Introduction to Incoherent Scatter 1

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Incoherent Scatter Radar

- Incoherent
- Scatter
- Radar

Incoherent Scatter Radar

- Radar
- Scatter
- Incoherent

Radar

- RADAR (RAdio Detection And Ranging)
  - is 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)

Radar equation

- The power P_r returning to the receiving antenna is given by the equation:

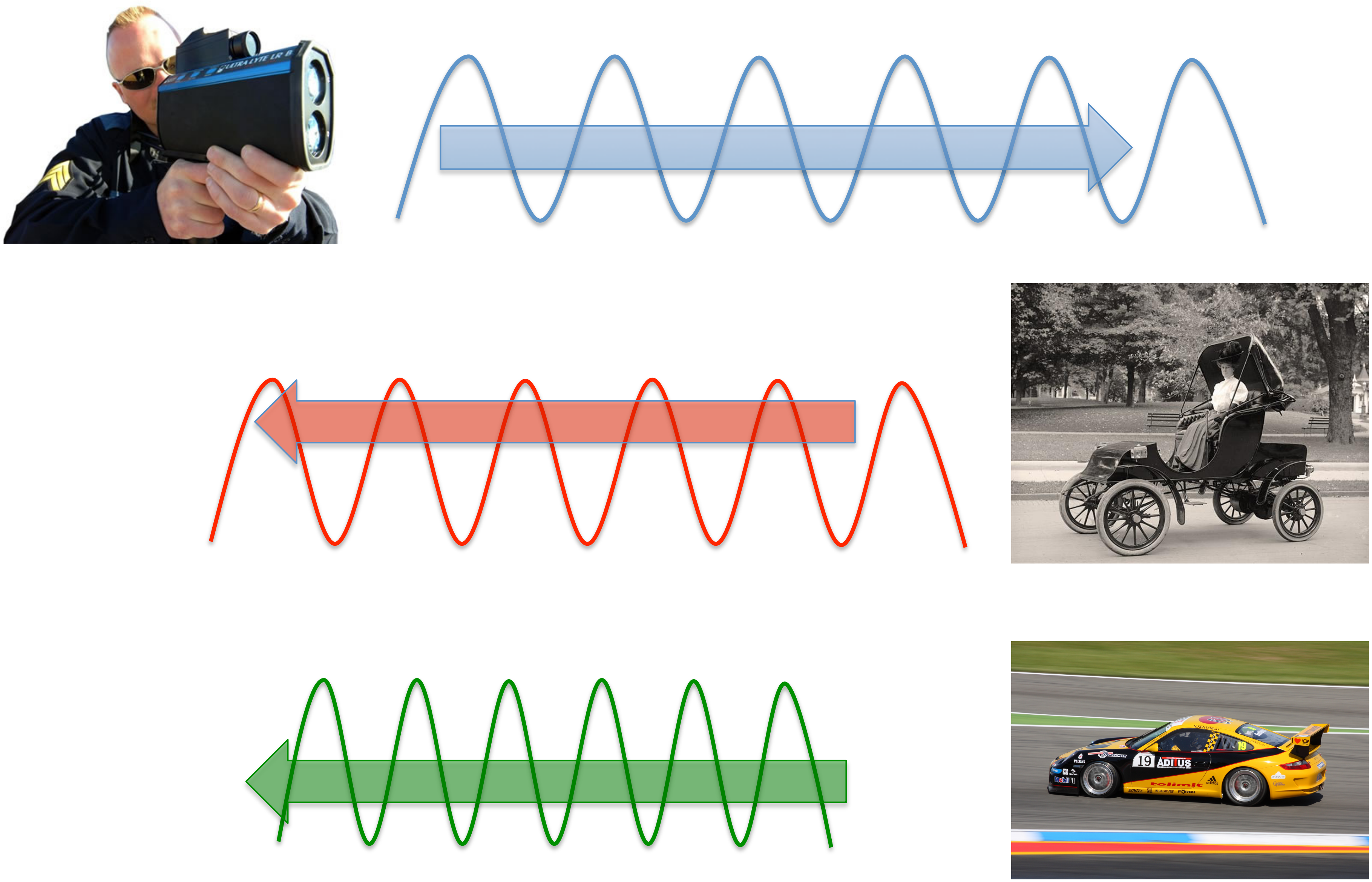
$$P_r = \frac{P_t G_t A_r \sigma}{(4\pi)^2 R_t^2 R_r^2}$$

