
900
800
700
600
500
400
300
200
100
0
10^0
10^1
10^2
10^3
10^4
10^5
10^6


600 km
500 km
400 km
300 km
200 km
100 km
r = ct/2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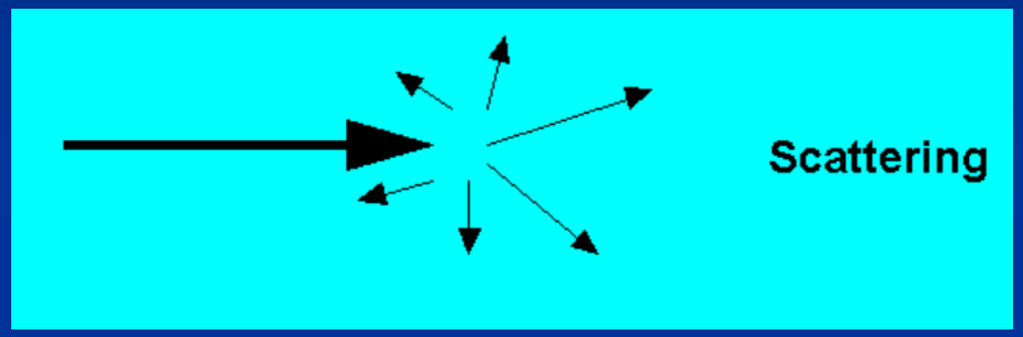
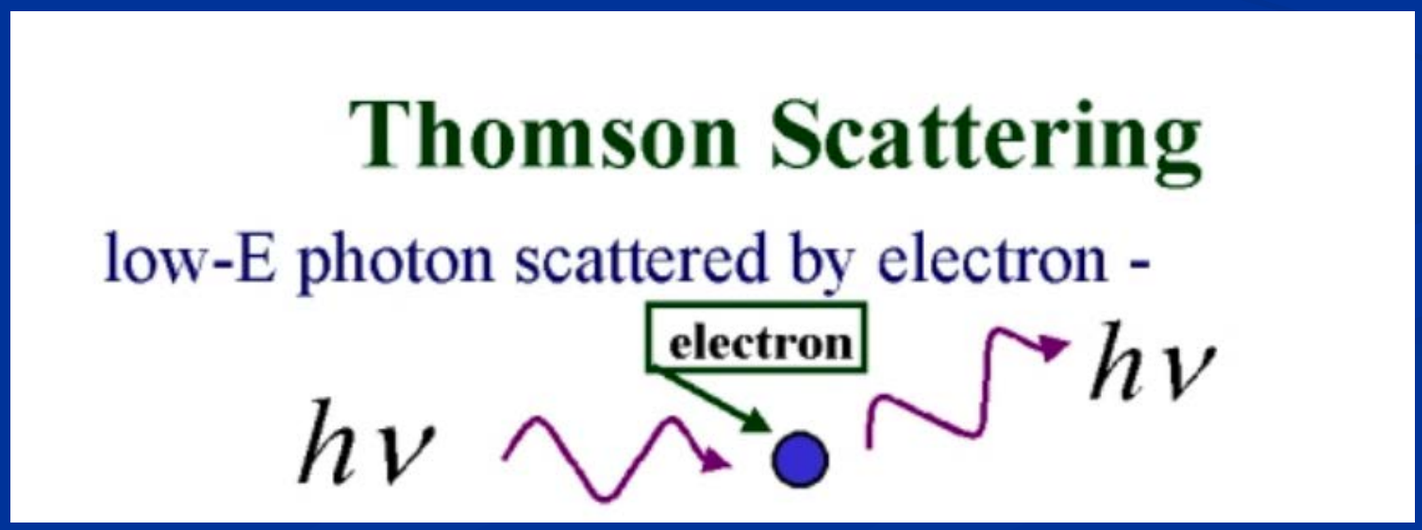
10^6

Thomson scattering

- Thomson scattering is the elastic scattering of electromagnetic radiation by a free charged particle, as described by classical electromagnetism.

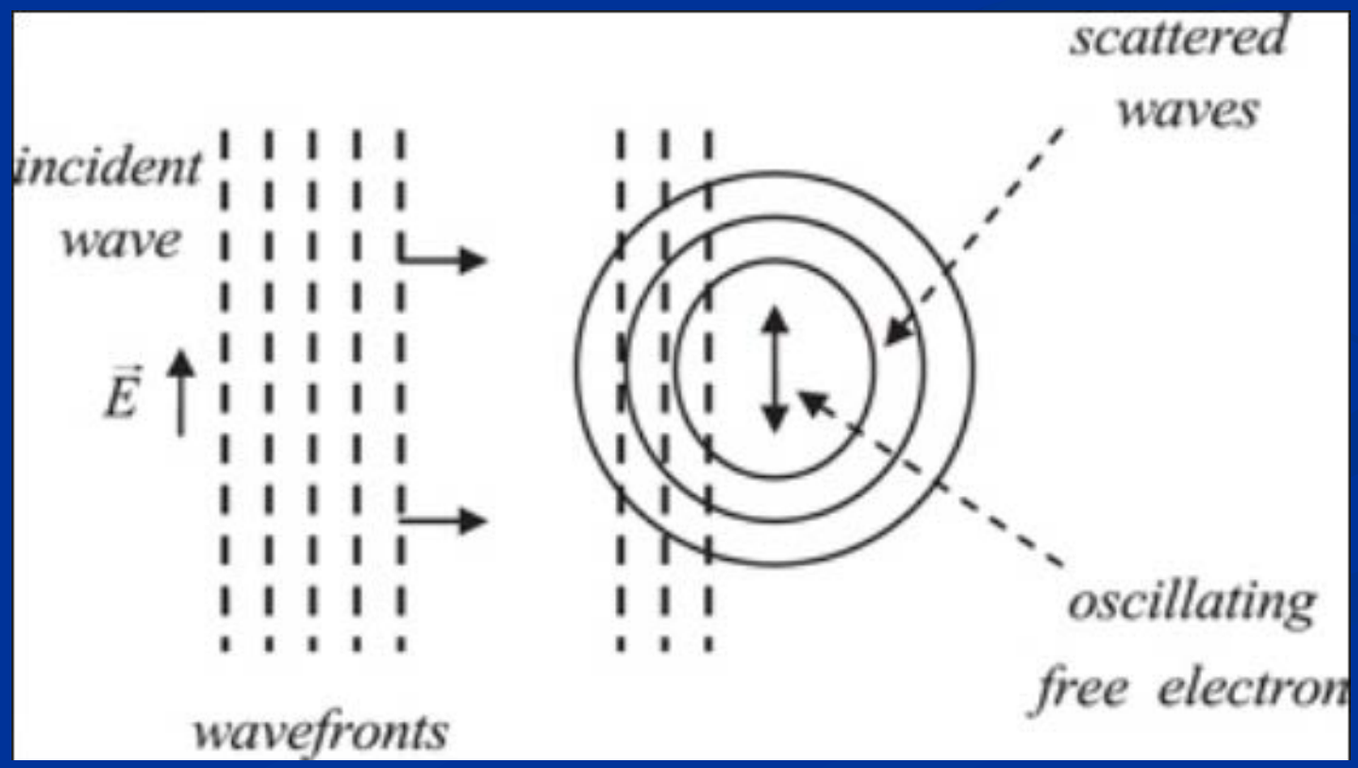


- In the low-energy limit, the electric field of the incident wave (radar wave) accelerates the charged particle, causing it, in turn, to emit radiation at the same frequency as the incident wave, and thus the wave is scattered.



Thomson scattering (con.)

- As long as the motion of the particle is non-relativistic (i.e. its speed is much less than the speed of light), the main cause of the acceleration of the particle will be due to the electric field component of the incident wave, and the magnetic field can be neglected. The particle will move in the direction of the oscillating electric field, resulting in electromagnetic dipole radiation



Thomson Scattering

$$E_x = E_0 e^{j(\omega t - kx)}$$

$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

$$v_x = -j\frac{q_e E_0}{m_e \omega} e^{j\omega t}$$

$$E_\phi = \frac{\mu_0 q_e^2}{4\pi m_e}\frac{\sin\phi}{r} e^{-jkr} E_0$$

$$\sigma_e = 4\pi\left(\frac{\mu_0 q_e^2}{4\pi m_e}\right)^2 \sin^2\phi = 4\pi r_e^2 \sin^2\phi$$

$$\approx 10^{-28}\sin^2\phi \quad (\mathrm{m}^2)$$

Definition of Incoherent

- Property of being coherent
- Antonym: incoherent
- Incoherent=Random
- Example: The drunk man made no sense. He was incoherent.
- In radar: Incoherent scatter is the process by which radio waves are randomly scattered by electrons in the ionosphere

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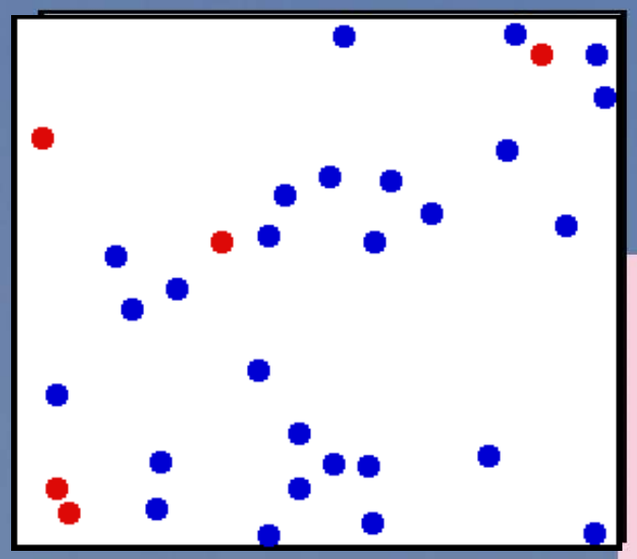
Incoherent scatter is neither incoherent nor incomprehensible

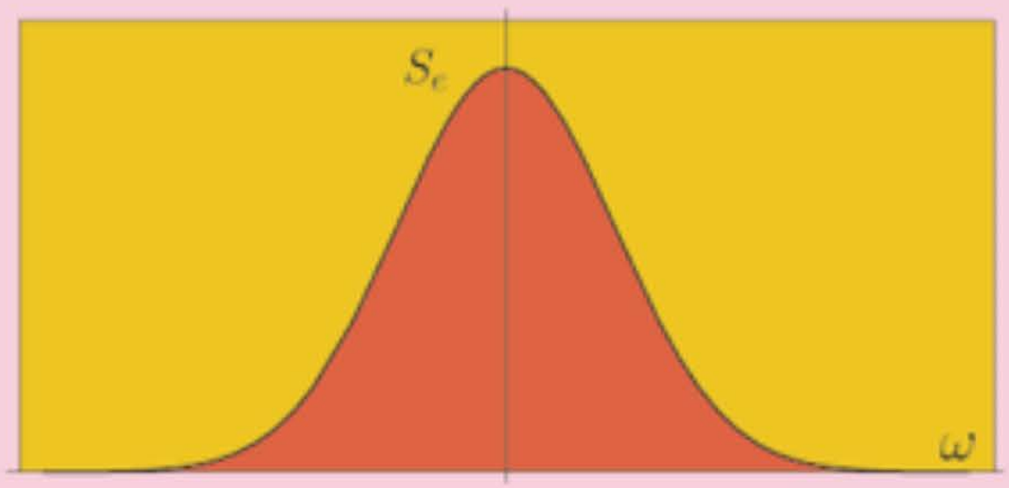
For TRUE incoherent scatter…



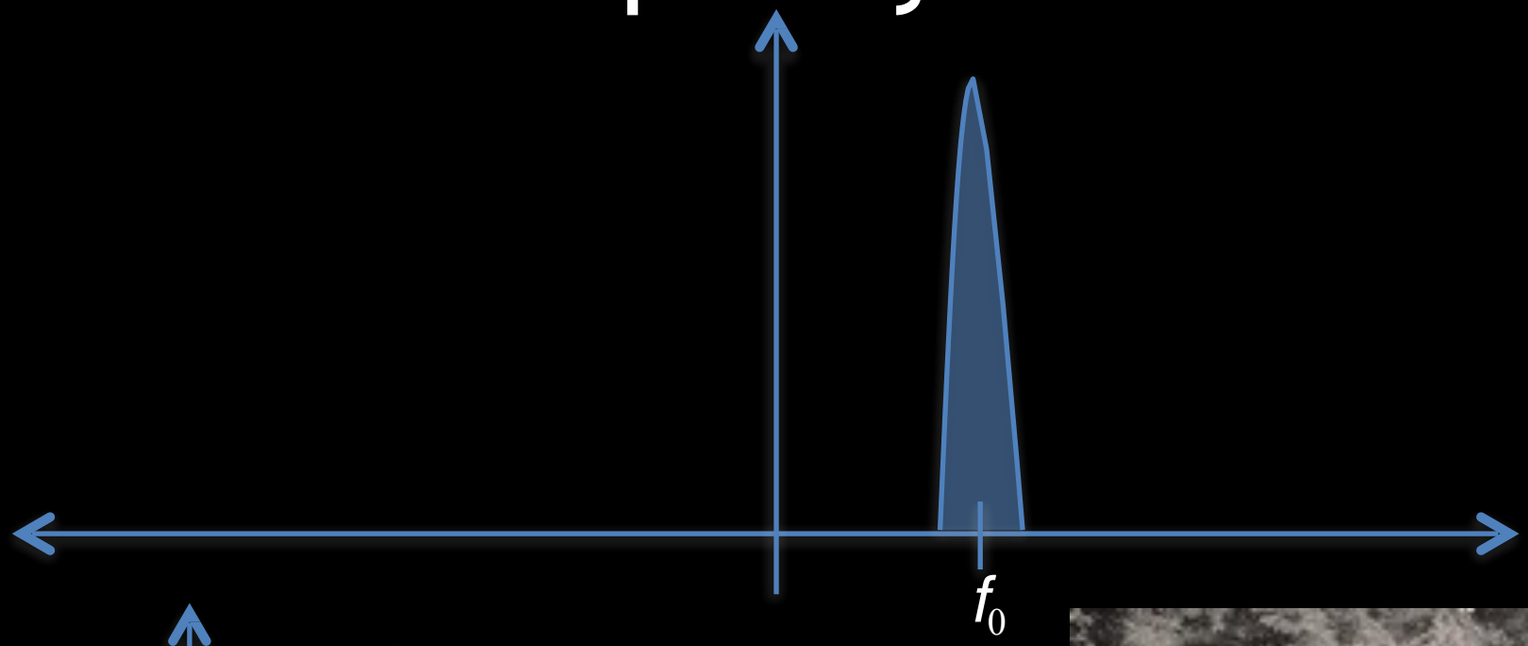
no collective interactions

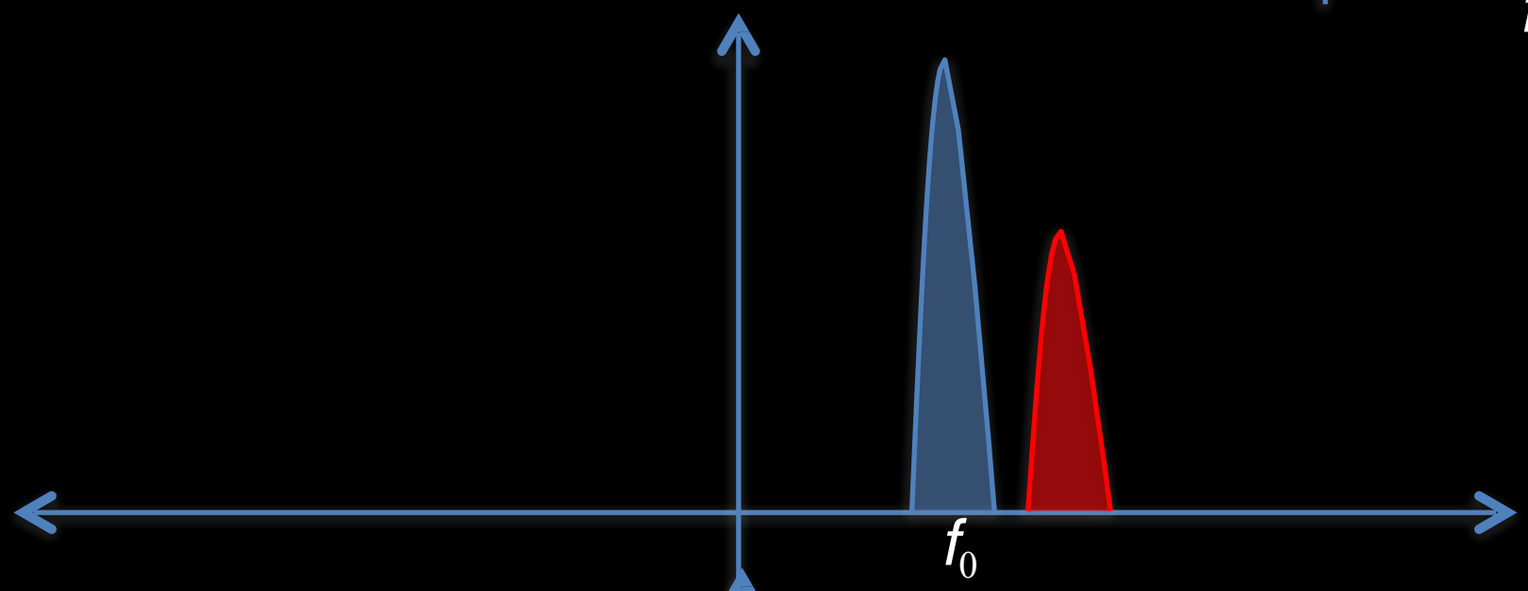
$$S_e(\mathbf{k},\omega) = N_e \left|1 - \frac{\chi_e(\mathbf{k},\omega)}{\epsilon(\mathbf{k},\omega)}\right|^2 \int d\mathbf{v} f_e(\mathbf{v}) \delta(\omega - \mathbf{k}\cdot\mathbf{v}) + N_i \left|\frac{\chi_e(\mathbf{k},\omega)}{\epsilon(\mathbf{k},\omega)}\right|^2 \int d\mathbf{v} f_i(\mathbf{v}) \delta(\omega - \mathbf{k}\cdot\mathbf{v})$$

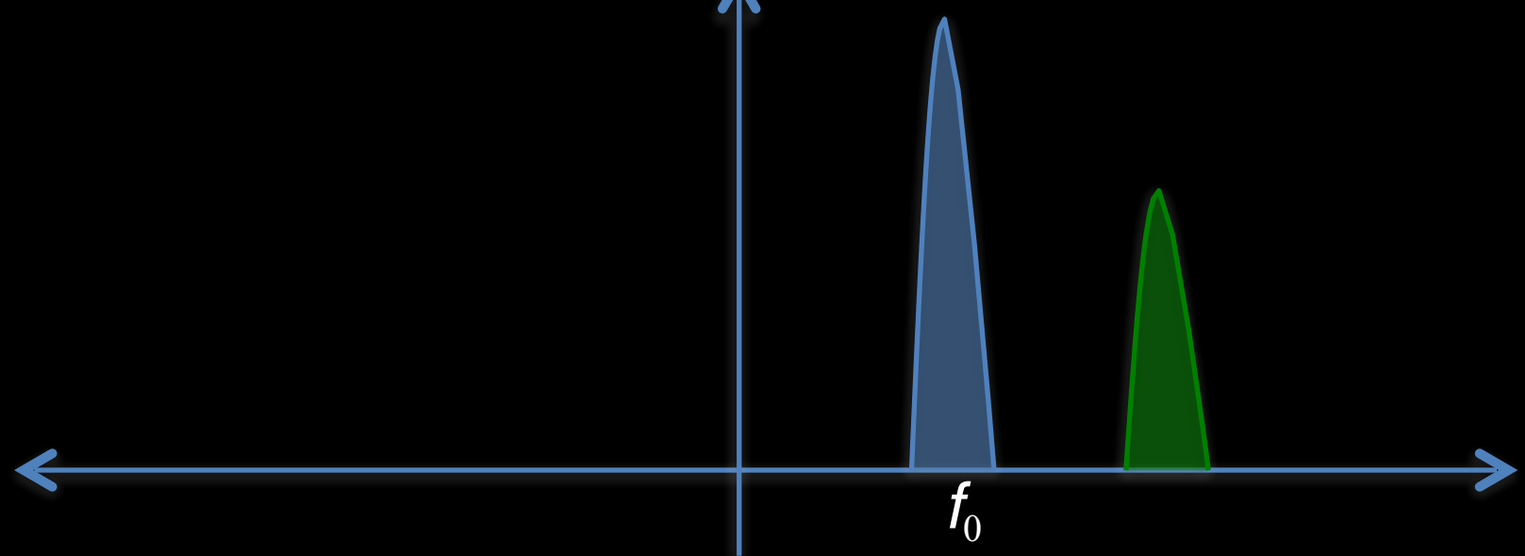
$$S_e(\mathbf{k},\omega) = N_e \int d\mathbf{v} f_e(\mathbf{v}) \delta(\omega - \mathbf{k}\cdot\mathbf{v})$$