where

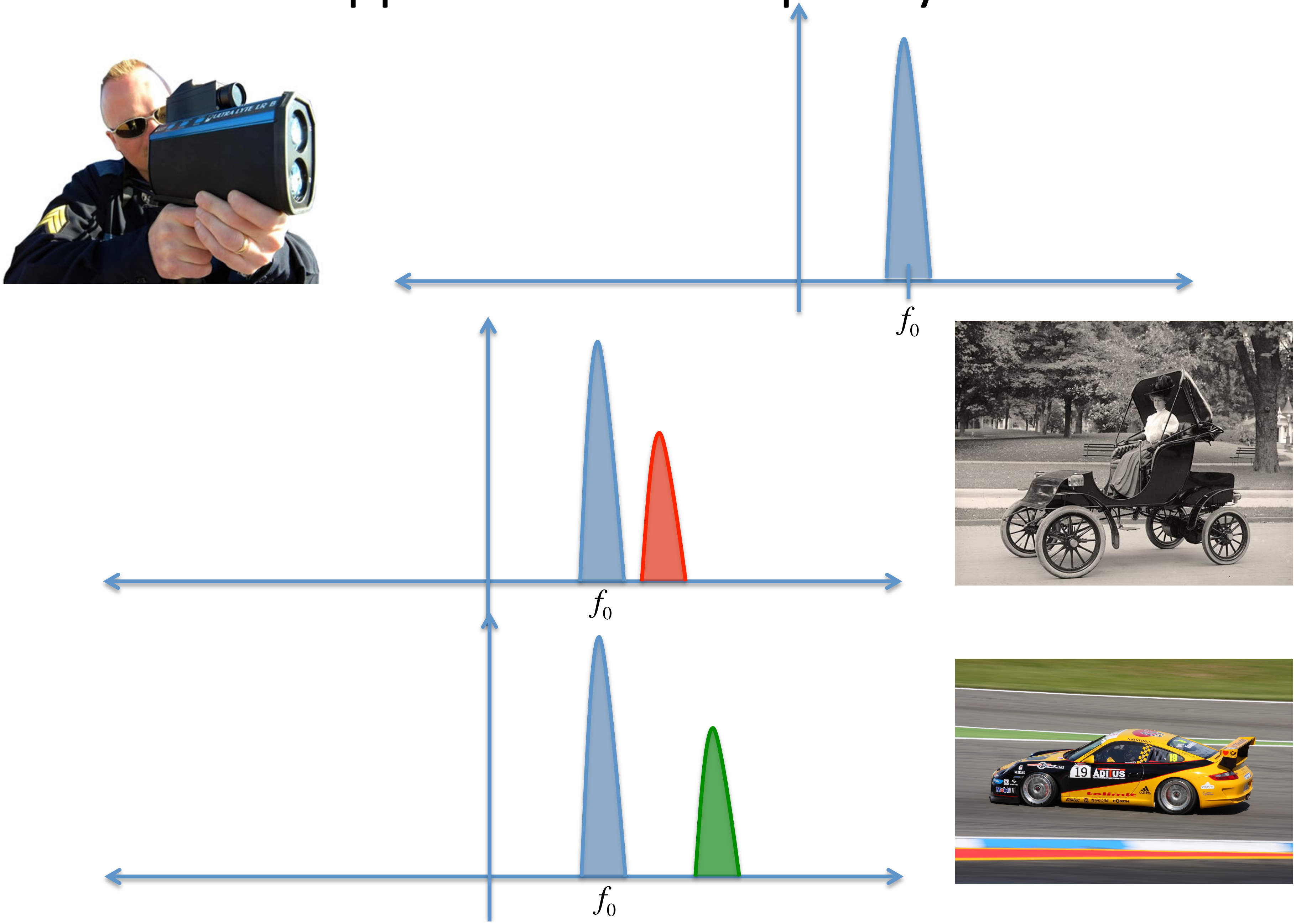
- P_t = transmitter power
- G_t = gain of the transmitting antenna
- A_r = effective apperture (area) of the receiving antenna
- σ = radar cross section, or scattering coefficient, of the target
- R_t = distance from the transmitter to the target
- R_r = distance from the target to the receiver.
- In the common case where the transmitter and the receiver are at the same location, $R_t = R_r$ and the term $R_t^2 R_r^2$ can be replaced by R^4, where R is the range. This yields:

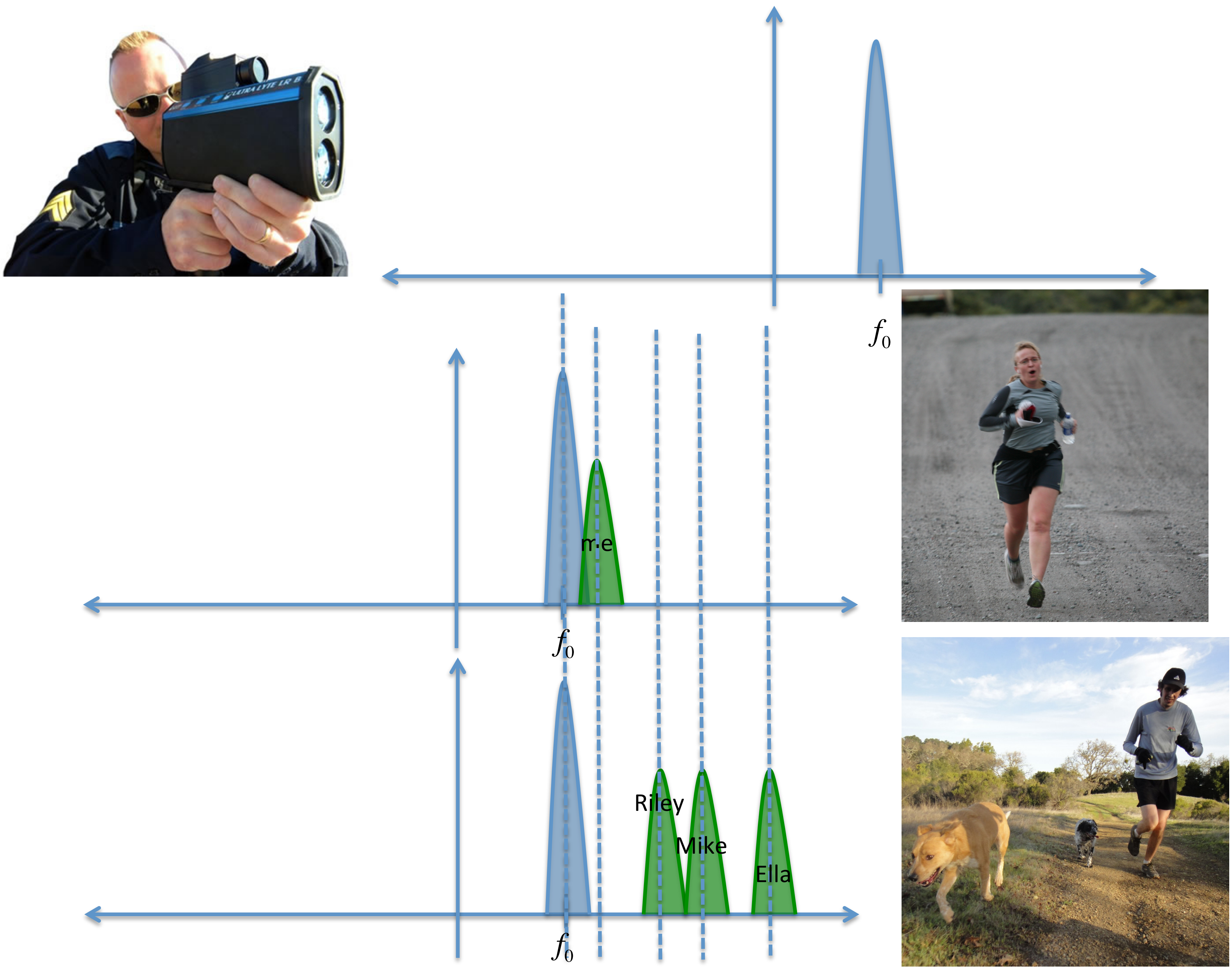
$$P_r = \frac{P_t G_t A_r \sigma}{(4\pi)^2 R^4}$$

Doppler Radar – time domain

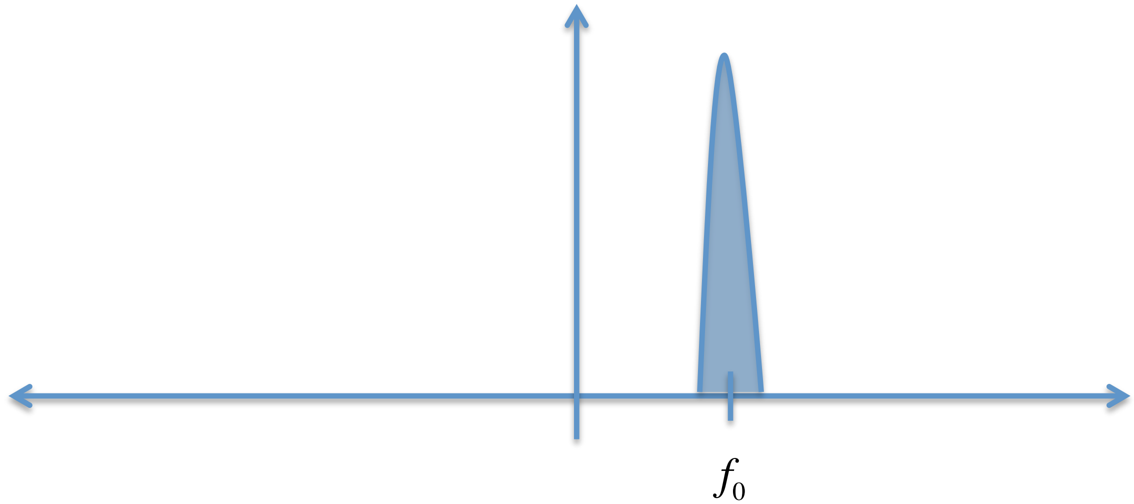


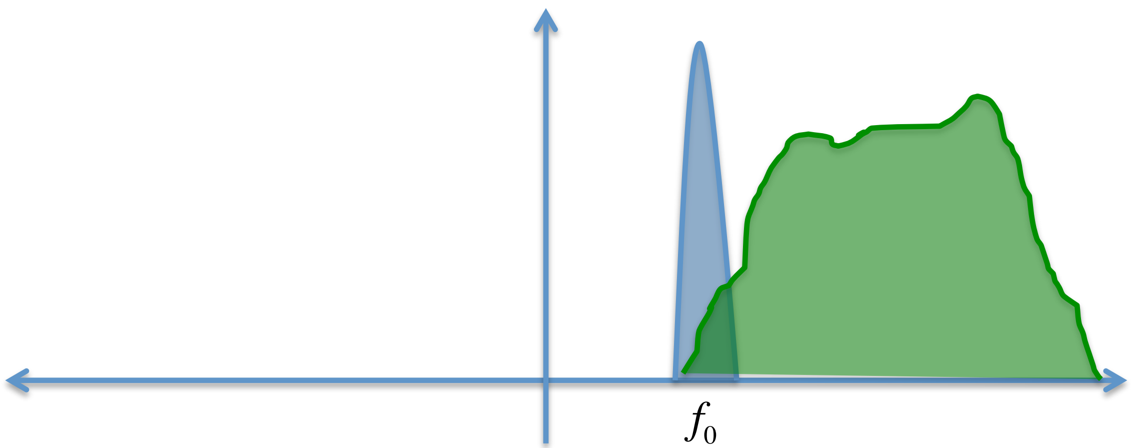
Doppler Radar – frequency domain





f_0
me
f_0
Riley
Mike
Ella
f_0


f_0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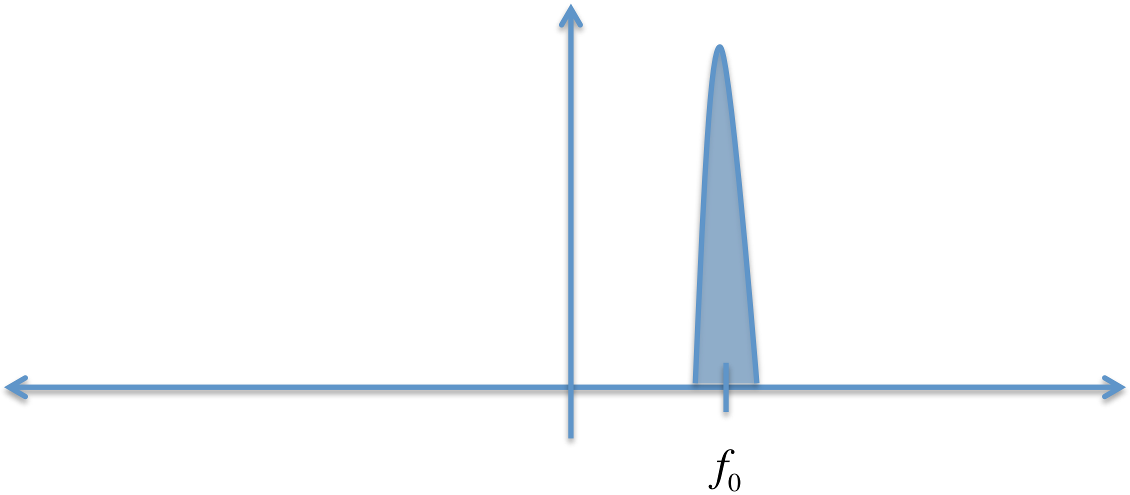
START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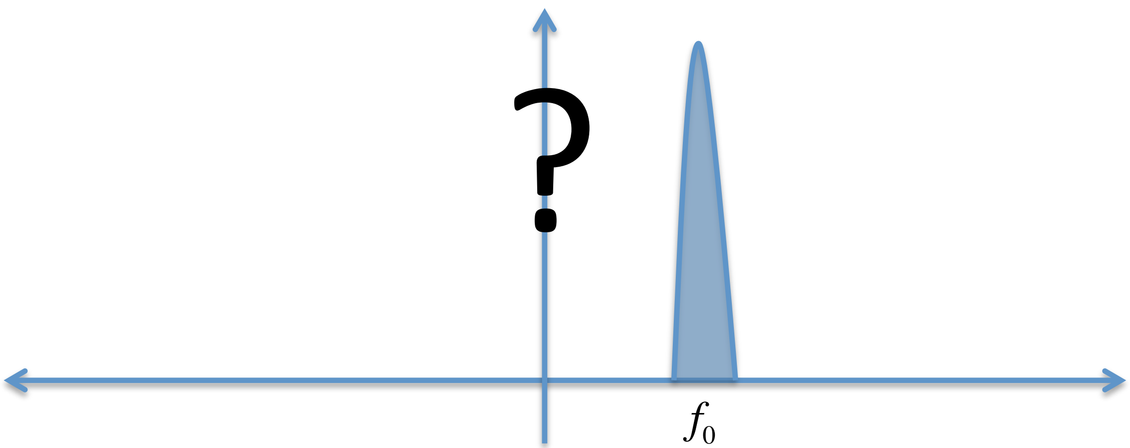
?
f_0