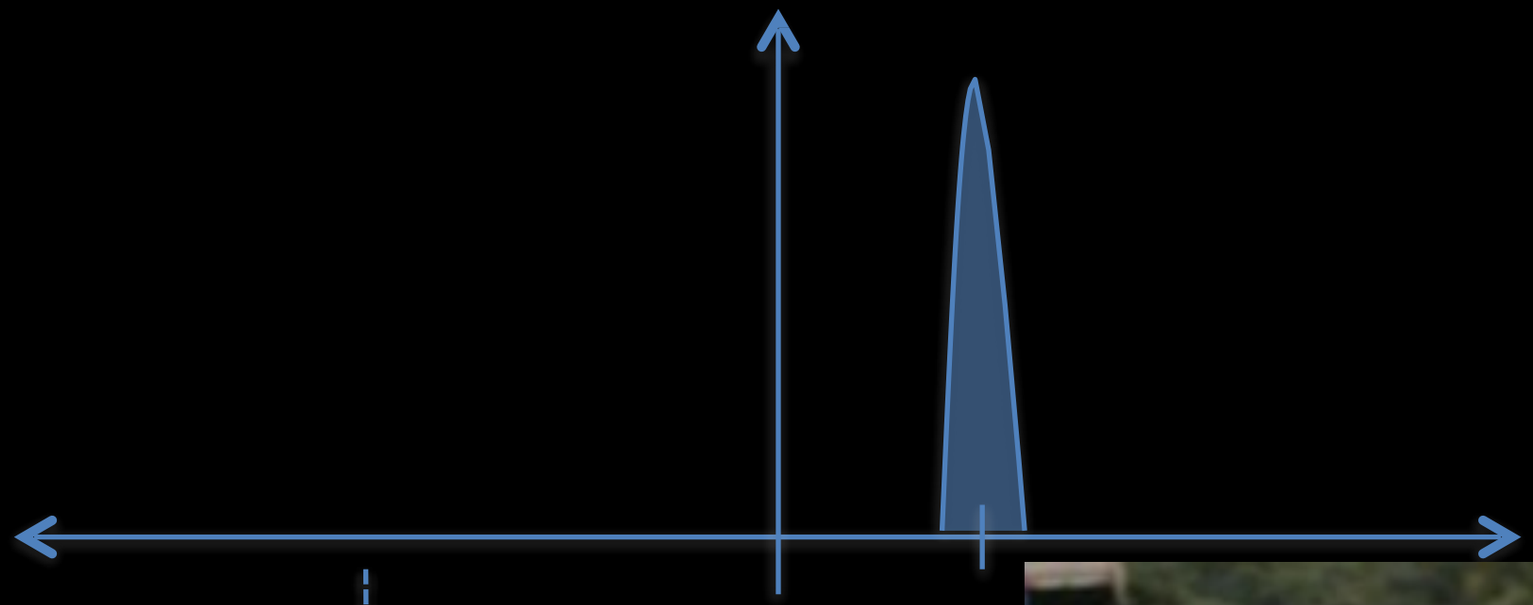


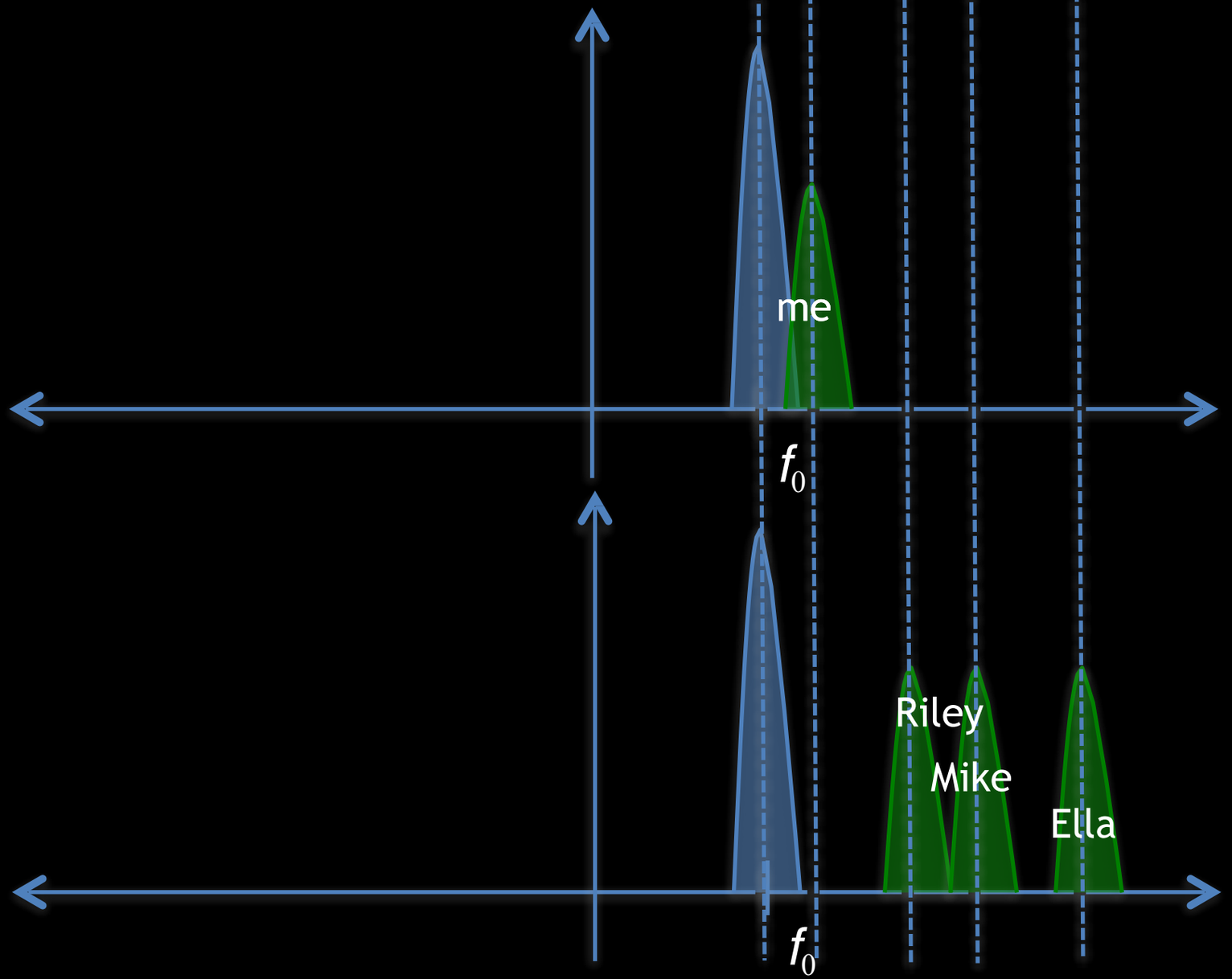
Doppler Radar – frequency domain

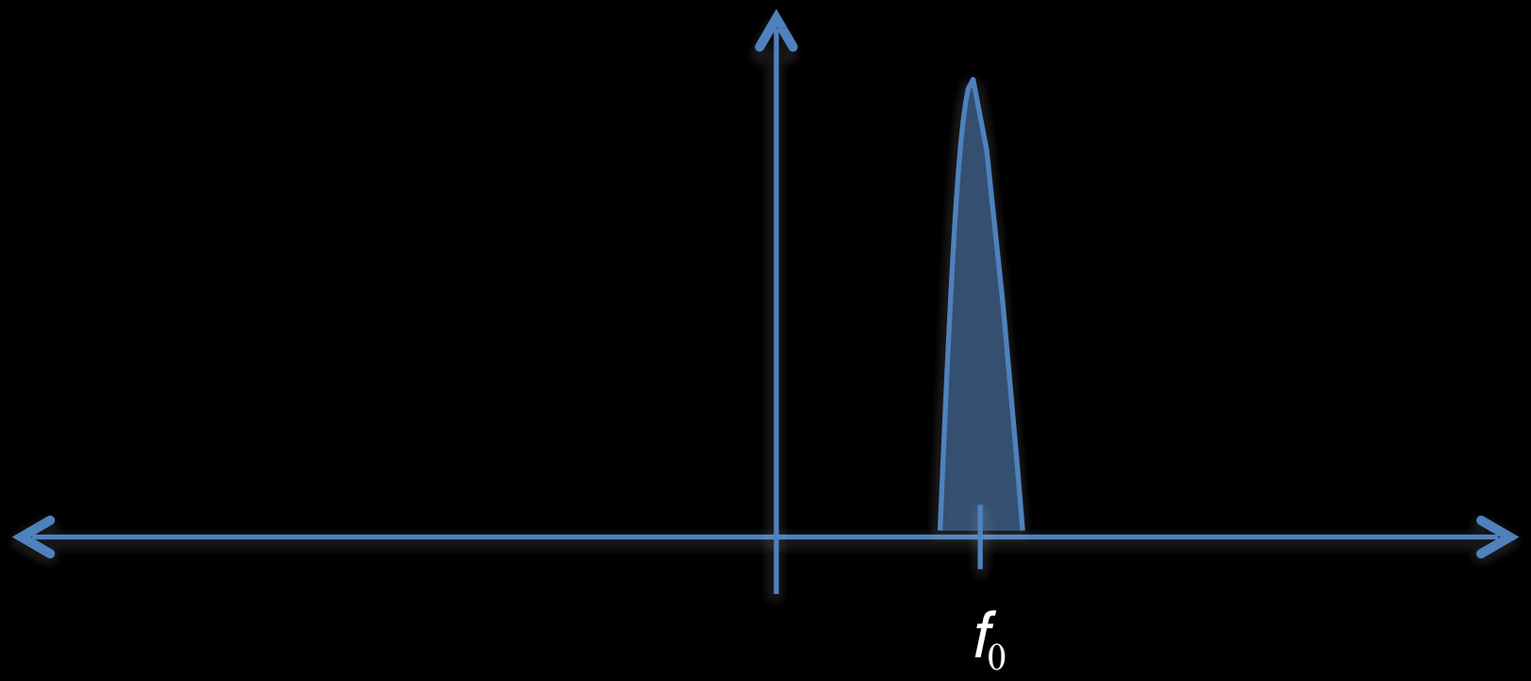







f_0


me
f_0
Riley
Mike
Ella
f_0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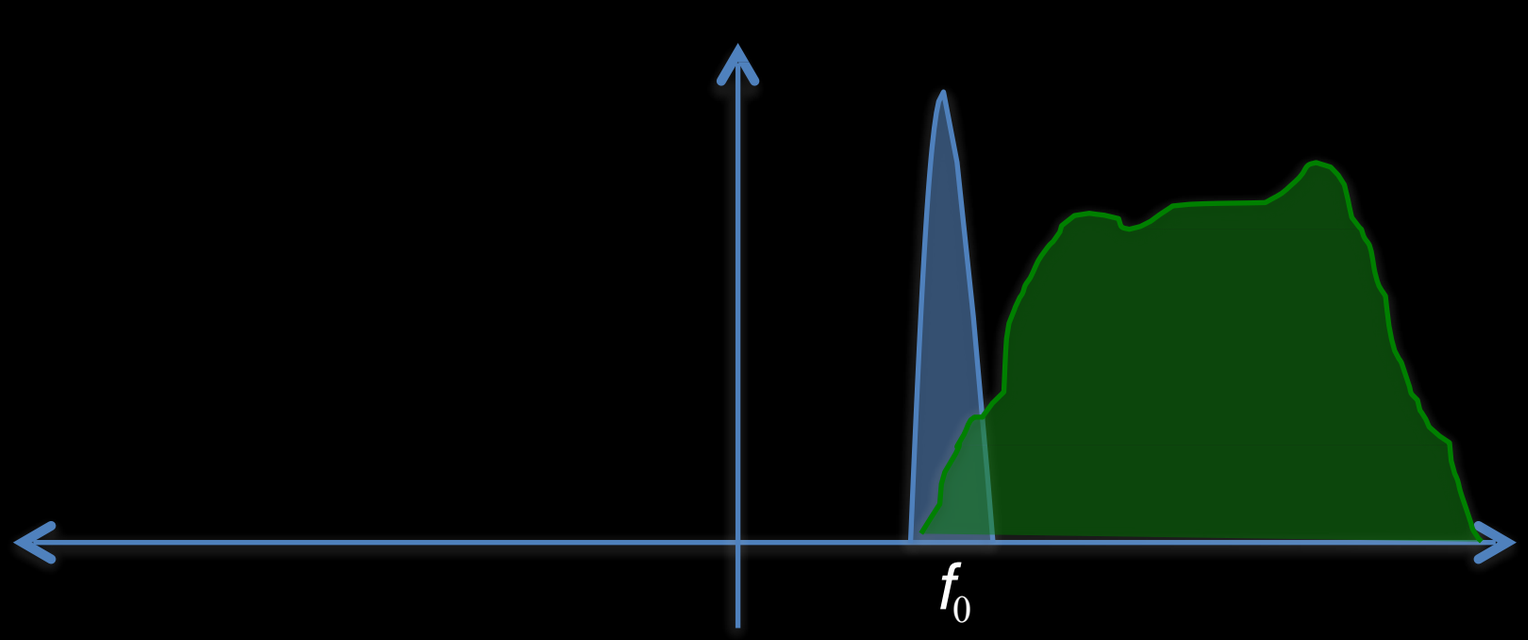
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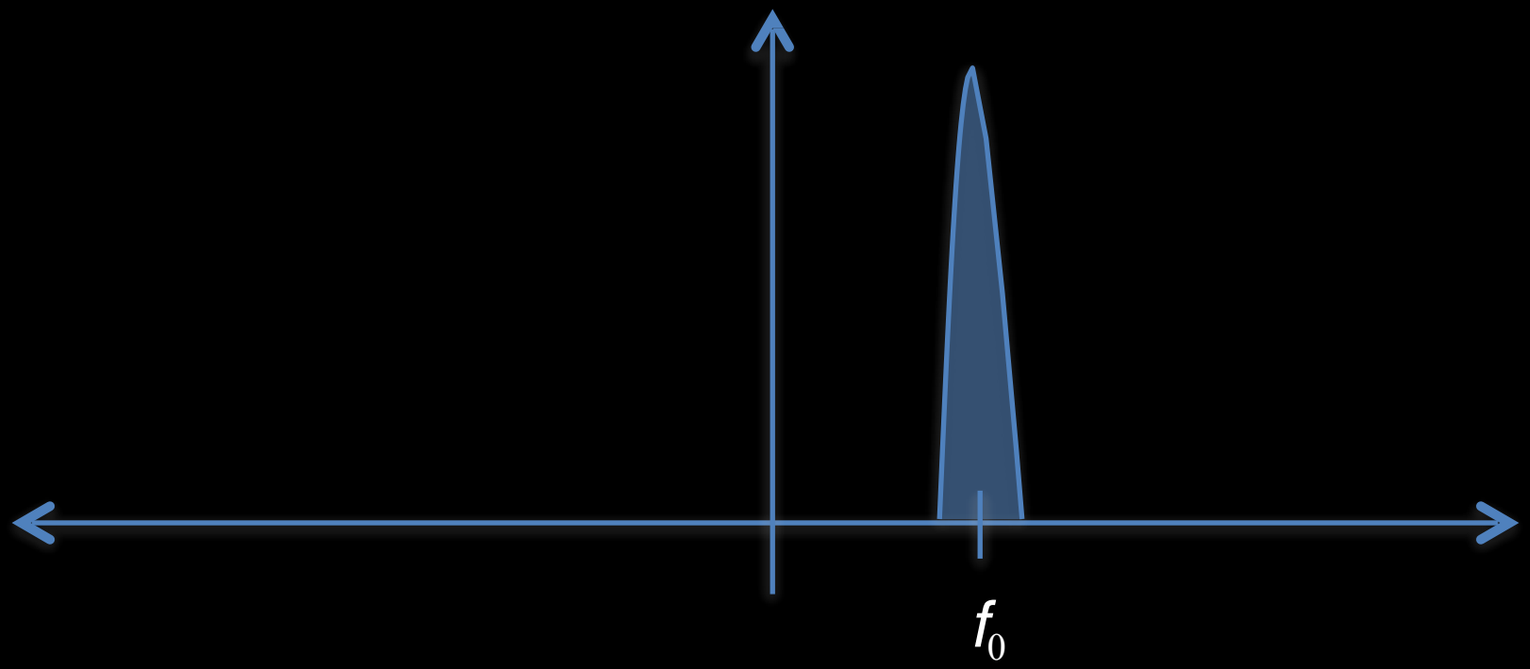
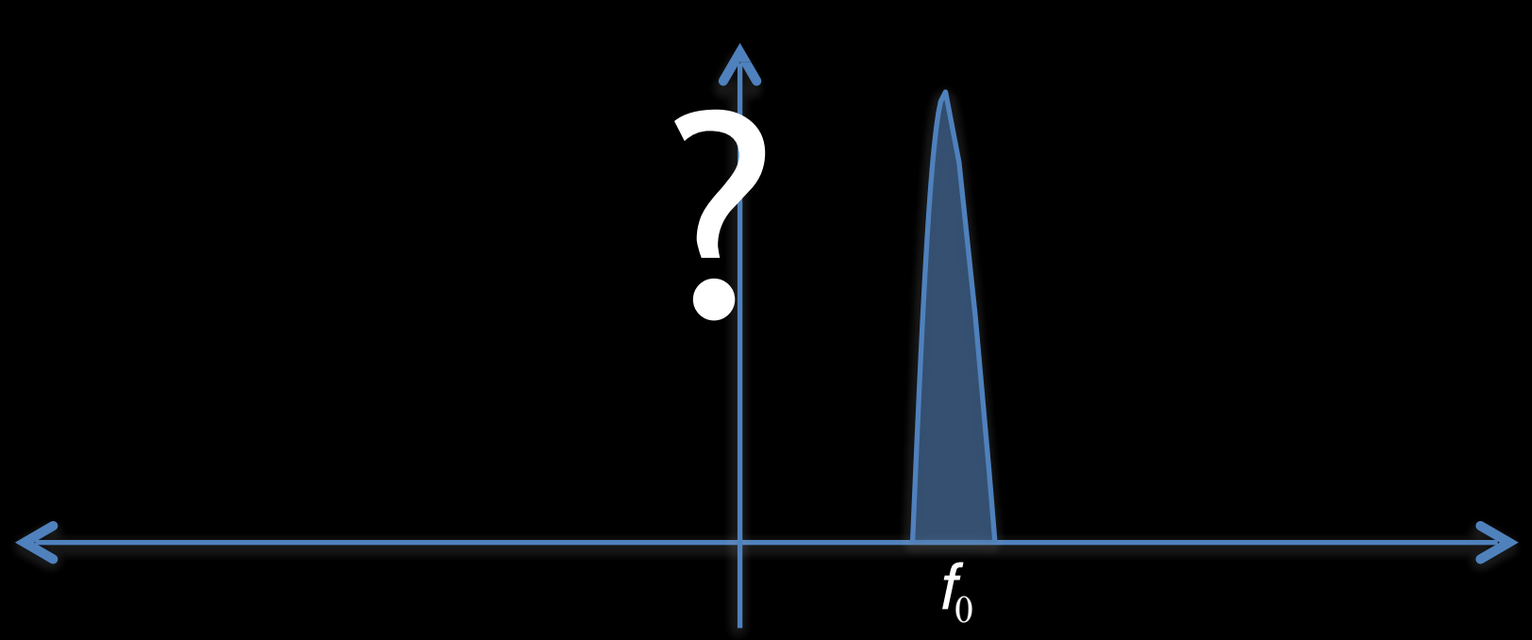
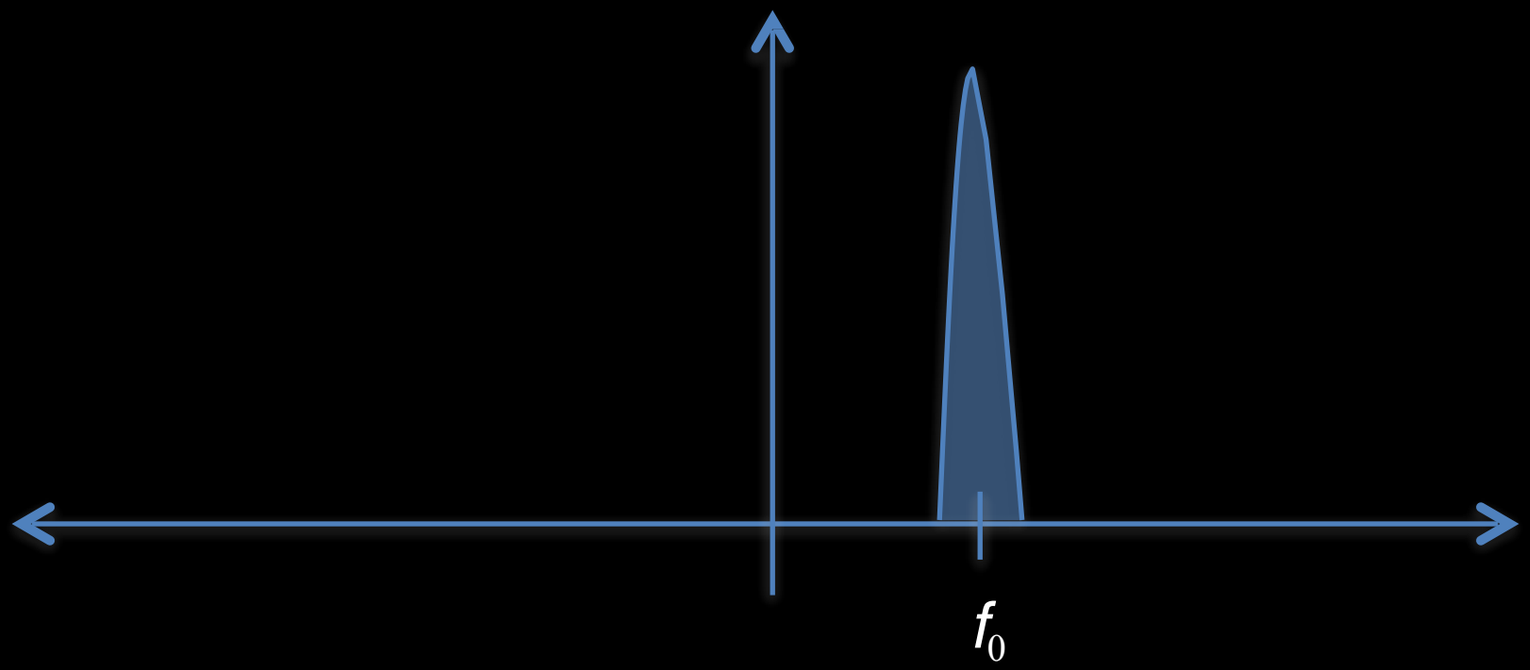