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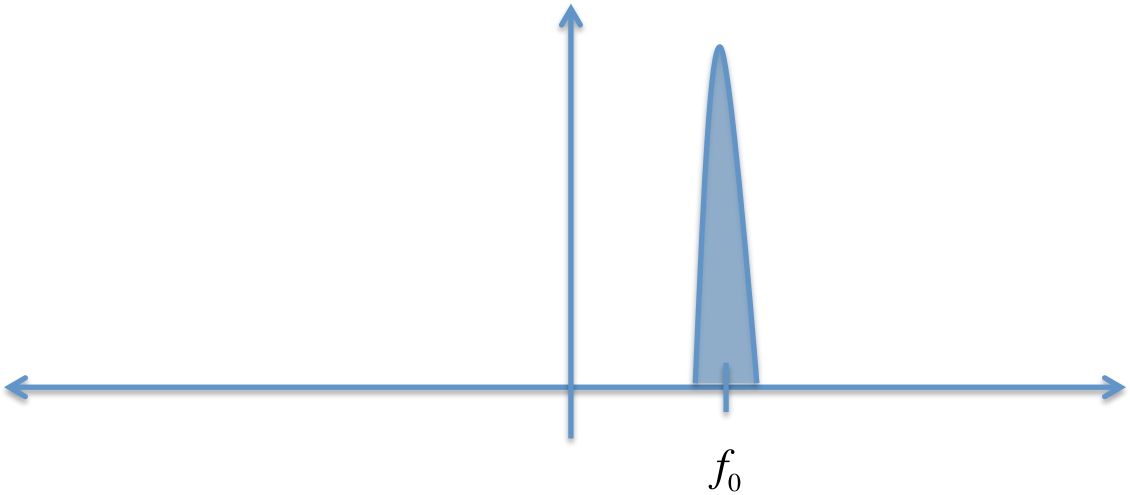
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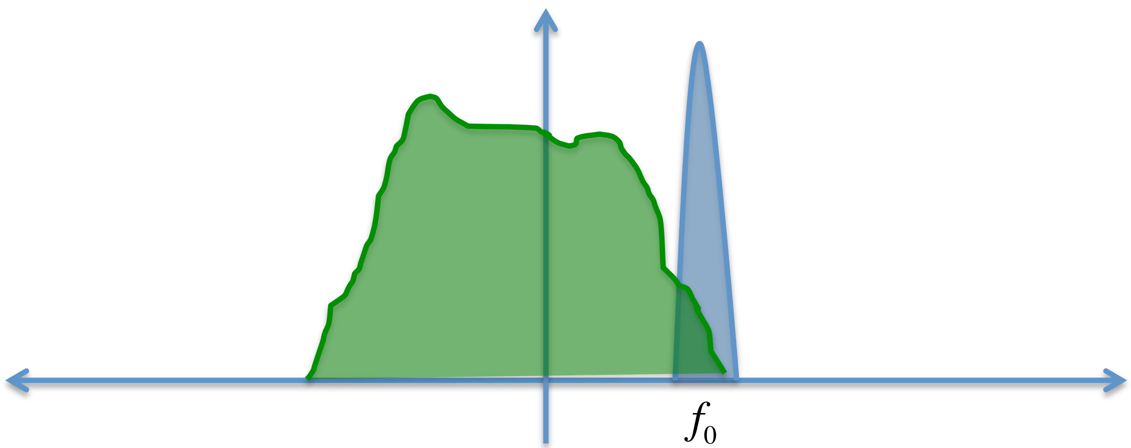

f_0


START

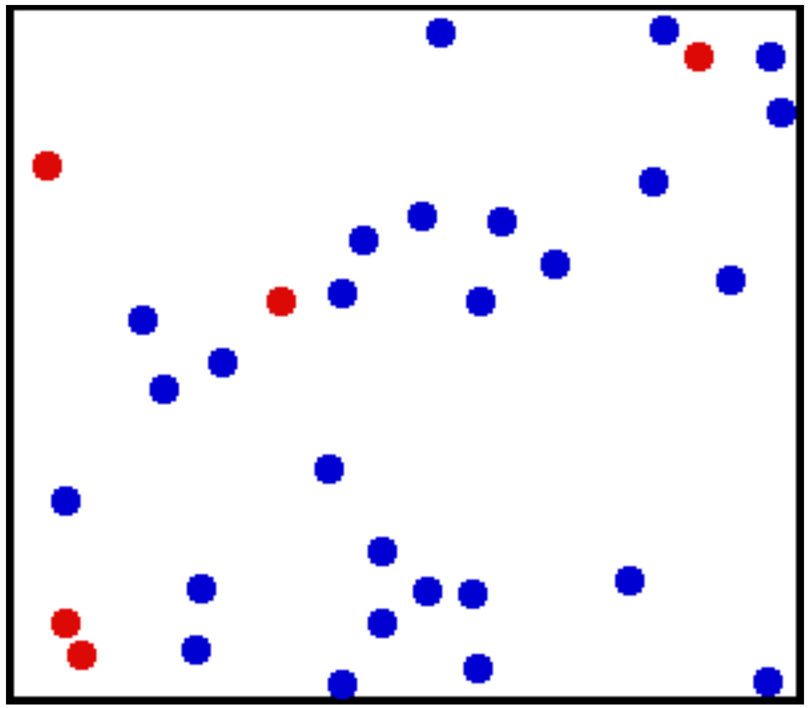
Thomson scattering

- 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.

- 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.

Thermal fluctuating electrons



Incoherent…?

- **Dictionary: The property of being coherent**
- **Antonym: Incoherent**

- **Incoherent=Random, viz. Incoherent scatter is the process by which radiowaves are randomly scattered by electrons in the ionosphere**

- **Media: Incoherent=Incomprehensible**

Incoherent…?

- **Dictionary: The property of being coherent**
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- **Incoherent=Random, viz. Incoherent scatter is the process by which radiowaves are randomly scattered by electrons in the ionosphere**

- **Media: Incoherent=Incomprehensible**

Incoherent scatter is neither incoherent nor incomprehensible

Radar Equations

Hard target:

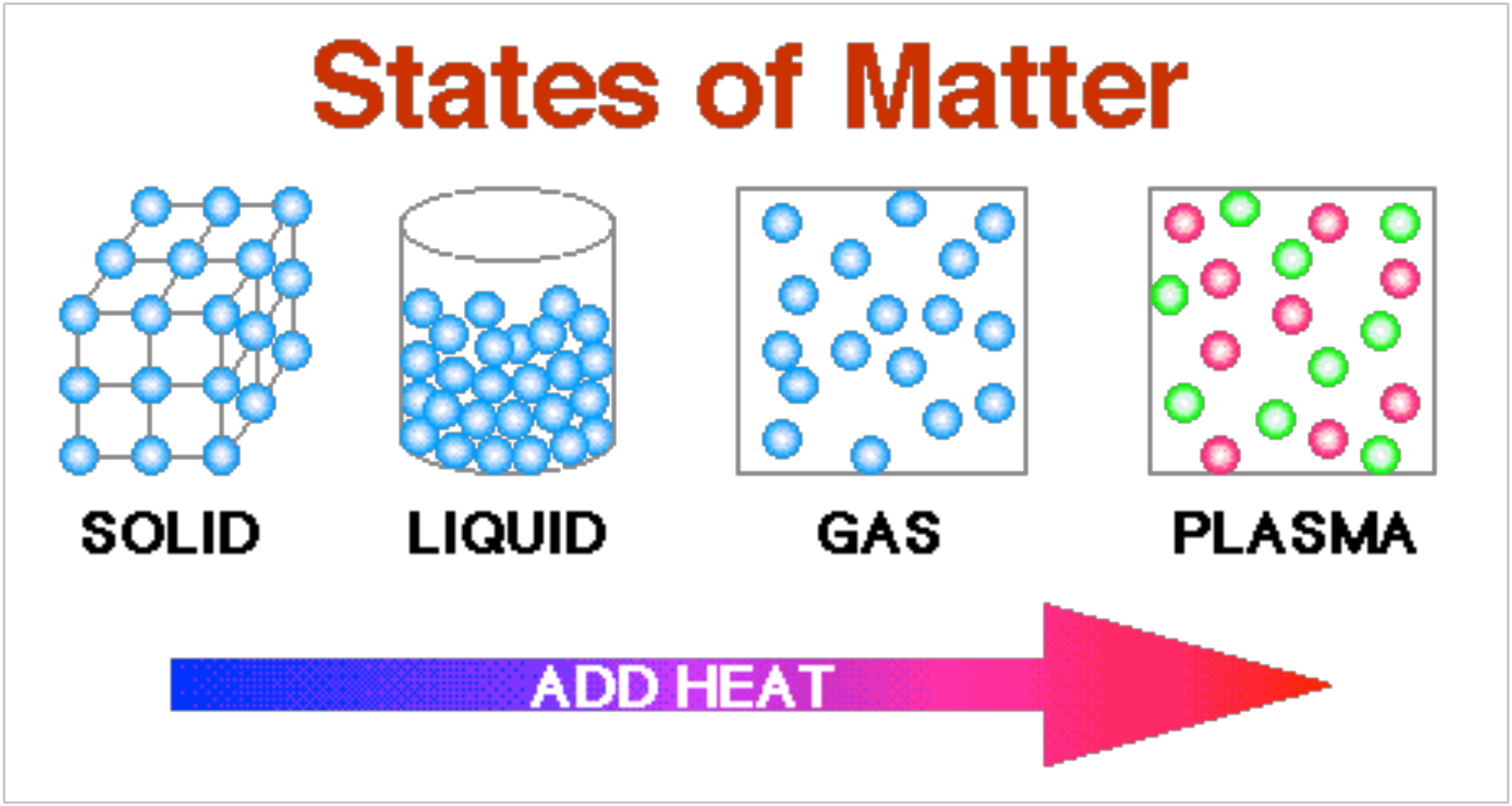
$$P_r = \frac{P_t G_t A_r \sigma}{(4\pi)^2 R^4}$$