f_0


?
f_0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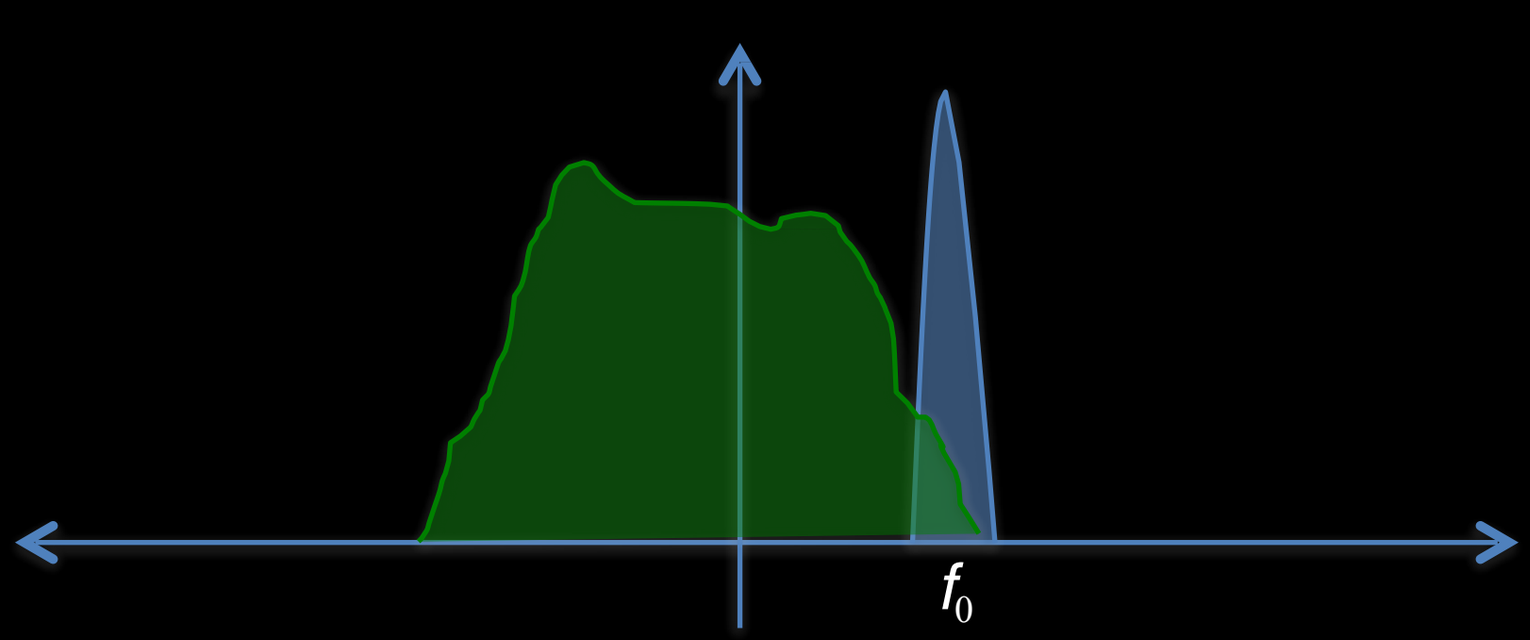
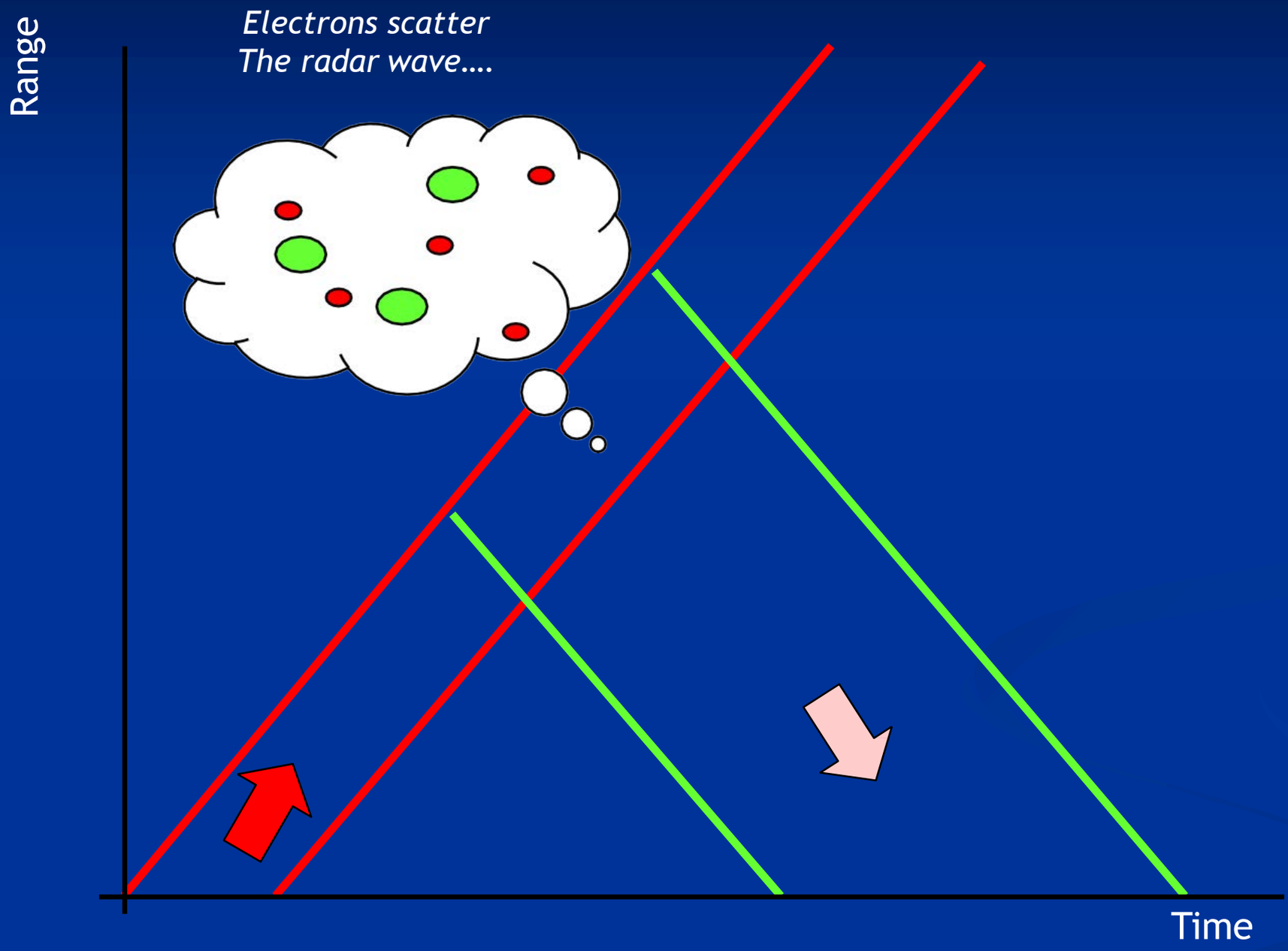

f_0

How ISRs work



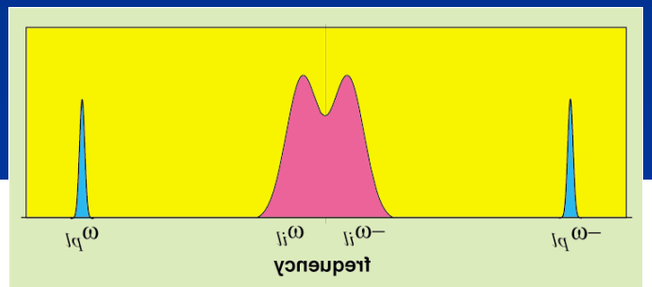
High power transmitter

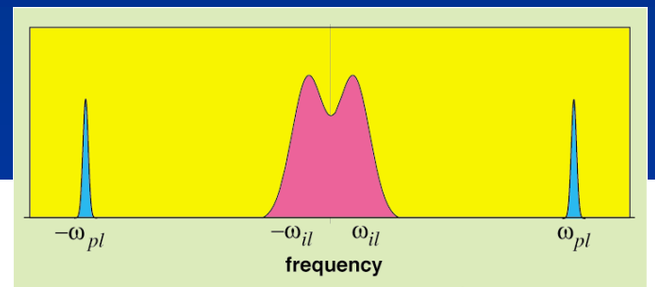
Very sensitive receiver

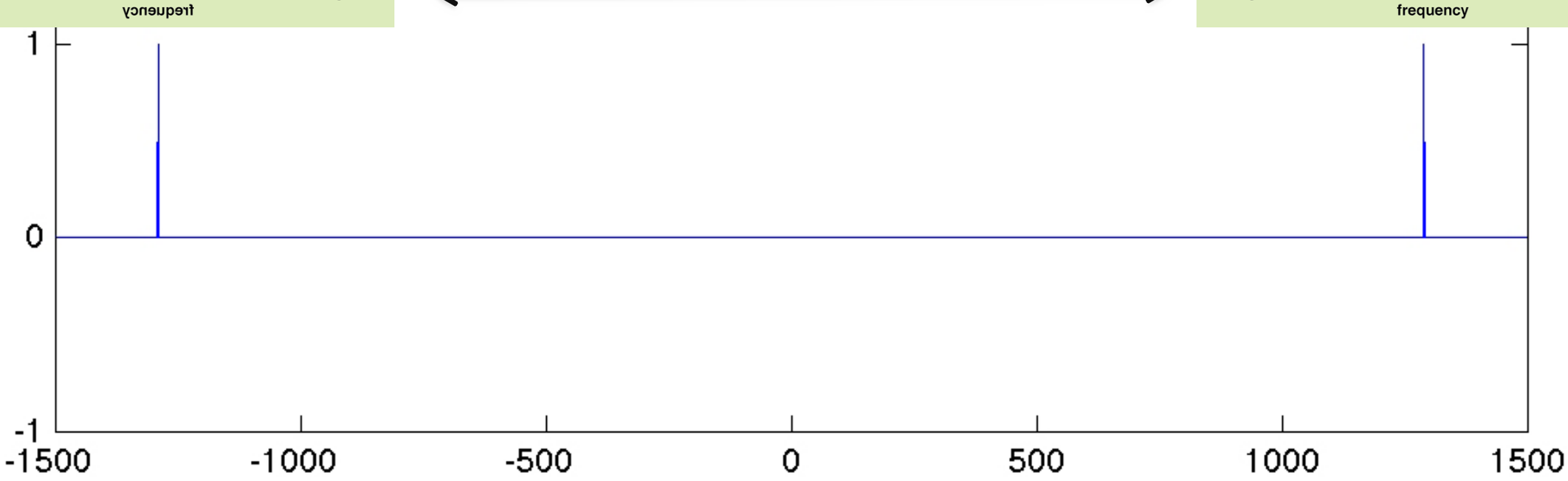
Only ~0.00000000000000000001% of the transmitted power is returned!

IS Received Spectrum

The individual sides are **not** symmetric about their center frequencies!







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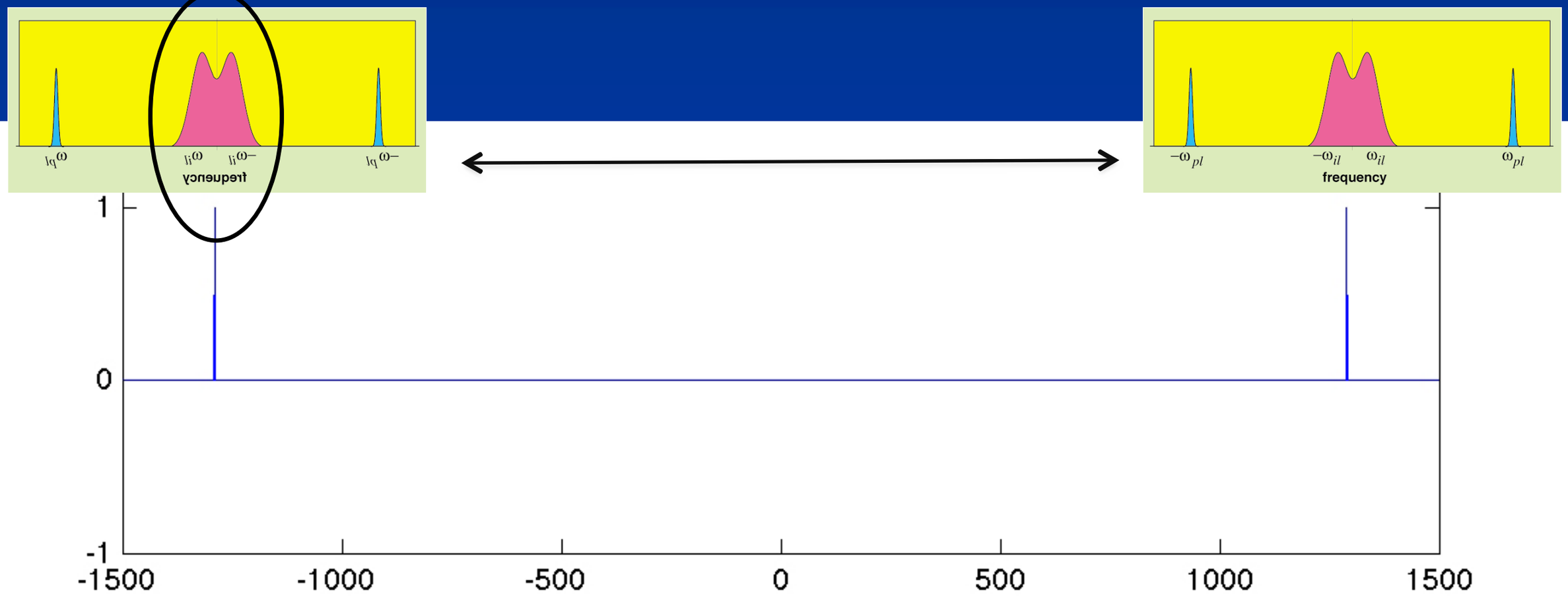


Outline

Distribution of ISRs across the world

Introduction to ISR principles and Incoherent Scatter Spectrum

Ion acoustic waves, Langmuir waves, Debye Spheres, Landau Damping ……

- We only see scattering from the electrons

…but they also tell the story about the ion dynamics…

Collective behavior

- There are a number of wave modes existing inherently in the ionospheric plasma

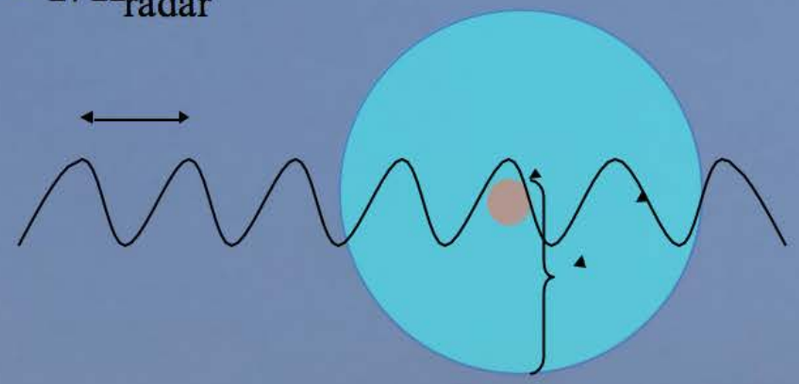
Debye length dependence

Ion

Electron cloud

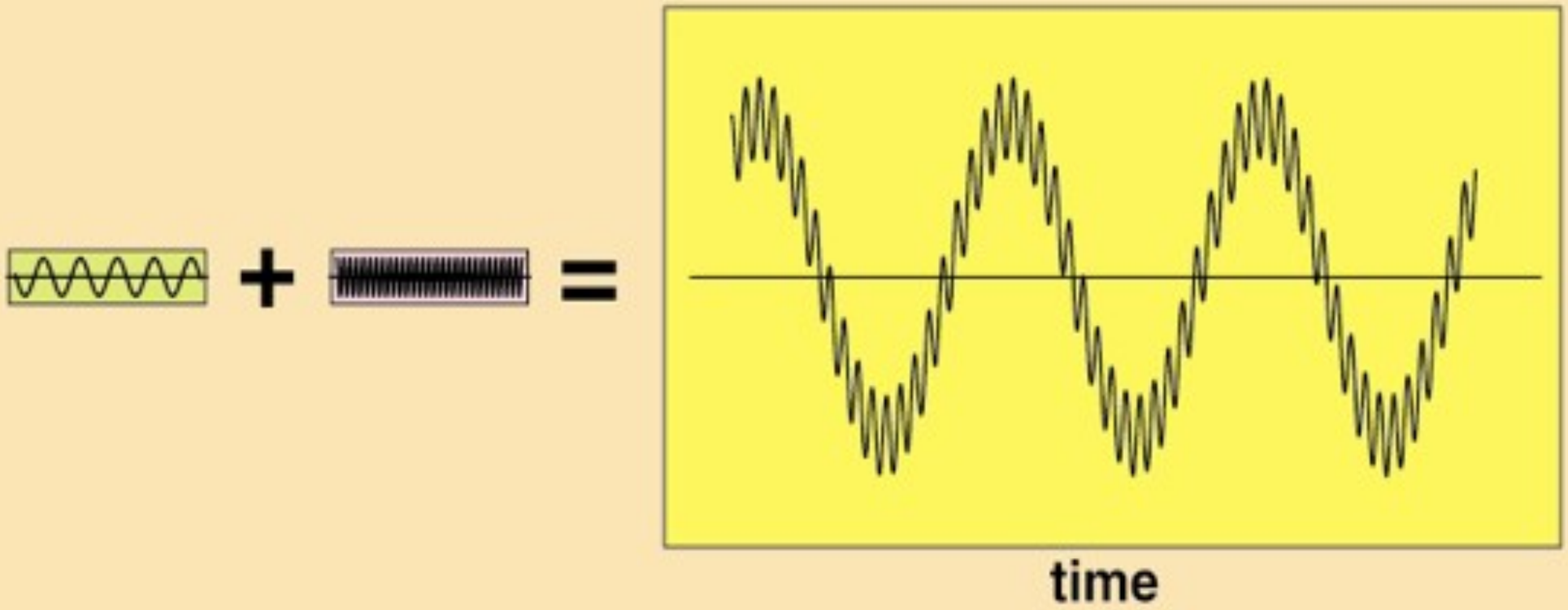
Debye length λ_D

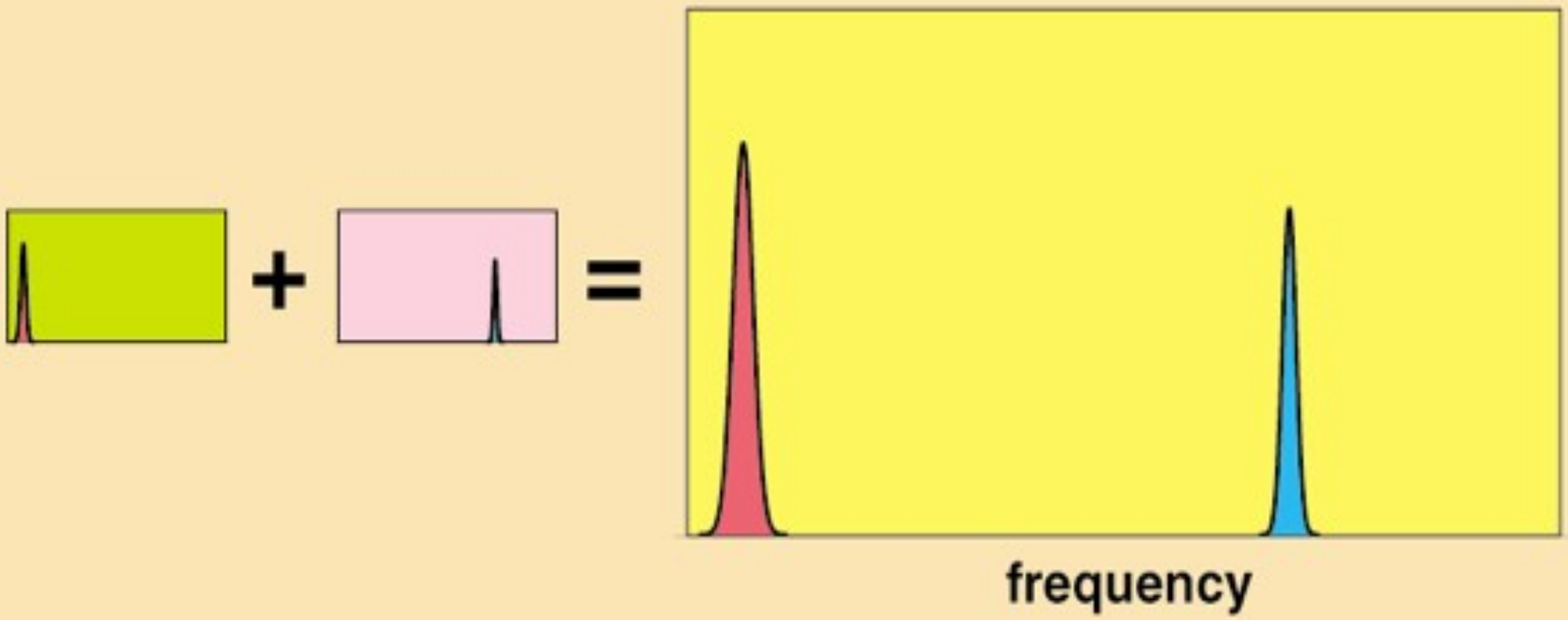
$\lambda_{radar} \propto 1/k_{radar}$



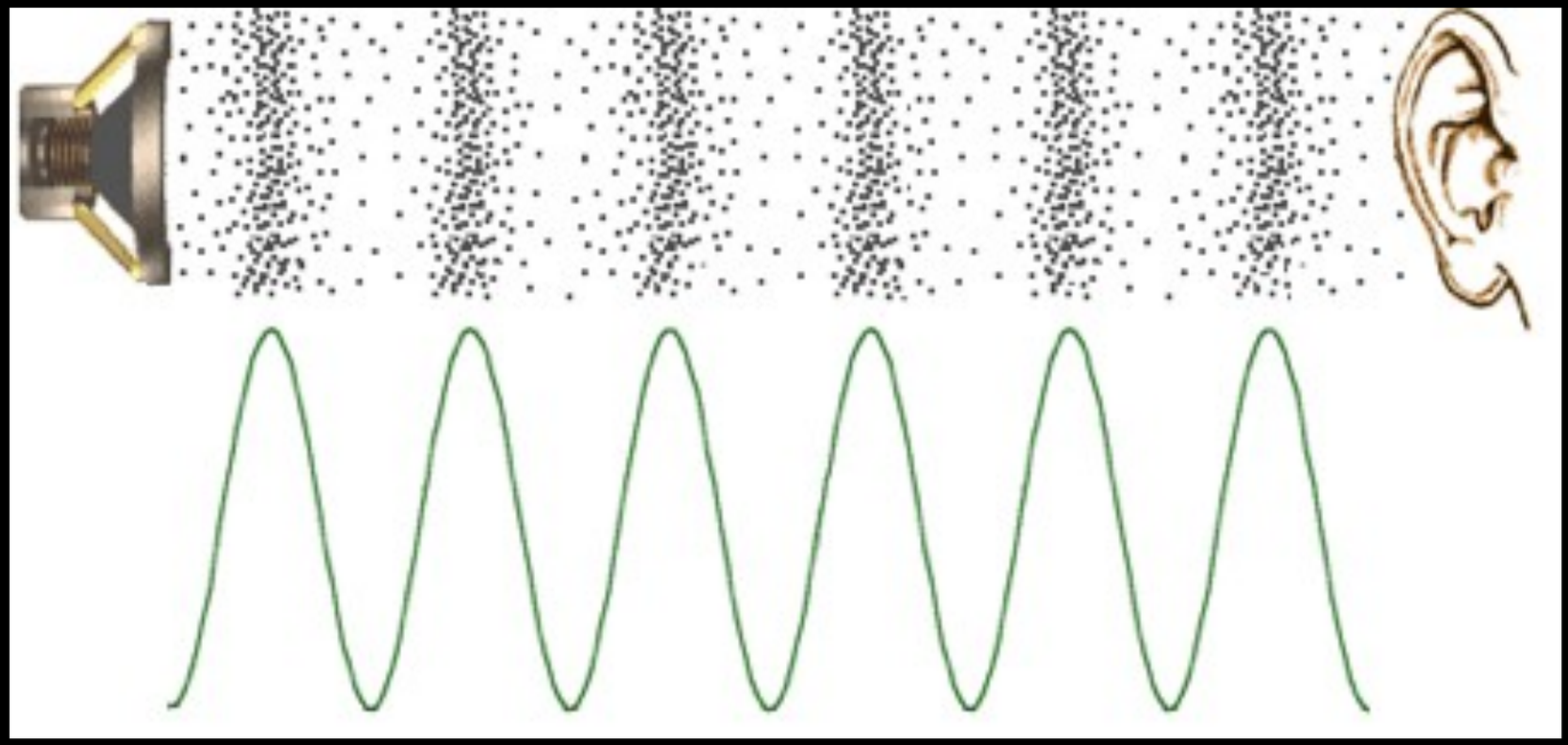
$(\lambda_D / \lambda_{radar})^2 > 1$

- $(k_{radar}\, \lambda_D)^2 > 1$
- No collective interactions

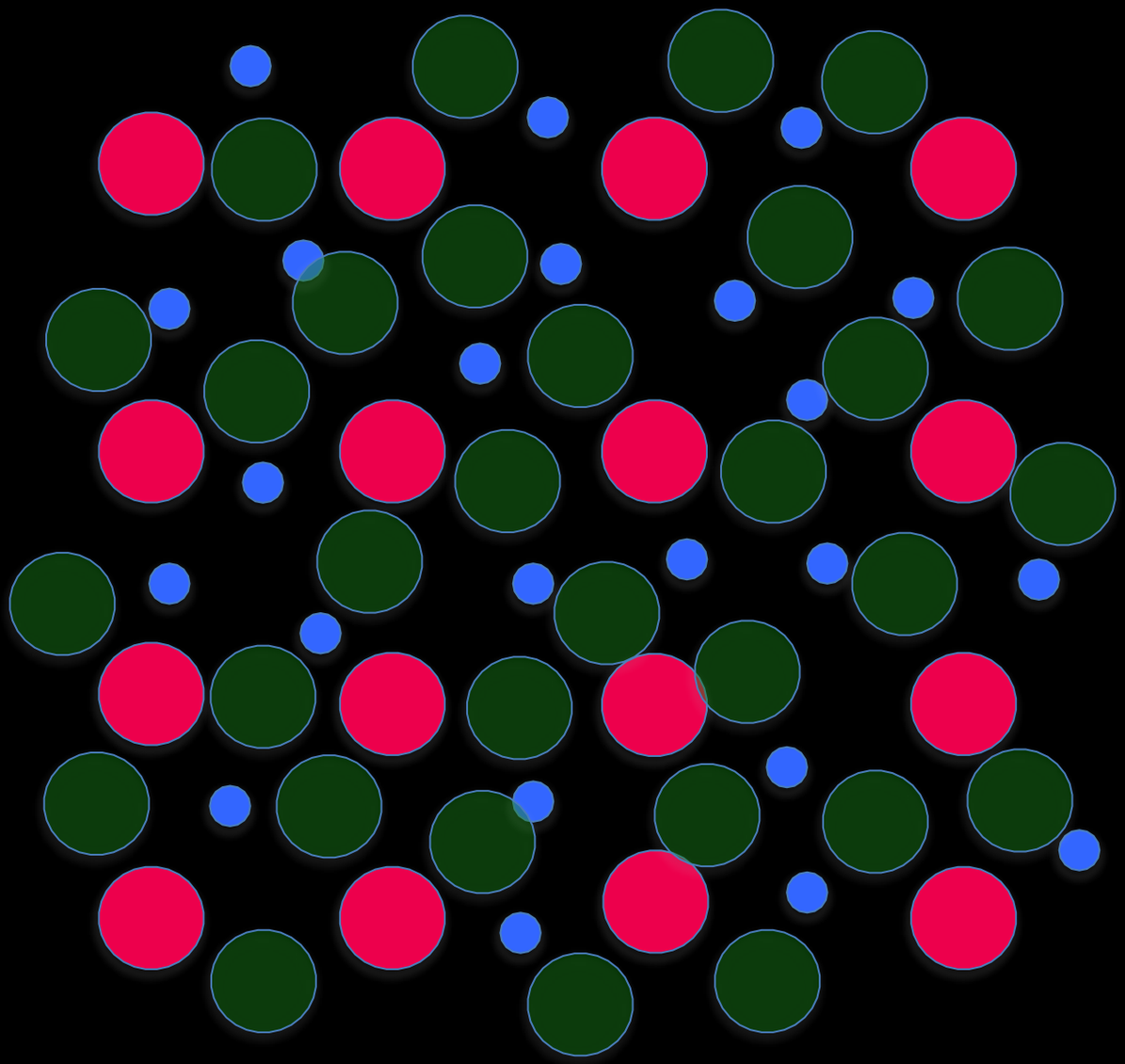

time


frequency

Ion Acoustic Waves



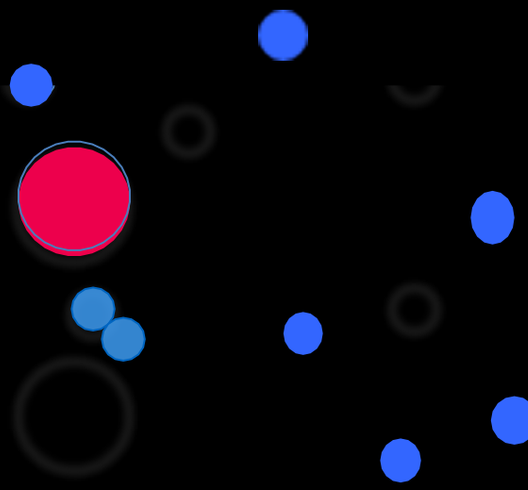