Incoherent Scatter Radar

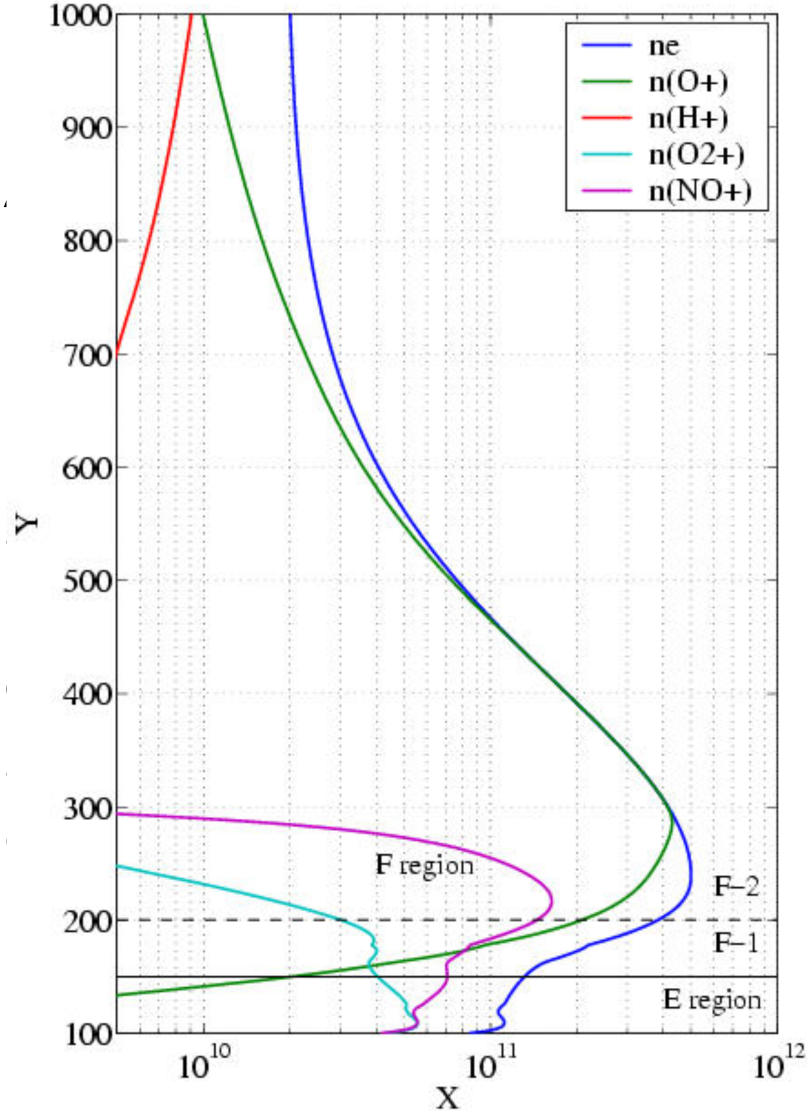
$$P_r = \frac{C c_0 G \lambda^2}{2(4\pi)^2} \frac{P_t \tau_p}{R^2} \frac{\sigma_e n_e(R)}{(1+k^2\lambda_D^2)(1+k^2\lambda_D^2+T_r)}$$