"Pressure" waves in the ion density



Neutrals

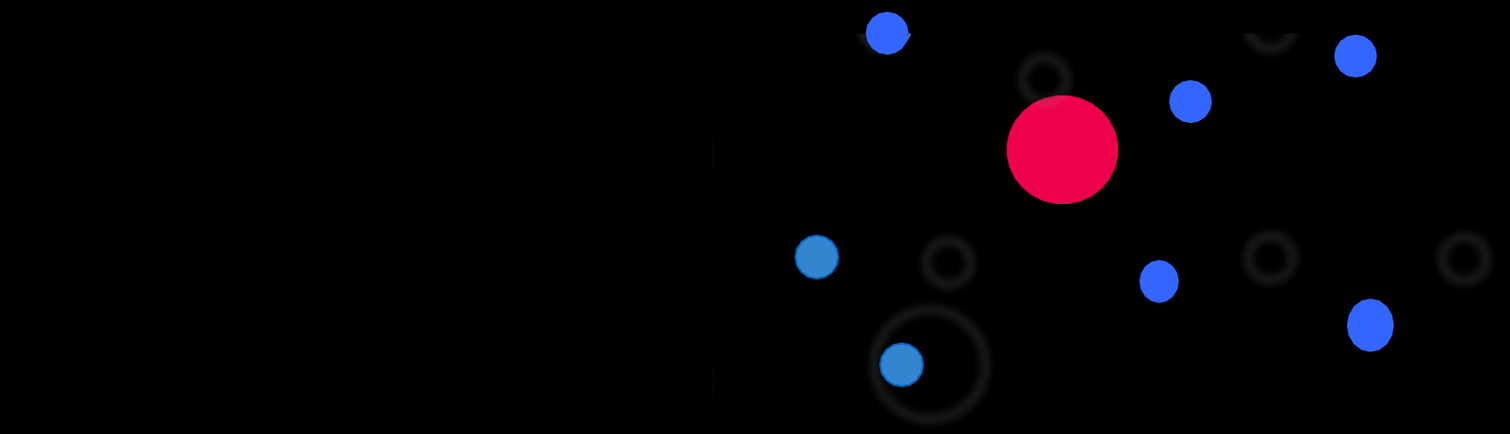
Positive Ions

Electrons



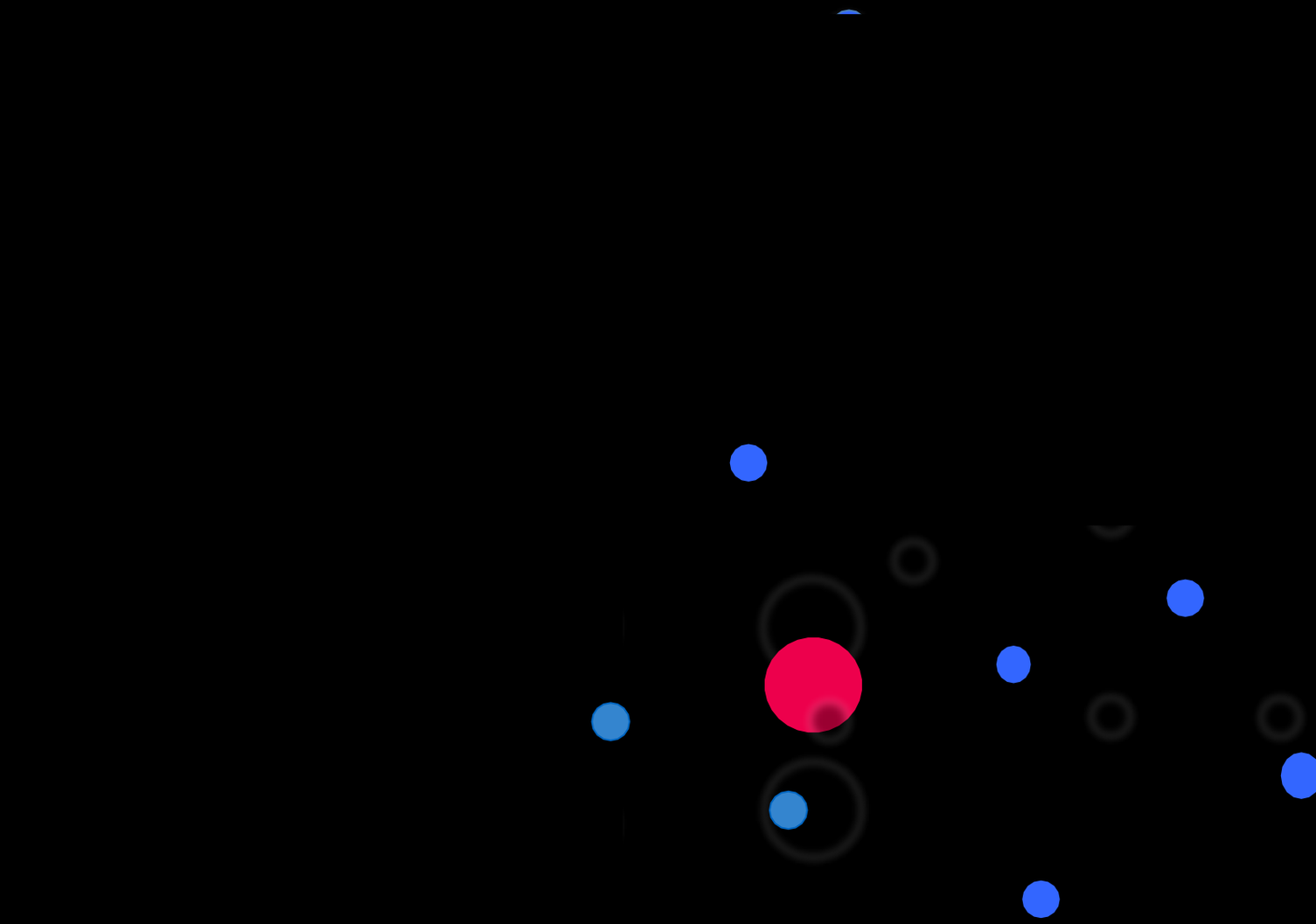
Positive Ions

Electrons



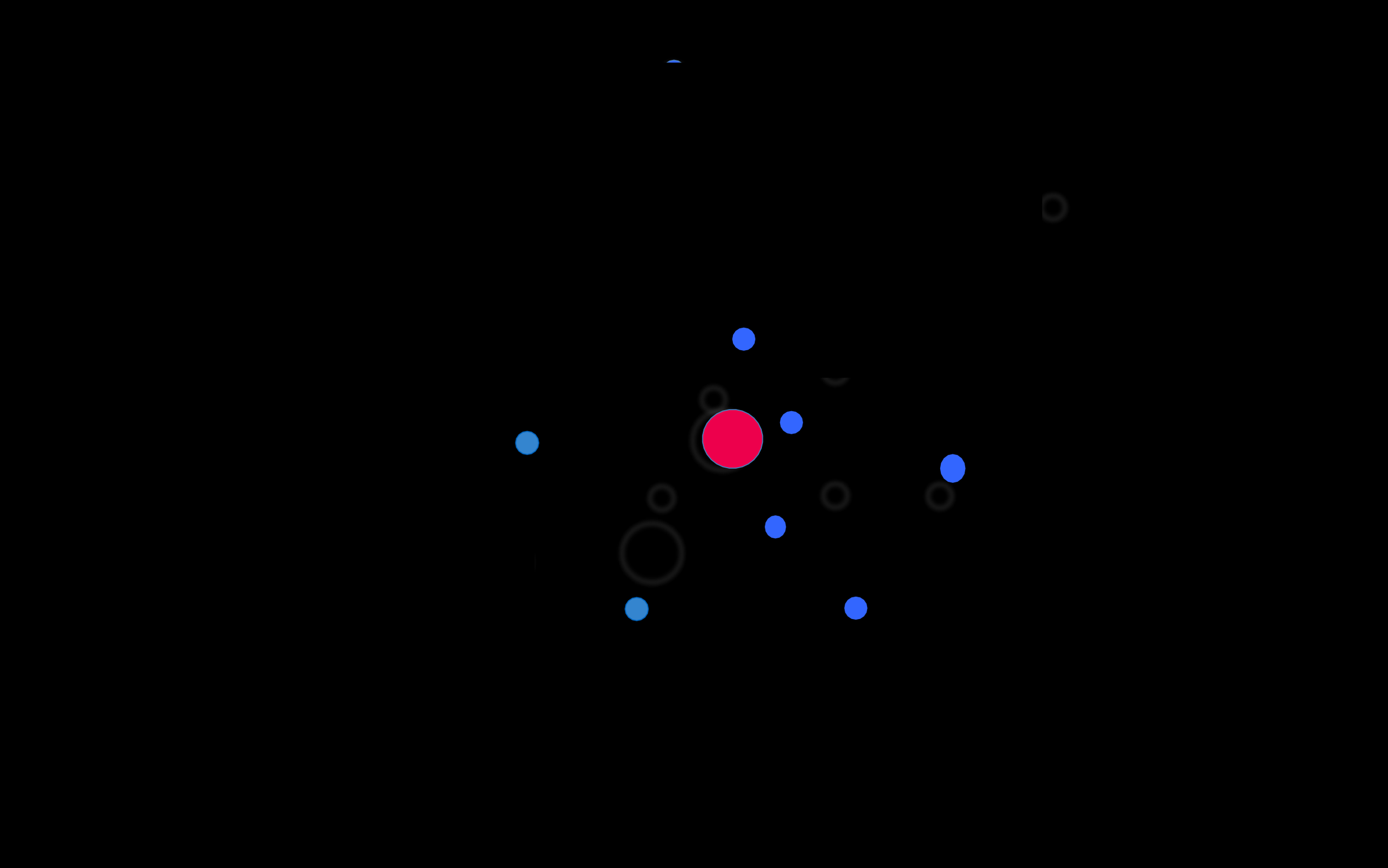
Positive Ions

Electrons



Positive Ions

Electrons



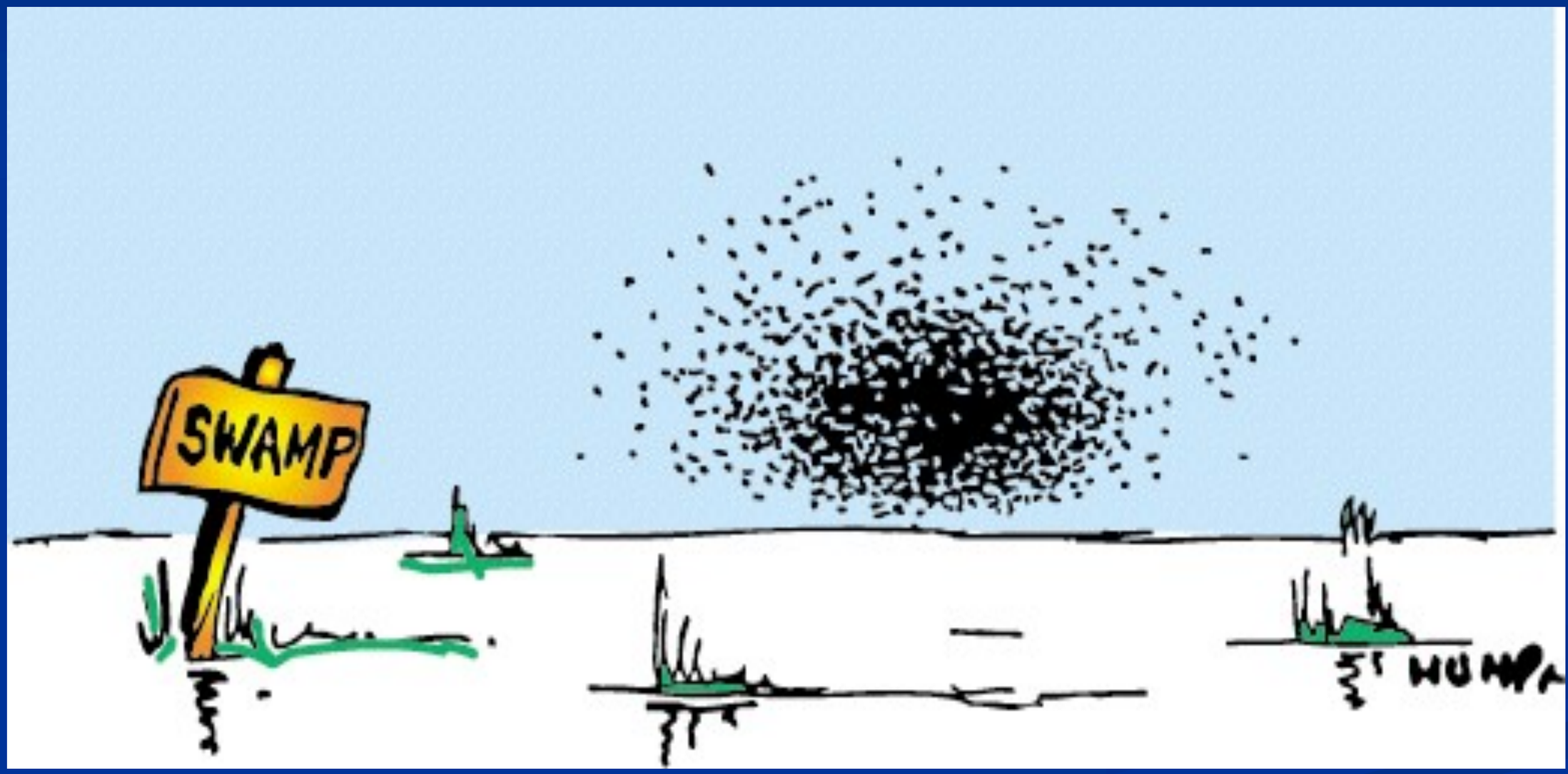
Positive Ions

Electrons

Positive Ions

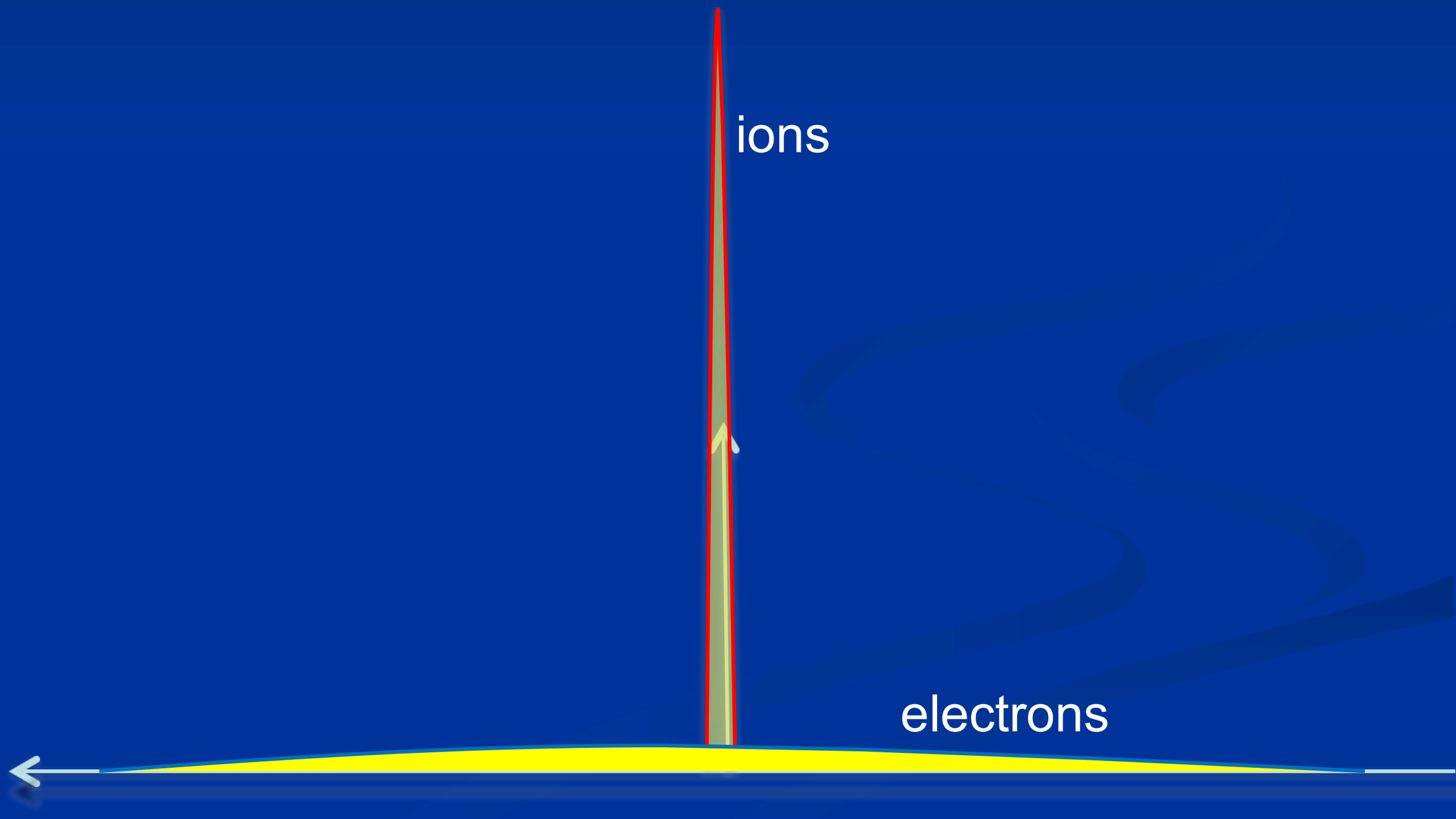
Electrons

Incoherent scattering: the short story



Incoherent scattering: the short story

The ionospheric ions acts as slooooow pacers for the electron gas



Plasma Frequency ~

$$\omega_p^2 = \frac{n_0 e^2}{m\epsilon_0}$$

From Attila Komjathy, JPL

Plasma Frequency ~

$$\omega_p^2 = \frac{n_0 e^2}{m\epsilon_0}$$

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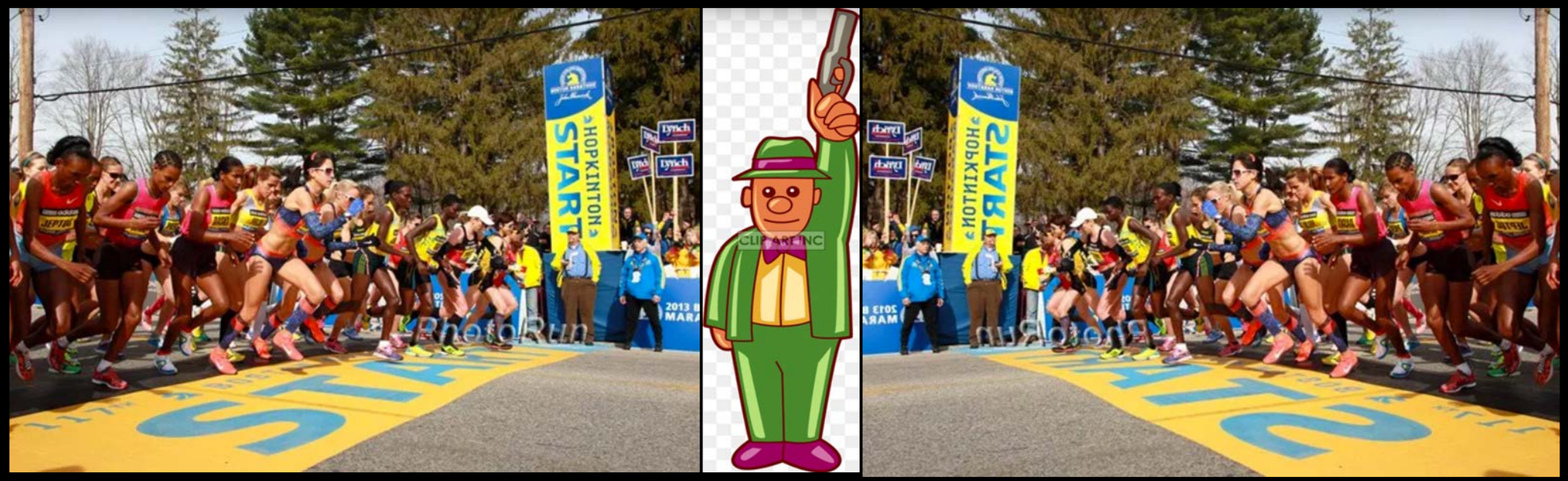
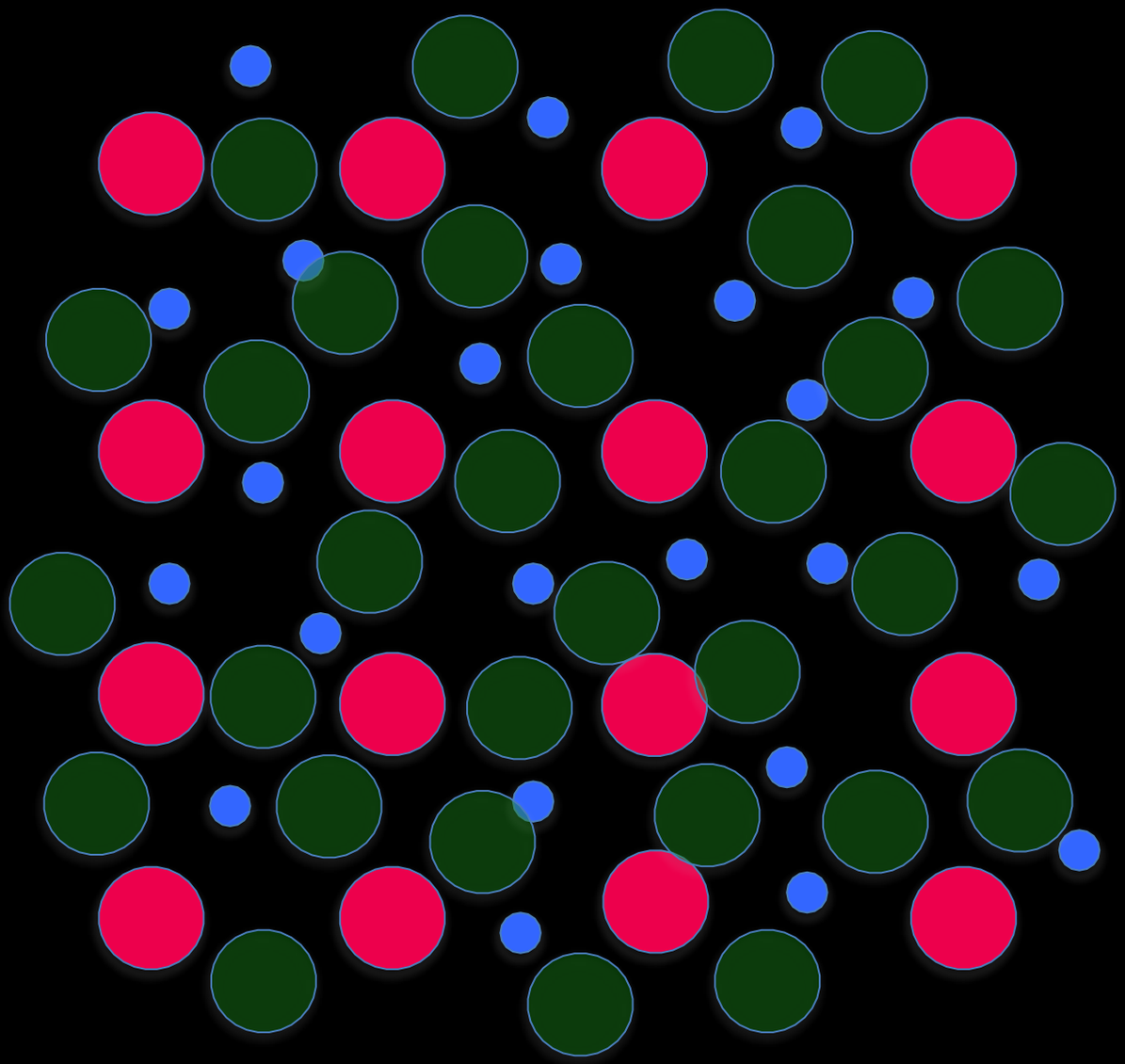
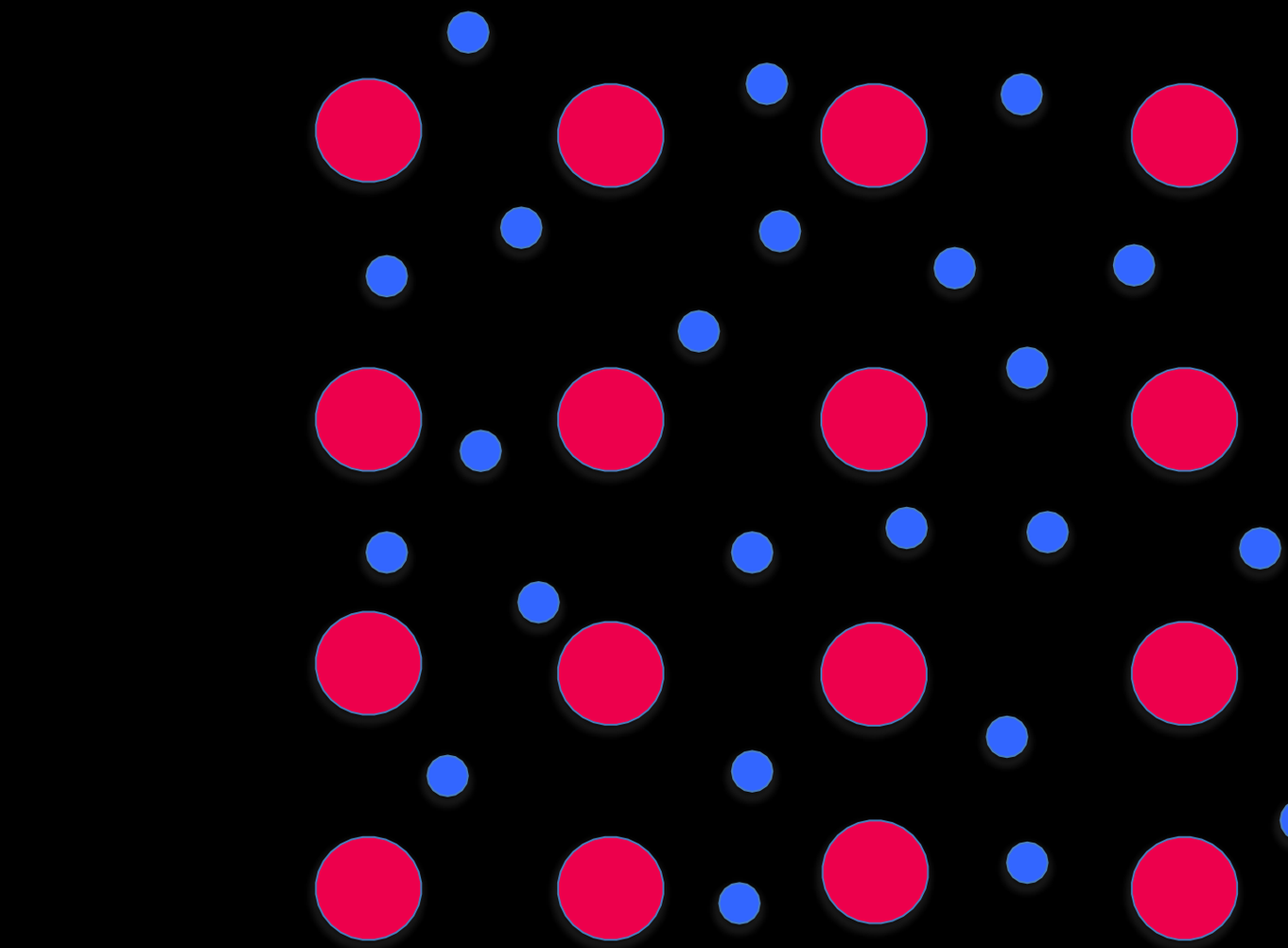