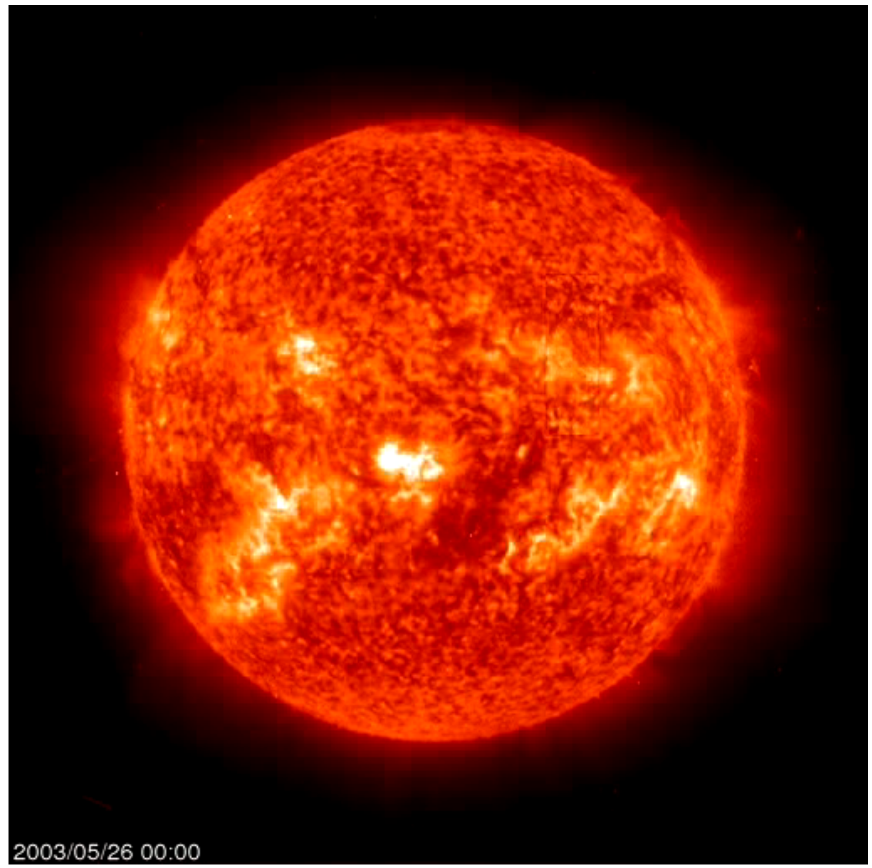
The ionospheric plasma

- So now we need electrons in the ionosphere to scatter the radar wave off…

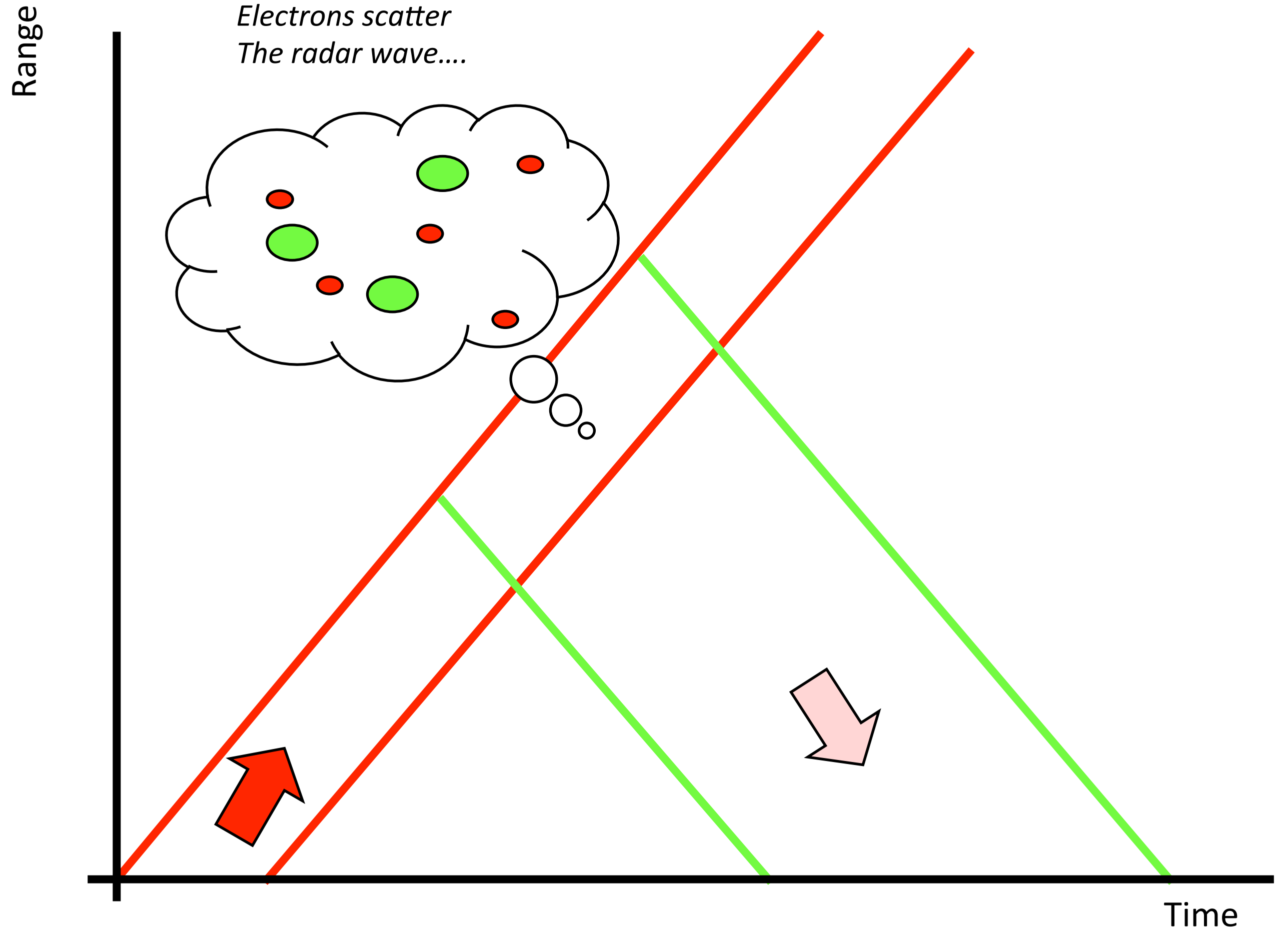

States of Matter
SOLID
LIQUID
GAS
PLASMA
ADD HEAT

…what Anita said this morning…





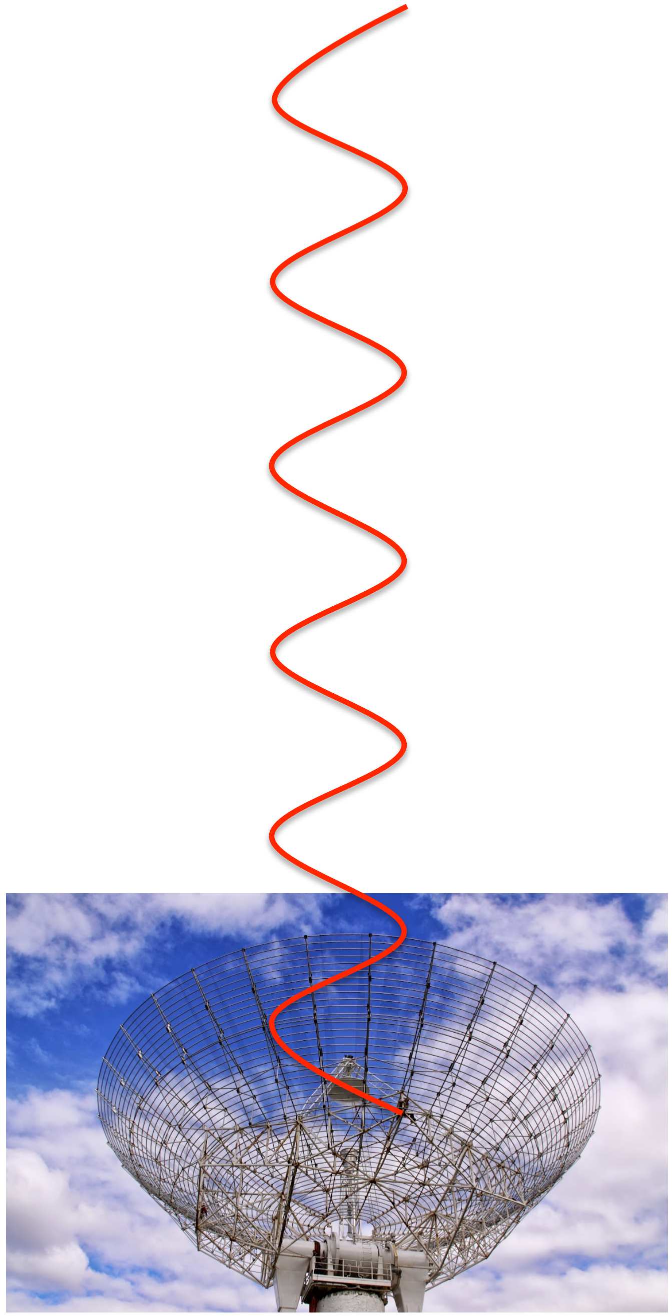
How ISRs work...