Neutrals

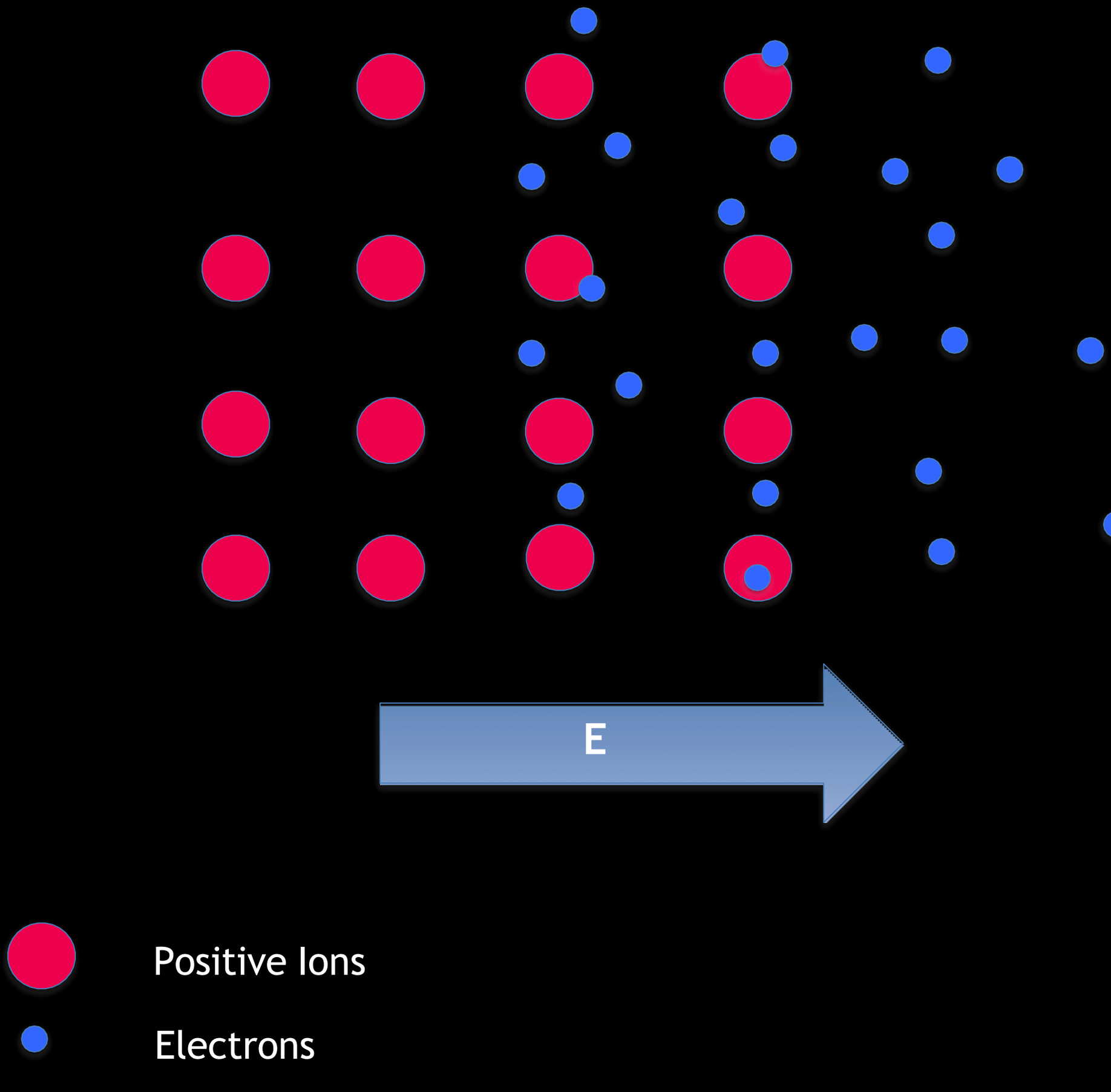
Positive Ions

Electrons



Positive Ions

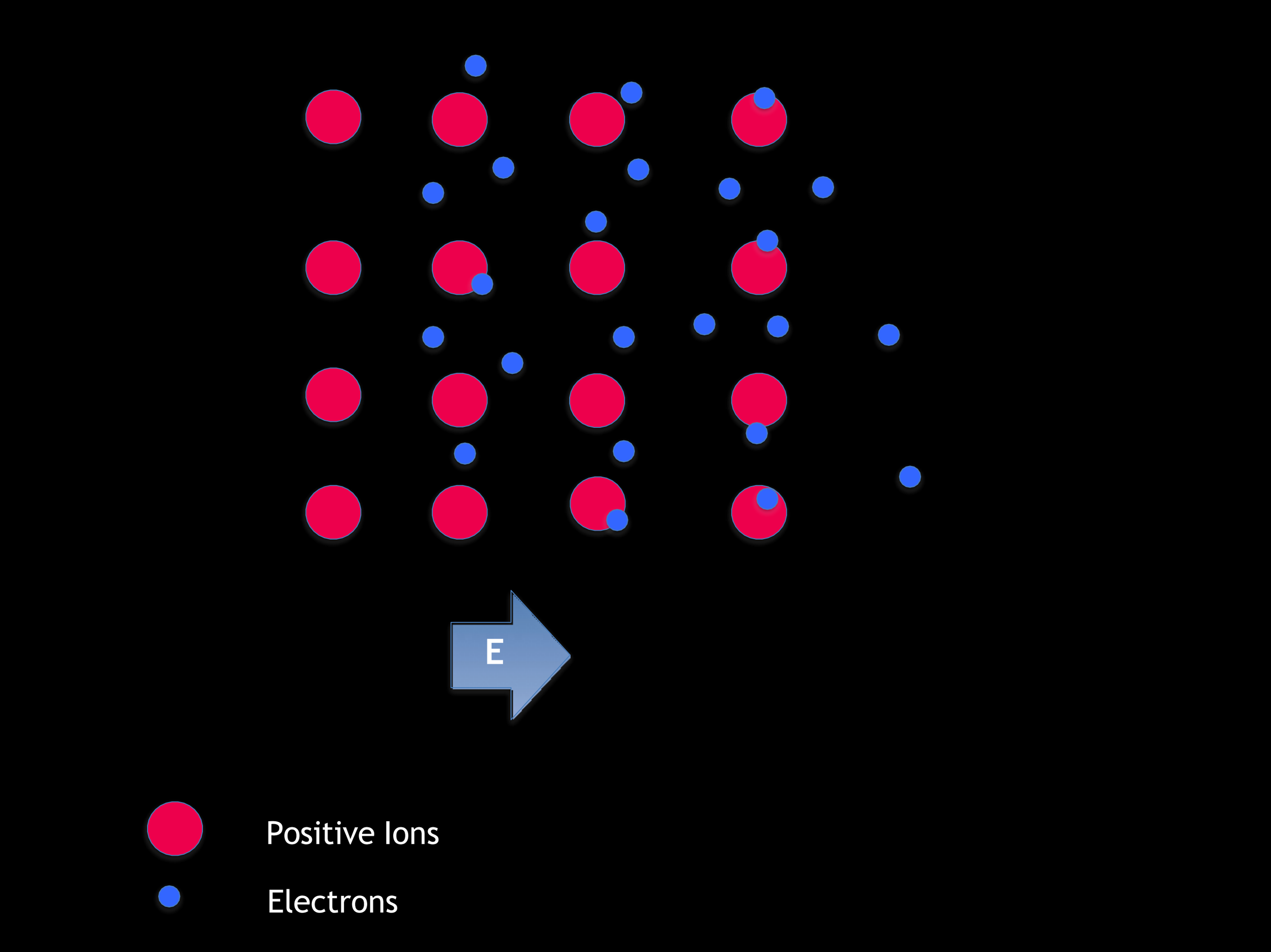
Electrons


E
Positive Ions
Electrons

E

Positive Ions

Electrons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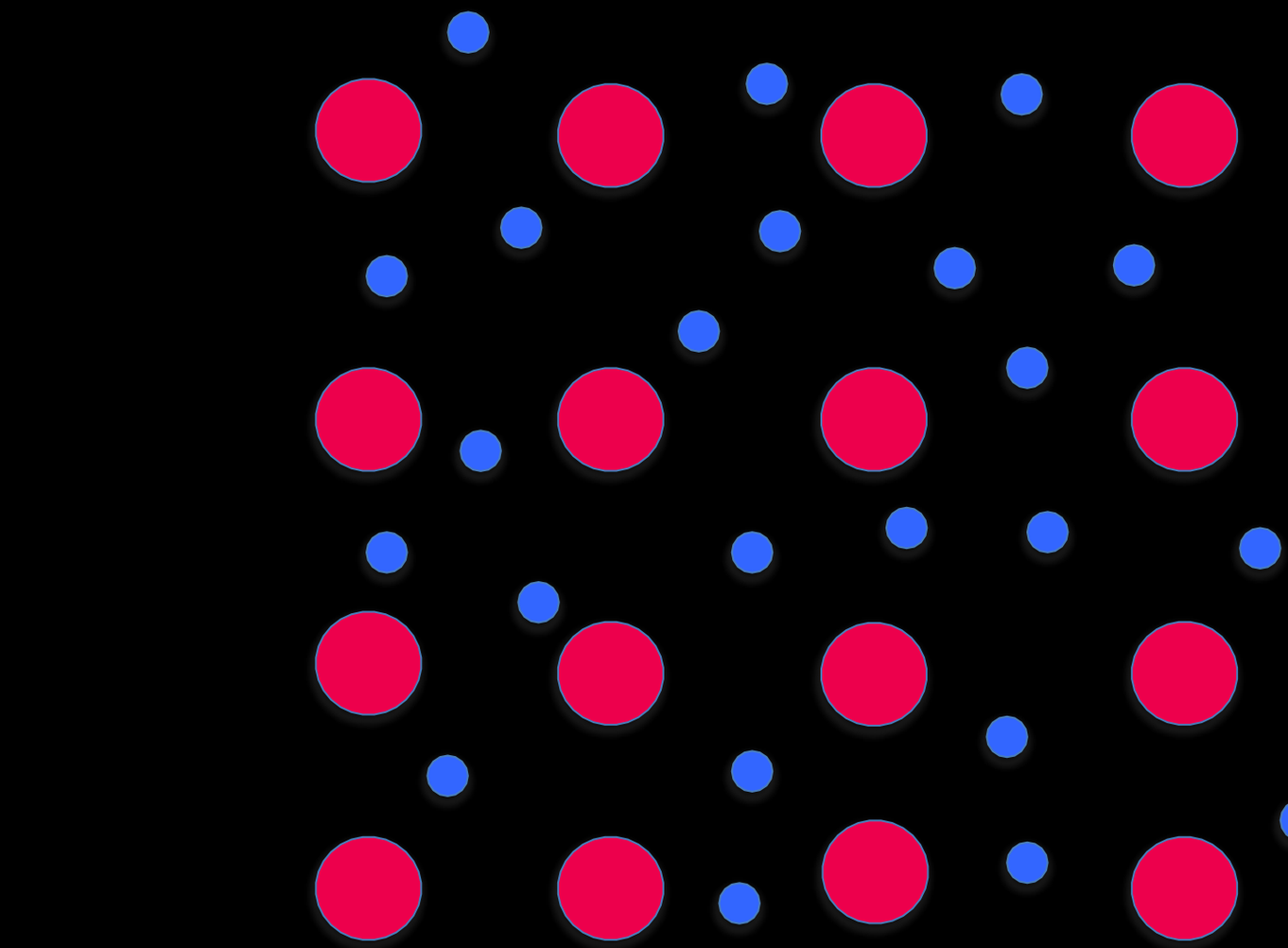
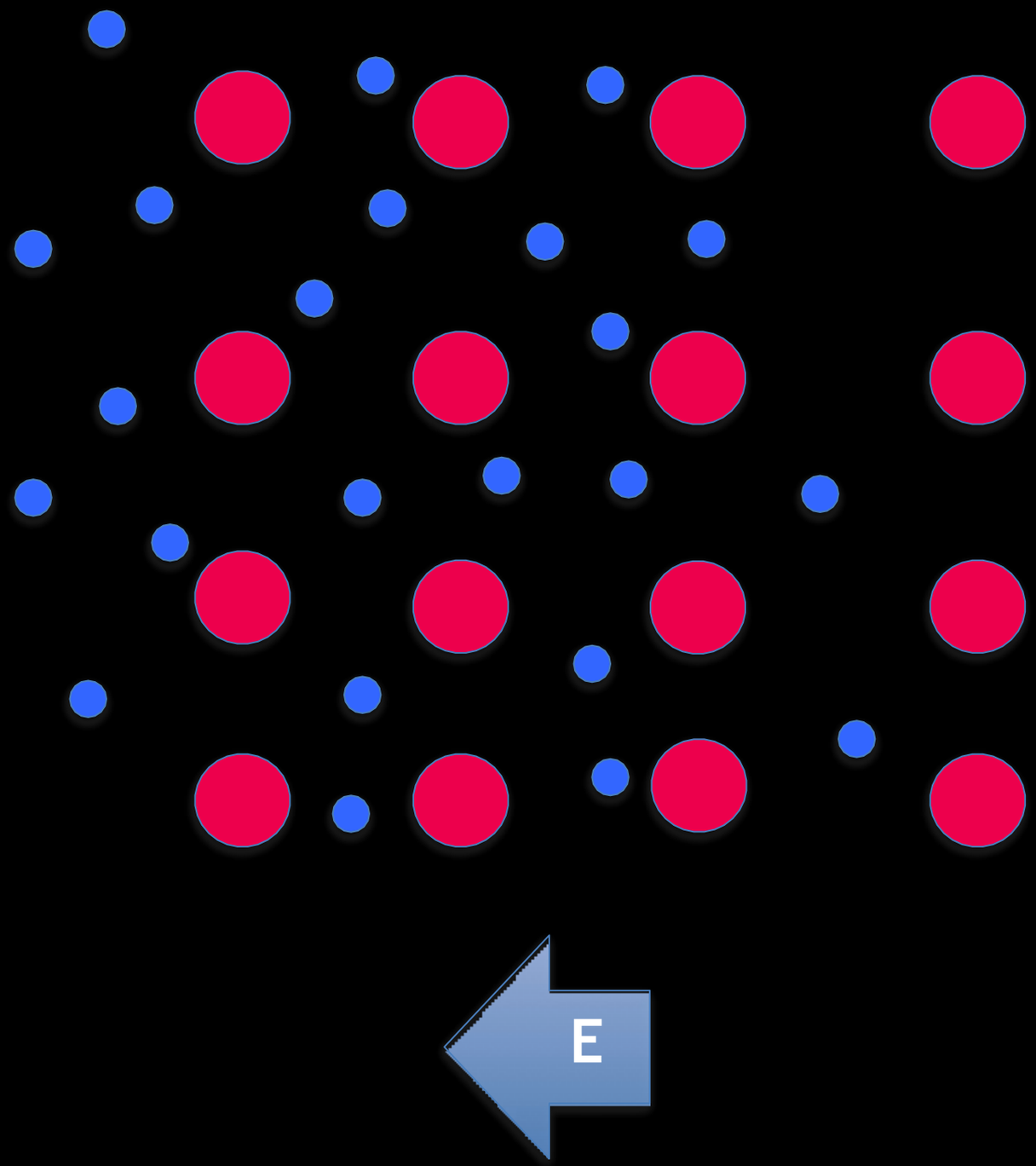
Electrons



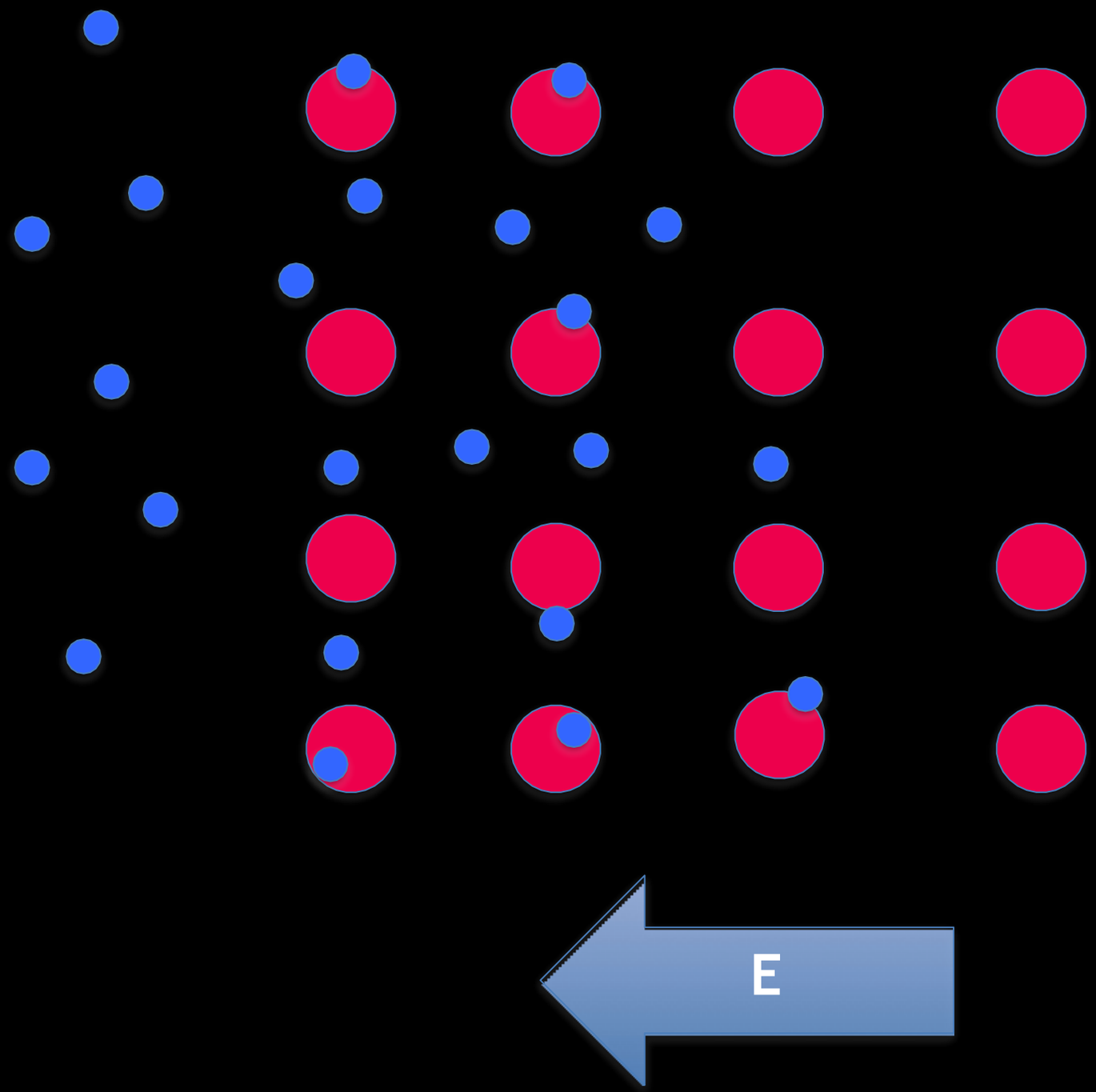
Positive Ions

Electrons



Positive Ions

Electrons



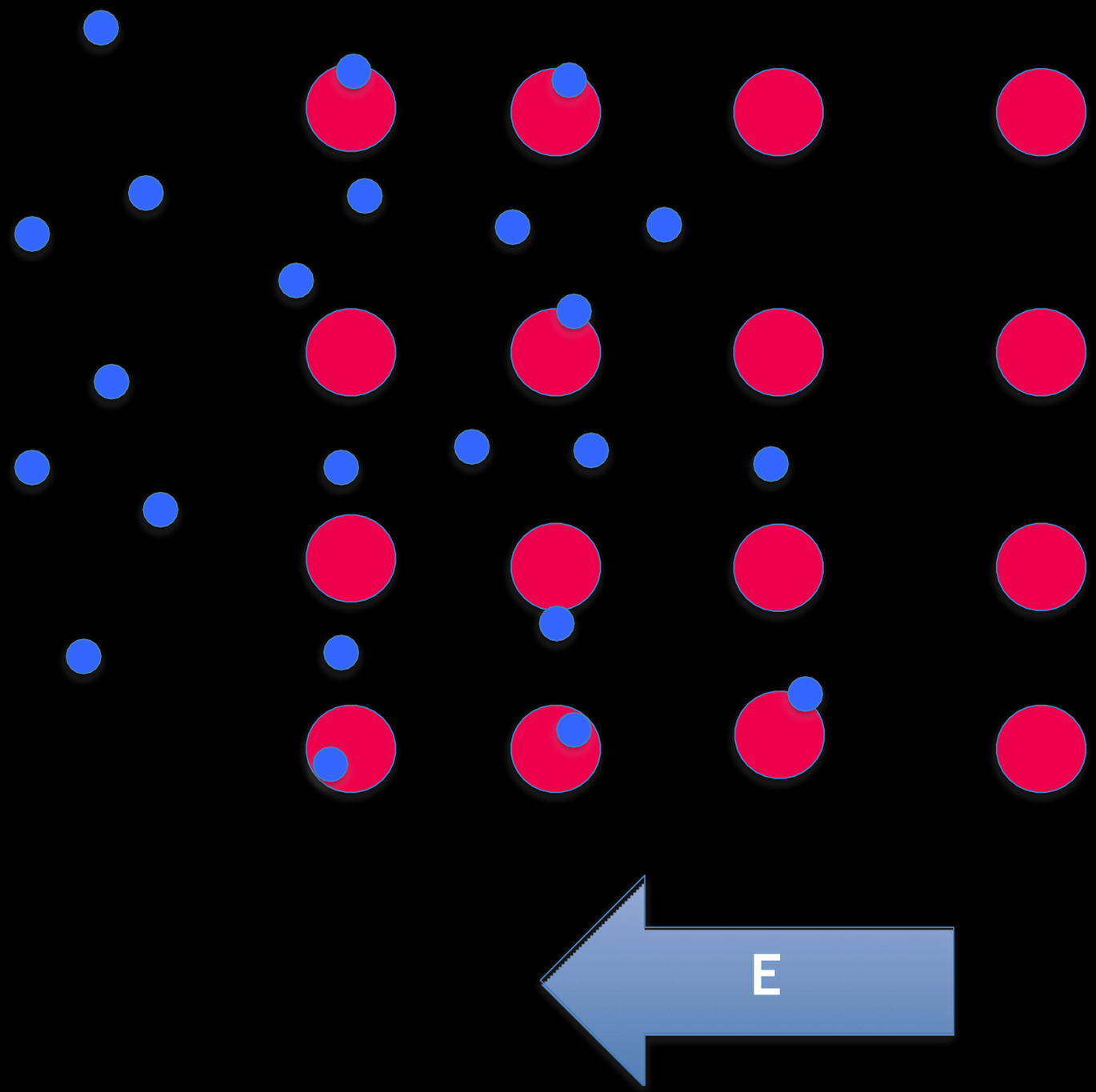
Positive Ions

Electrons

E

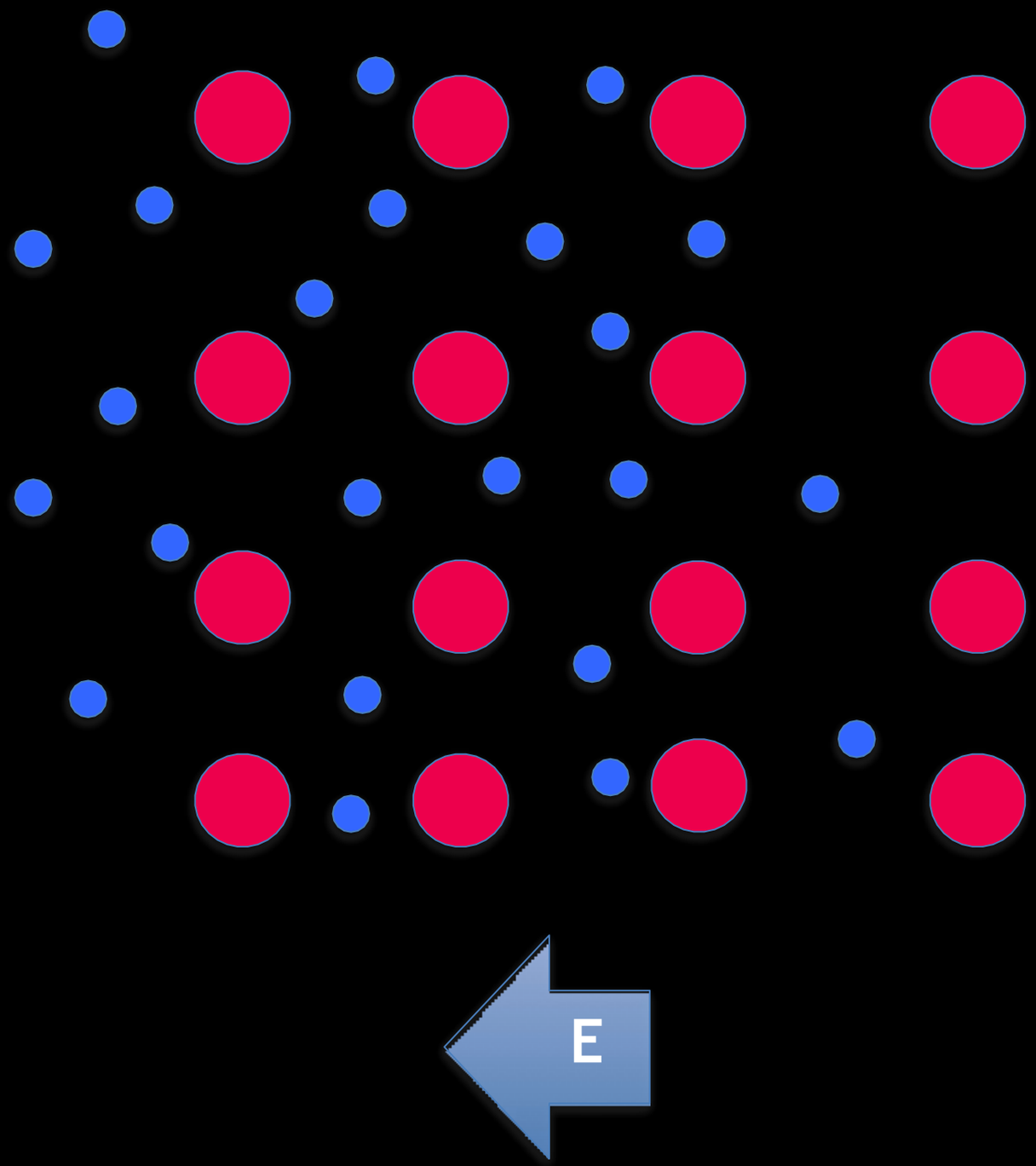
Positive Ions

Electrons



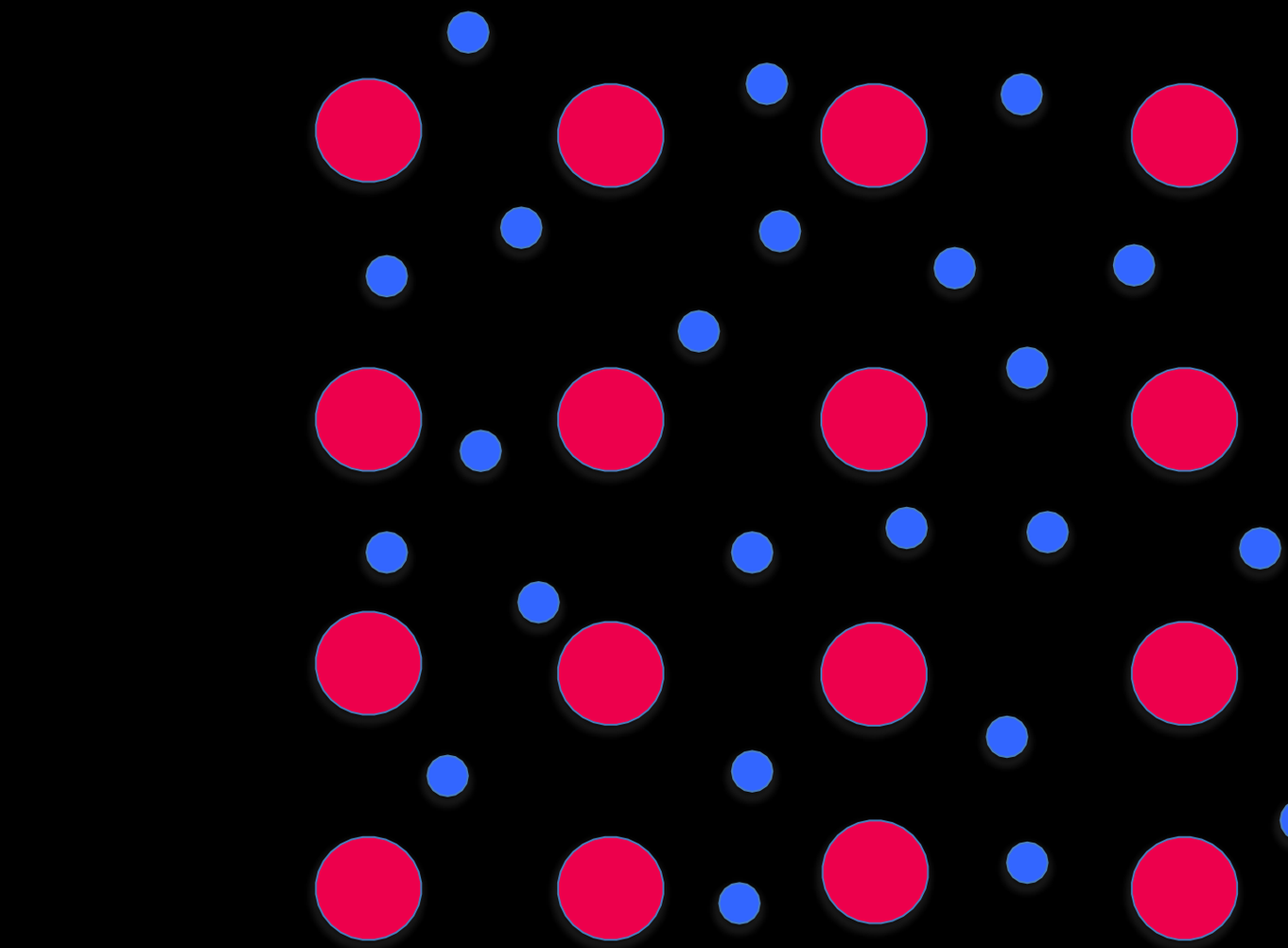
Positive Ions

Electrons



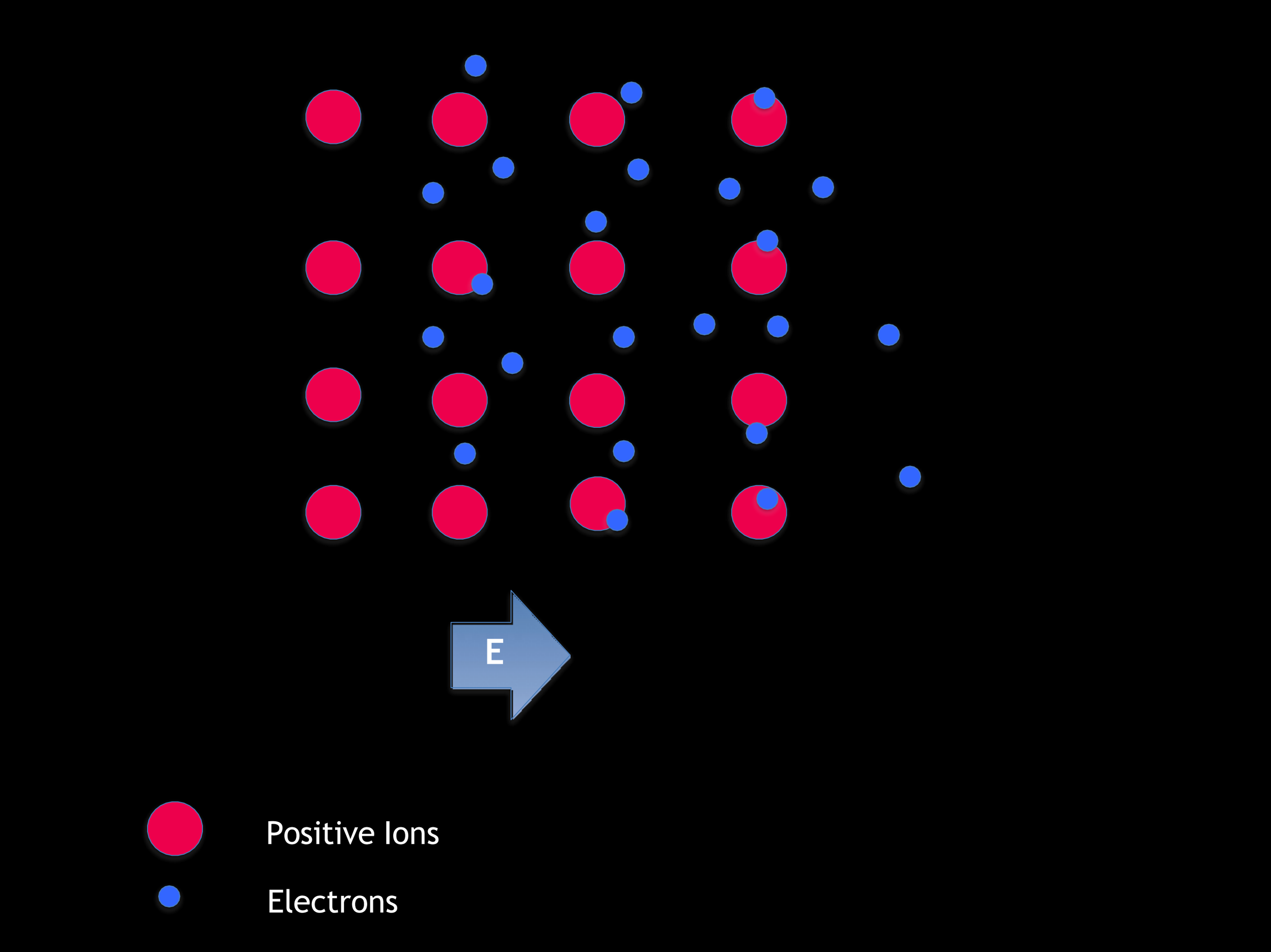
Positive Ions

Electrons



Positive Ions

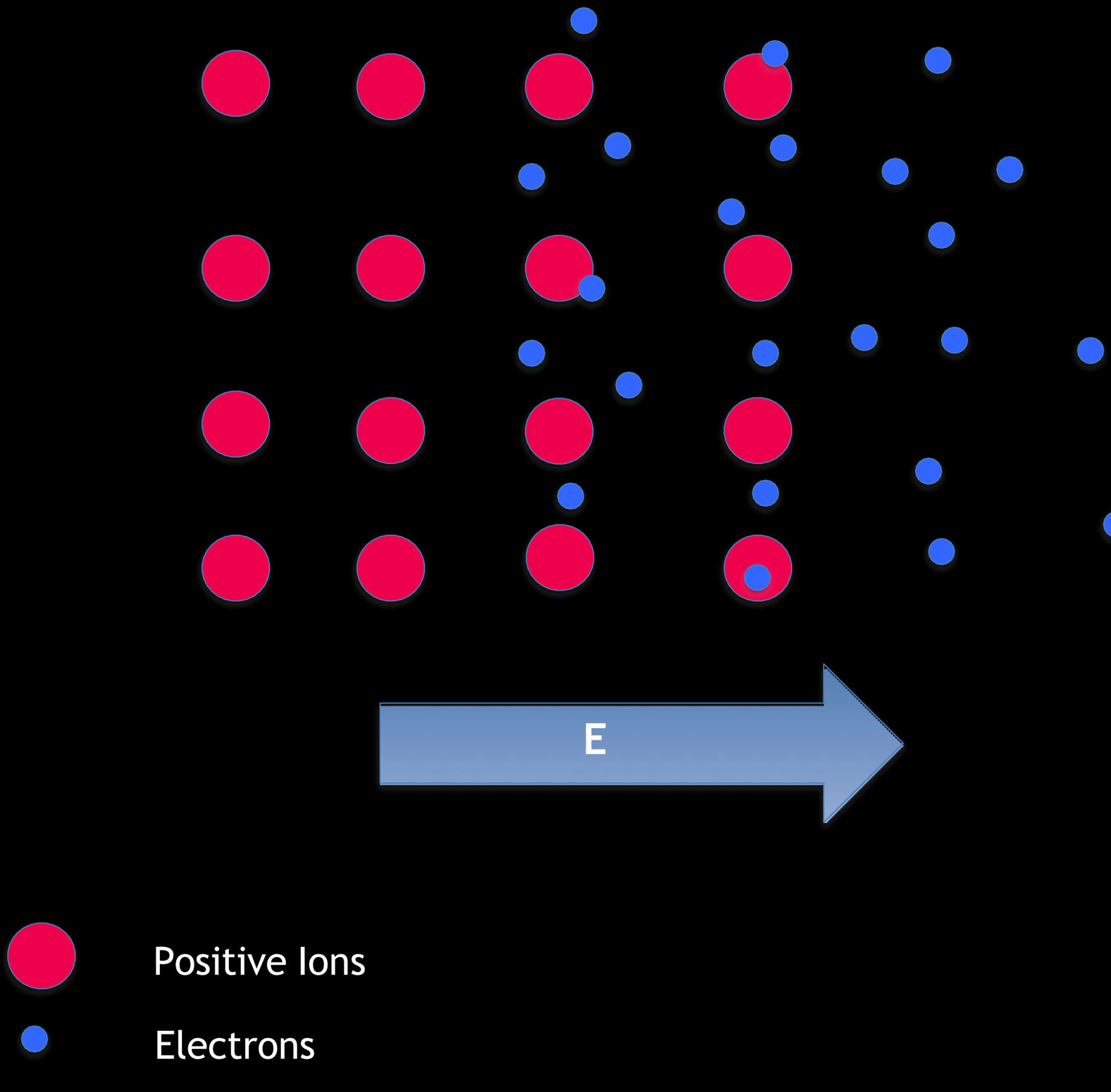
Electrons


E
Positive Ions
Electrons

E

Positive Ions

Electrons


E
Positive Ions
Electrons

The electron gas oscillates at a natural plasma oscillation frequency

Langmuir (or plasma) waves

High-frequency electrostatic waves

- Dispersion relation:

$$\omega_r = (\omega_{pe}^2 + 3k^2 v_{the}^2)^{1/2} = \omega_p (1 + 3k^2 \lambda_{De}^2)^{1/2}$$

$$\omega_i = -C \frac{\omega_{pe}}{(k\lambda_{De})^3} \exp(-\tfrac{1}{2} k^2 \lambda_{De}^2), \quad C = \sqrt{\frac{\pi}{8}} e^{-3/2}$$

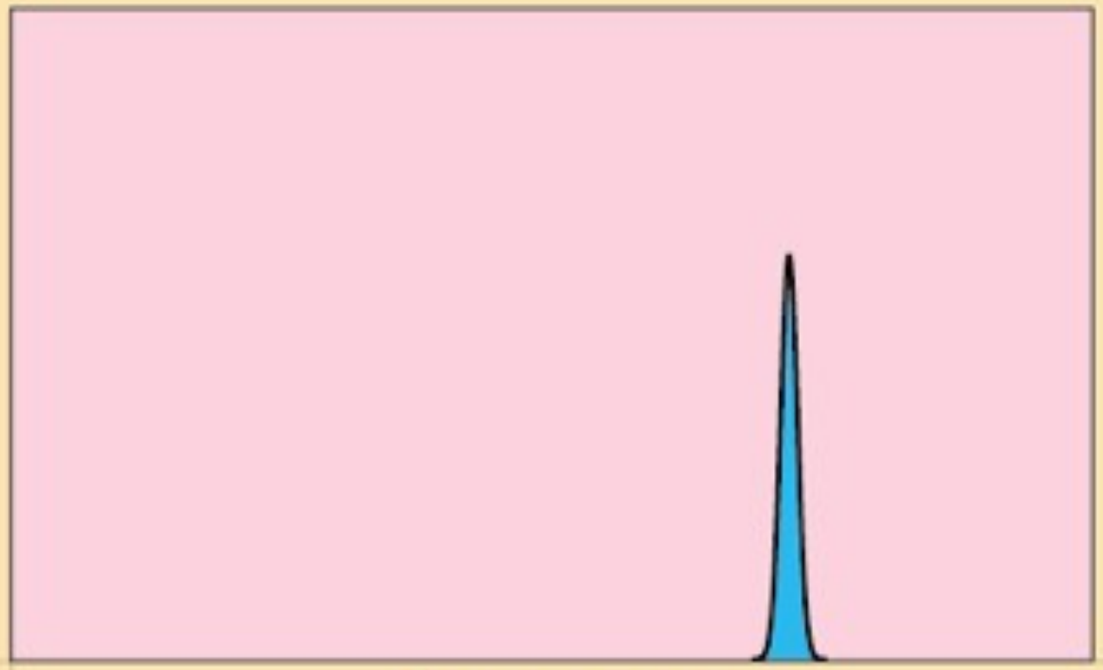
Ion acoustic waves

* Ion acoustic waves:

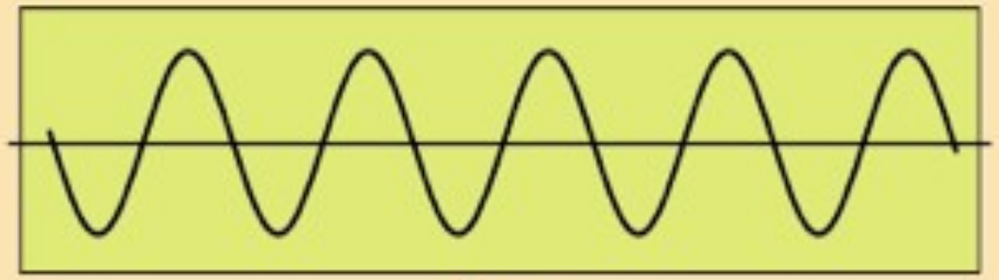
$$(63)\qquad \omega_r = \frac{kC_s}{1+k^2\lambda_{De}^2}, \qquad C_s = \left(\frac{k_B T_e + 3k_B T_i}{m_i}\right)^{1/2}$$

$$(64)\qquad \omega_i = -\sqrt{\frac{\pi}{8}}\,\frac{\omega_r}{(1+k^2\lambda_{De}^2)^{3/2}}\left[\left(\frac{T_e}{T_i}\right)^{3/2}\exp\left(-\frac{T_e/T_i}{2(1+k^2\lambda_{De}^2)}\right)+\sqrt{\frac{m_e}{m_i}}\right]$$

time

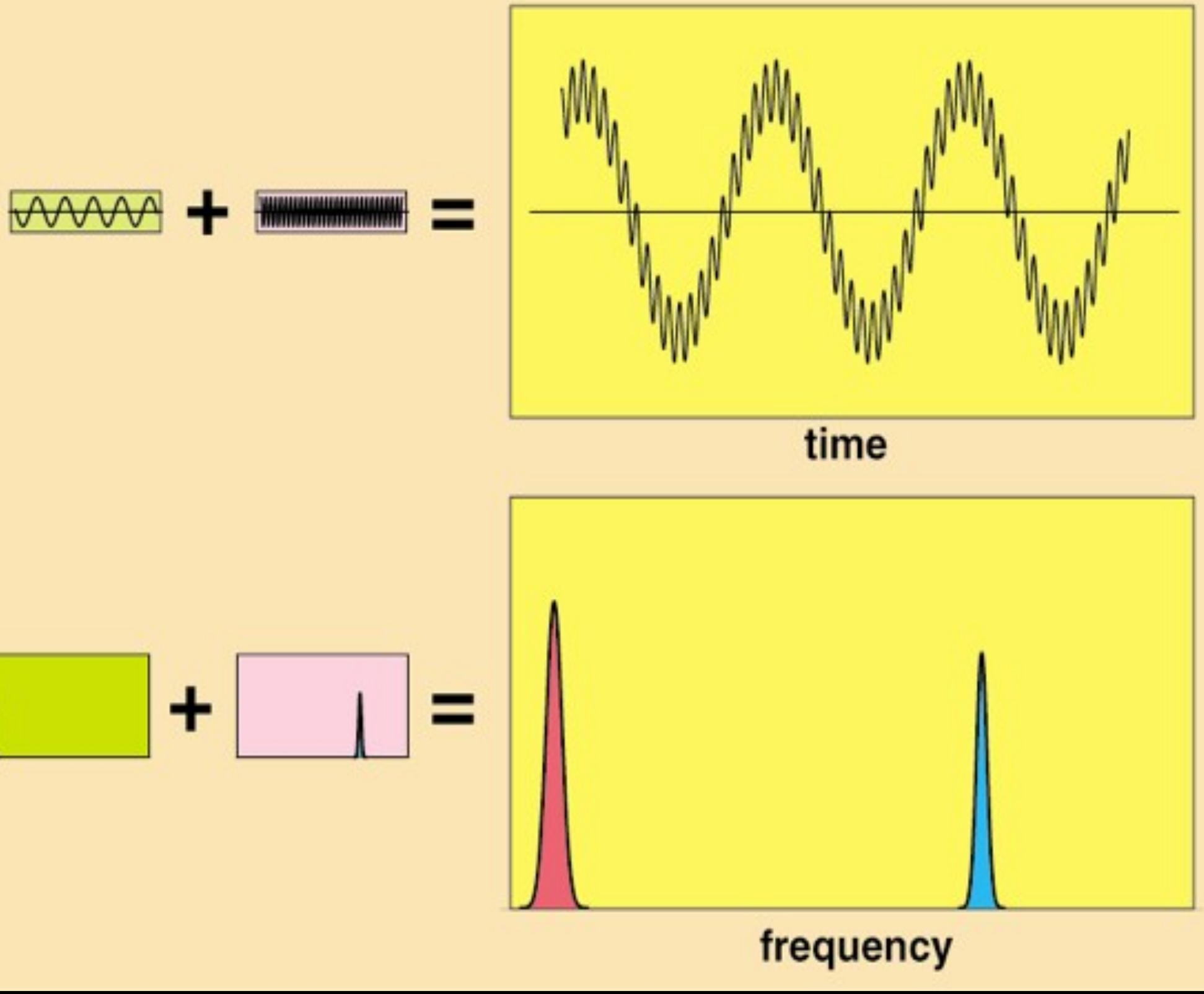


frequency

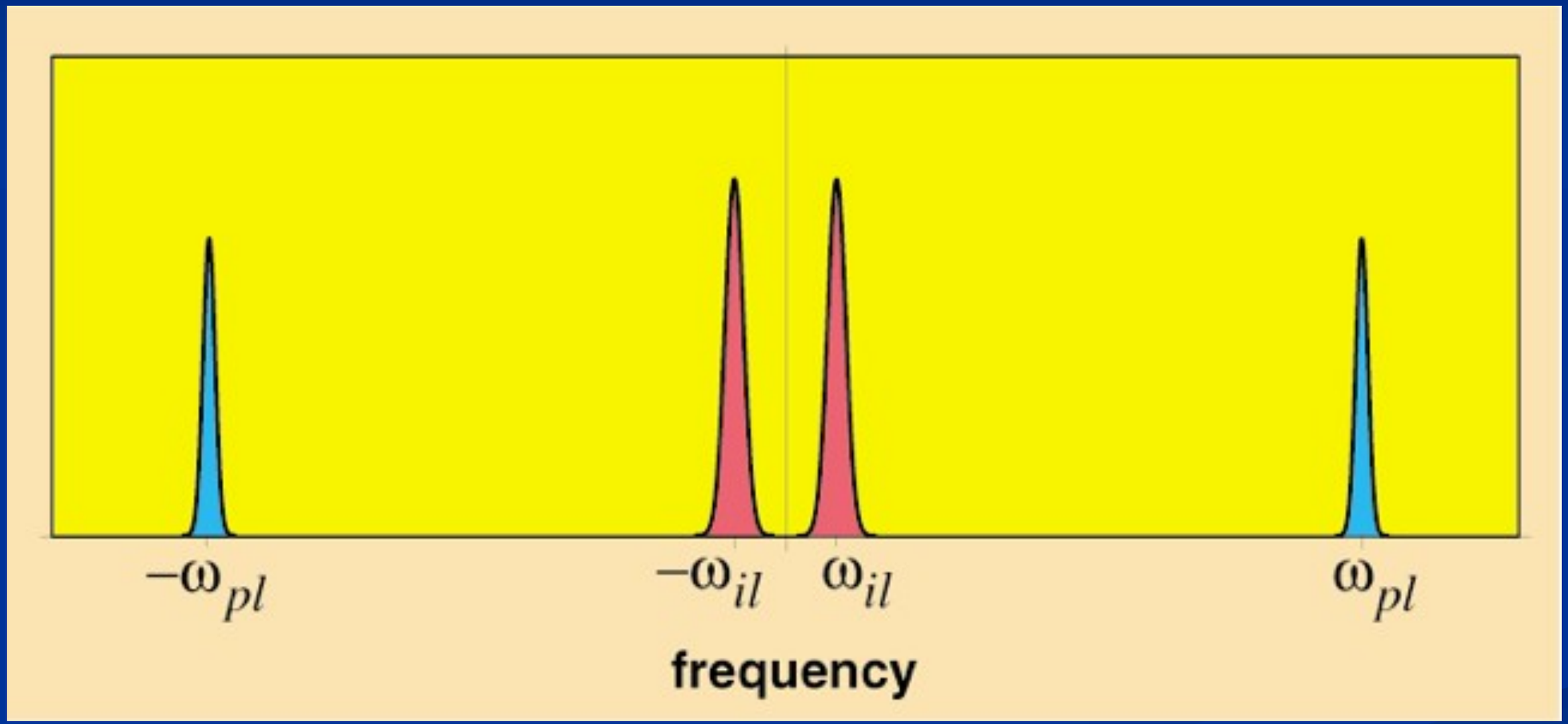


time

frequency


time
frequency

Plasma Wave Approach (cont'd)



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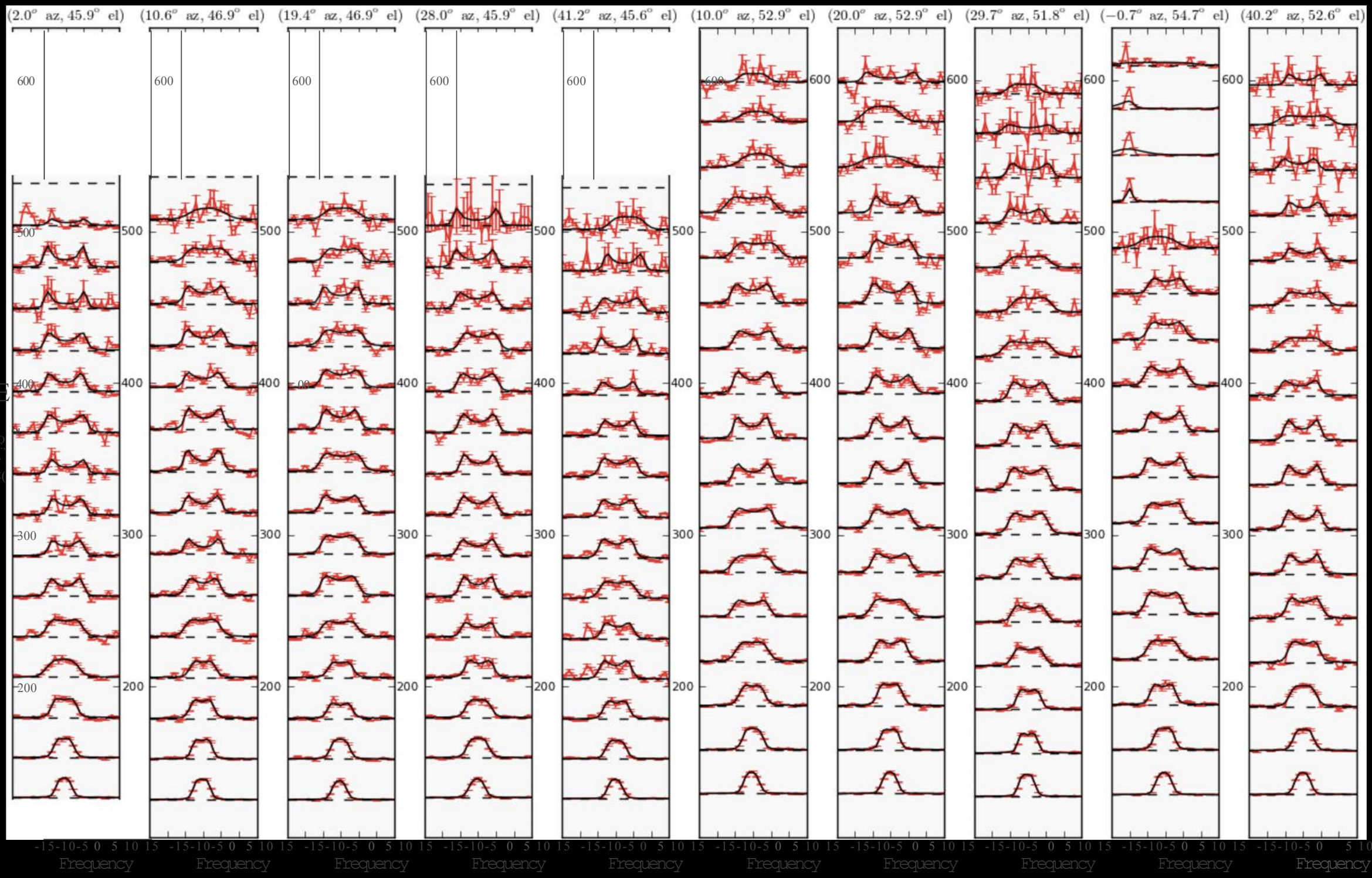


Landau wave-particle interactions

wave

particle gains energy

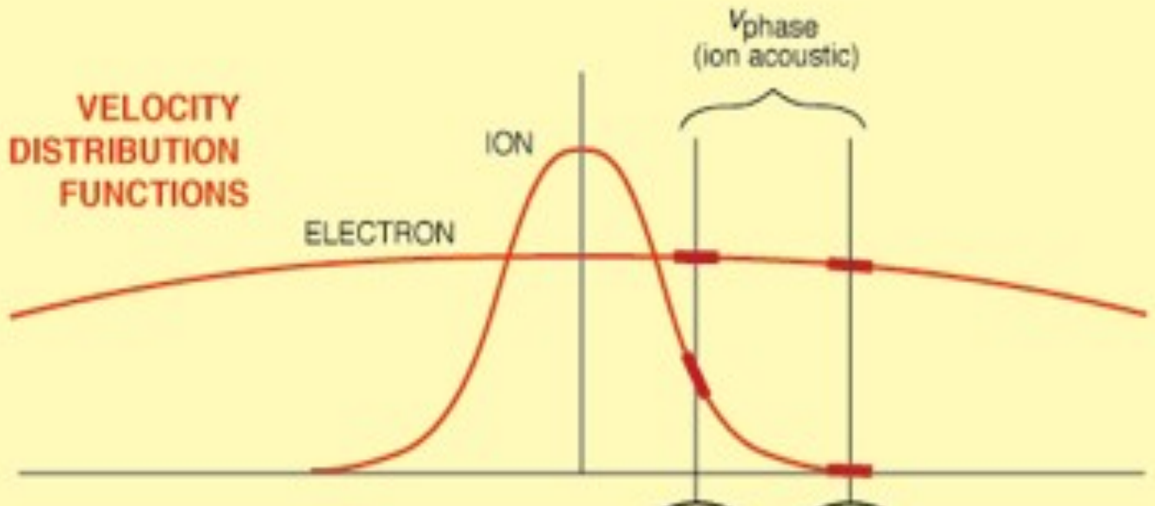
wave gains energy

THE EFFECT OF LANDAU DAMPING ON THE INCOHERENT SCATTER ION LINE SPECTRUM

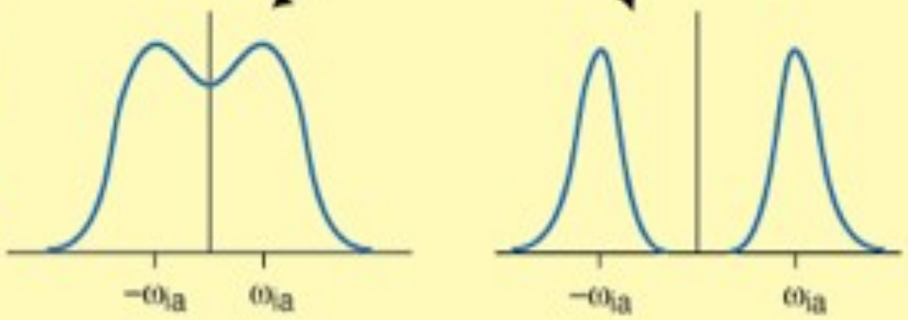
ION-ACOUSTIC DISPERSION EQUATION

$$\omega_{ia} = k\, v_{phase} = k\left(\frac{T_e + 3T_i}{m_i}\right)^{1/2}$$

VELOCITY DISTRIBUTION FUNCTIONS



INCOHERENT SCATTER ION LINE SPECTRA



$T_e/T_i = 1$

STRONG LANDAU DAMPING

$T_e/T_i \gg 1$

WEAK LANDAU DAMPING

electron
density profile

Incoherent scatter spectra

height

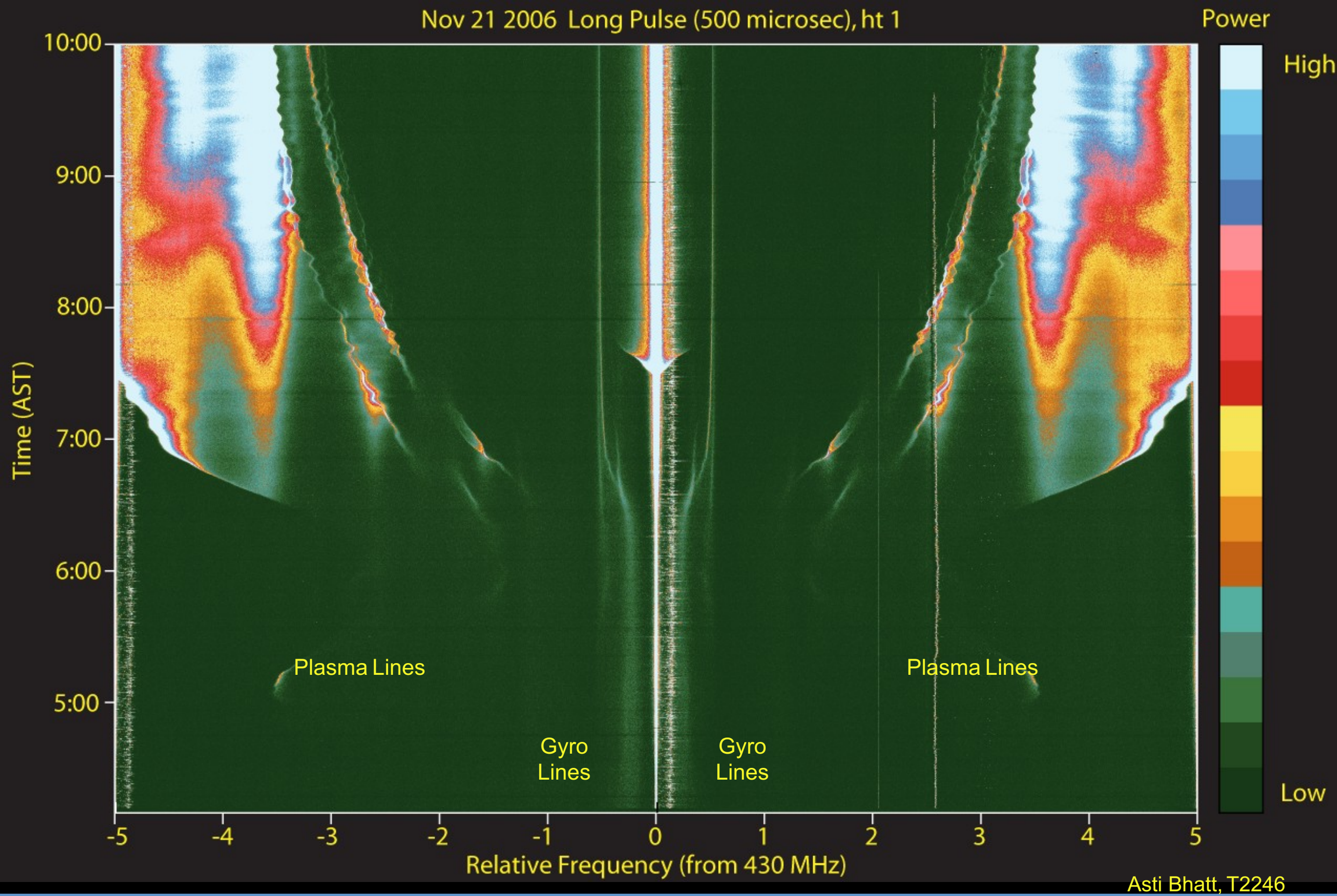
spectral amplitude

plasma
line
downshifted

ion
line

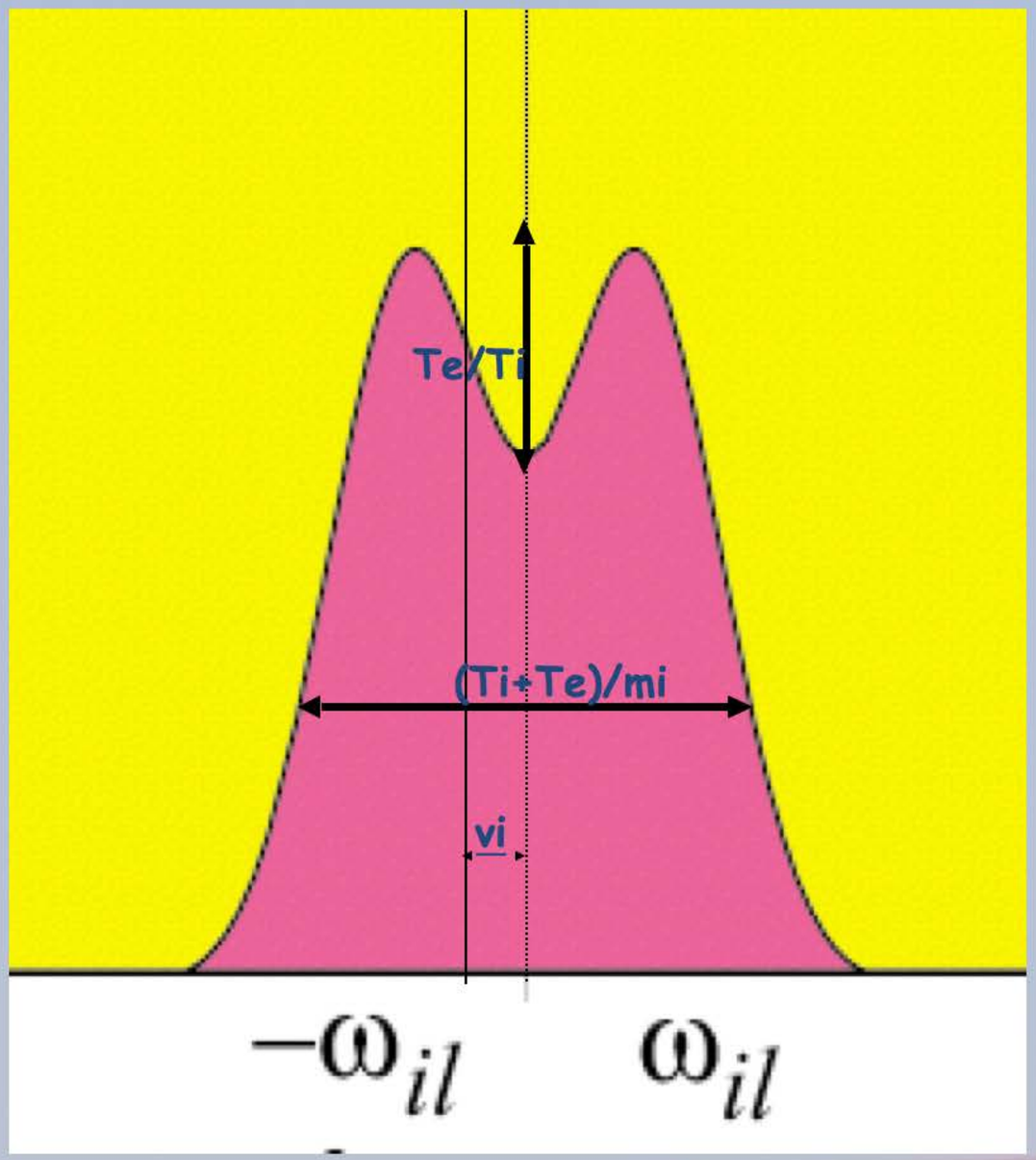
plasma
line
upshifted

frequency



Arecibo Sensitivity: The 305 m dish, 2.5 MW of power, and Tsys of about 80 K (condition dependent) provide high time resolution on even weak features such as the gyro line. The data above are centered on the E region. The strong plasma line after sunrise is “leakage” from the low F region. The complicated behavior of the gyro line is probably due to multiple layers, but is not completely understood.!

…or to sum up…



- Ion (and electron) temperature (Ti and Te) to ion mass (mi) ratio from the width of the spectra
- Electron to ion temperature ratio (Te/Ti) from "peak_to_valley" ratio
- Electron (= ion) density from total area (corrected for temperatures)
- Ion velocity (vi) from the Doppler shift

Plasma Line $S_{PL}(\mathbf{k},\omega)$ **Ion Line** $S_{IL}(\mathbf{k},\omega)$

$$S_e(\mathbf{k},\omega) = N_e\left|1-\frac{\chi_e(\mathbf{k},\omega)}{\epsilon(\mathbf{k},\omega)}\right|^2\int d\mathbf{v}\, f_e(\mathbf{v})\delta(\omega-\mathbf{k}\cdot\mathbf{v}) + N_i\left|\frac{\chi_e(\mathbf{k},\omega)}{\epsilon(\mathbf{k},\omega)}\right|^2\int d\mathbf{v}\, f_i(\mathbf{v})\delta(\omega-\mathbf{k}\cdot\mathbf{v})$$

$$\epsilon(\mathbf{k},\omega)=0$$

$$\omega_{pl}(k)\approx\omega_{pe}(1+3\lambda_D^2k^2)$$

$$\omega_{ia}(k)\approx k\sqrt{\frac{T_e+3T_i}{m_i}}$$