High power transmitter

Very sensitive receiver

Only ~0.0000000000000000001% of the transmitted power is returned!



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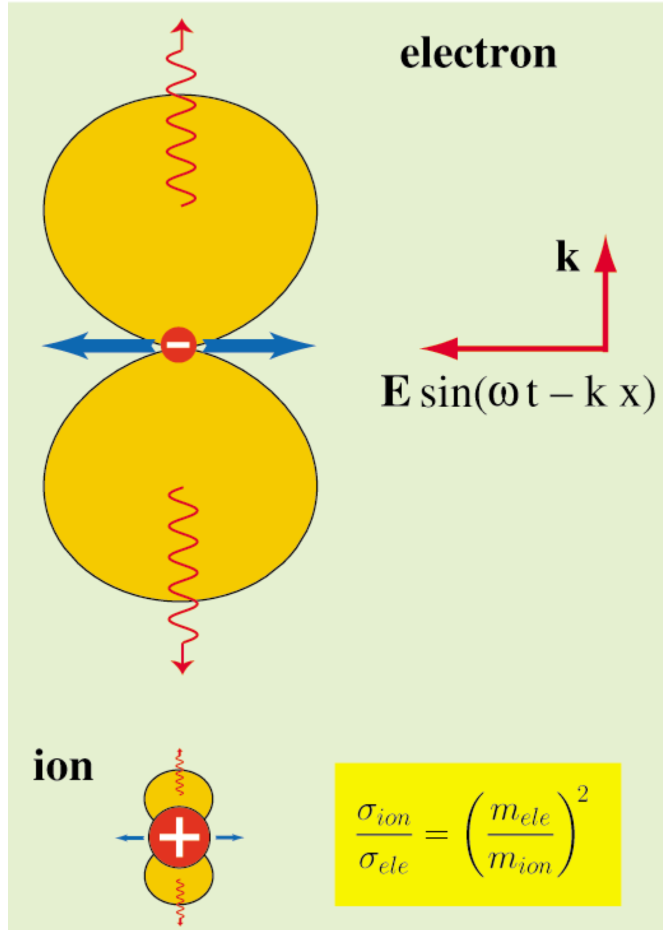
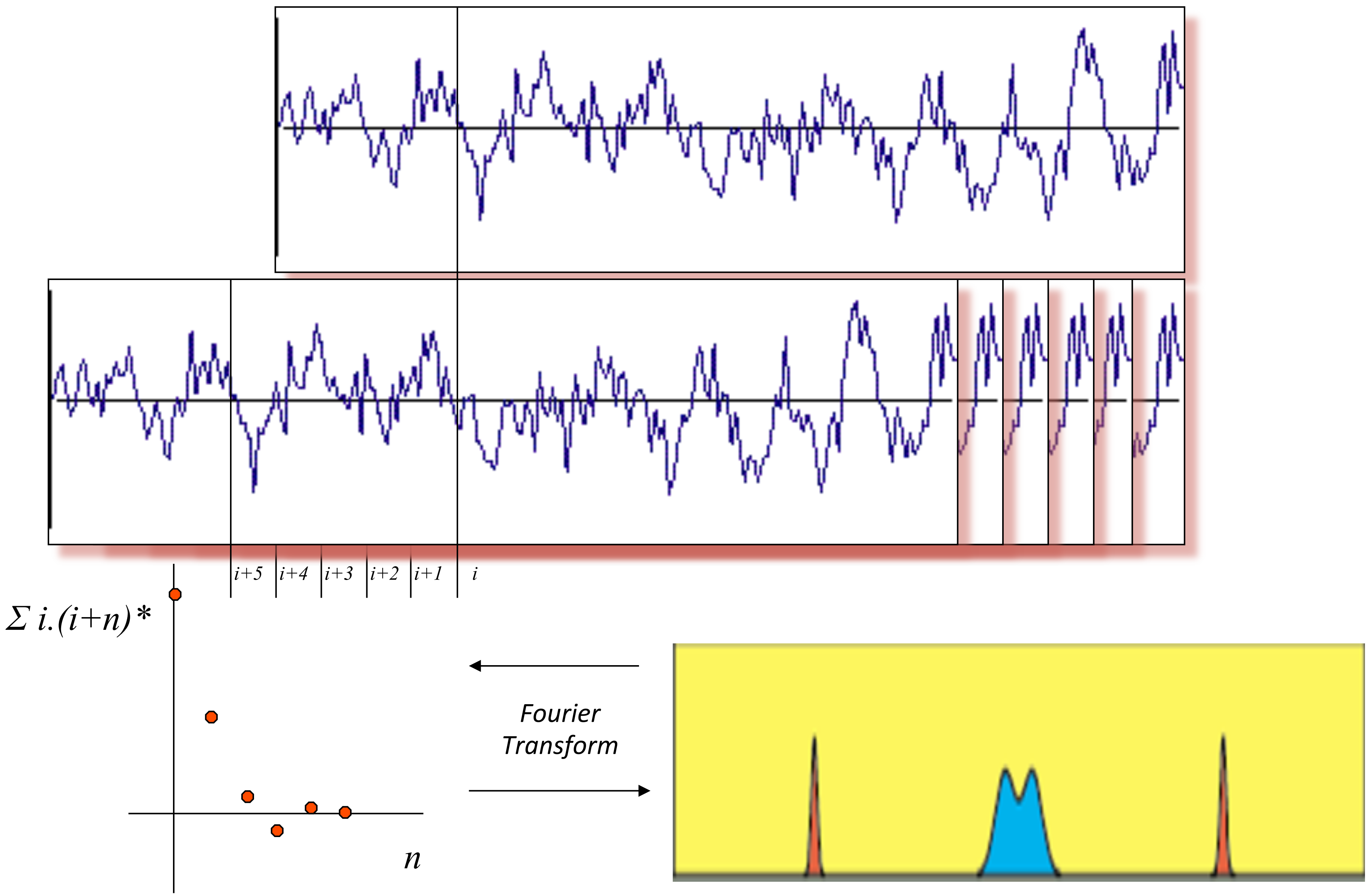
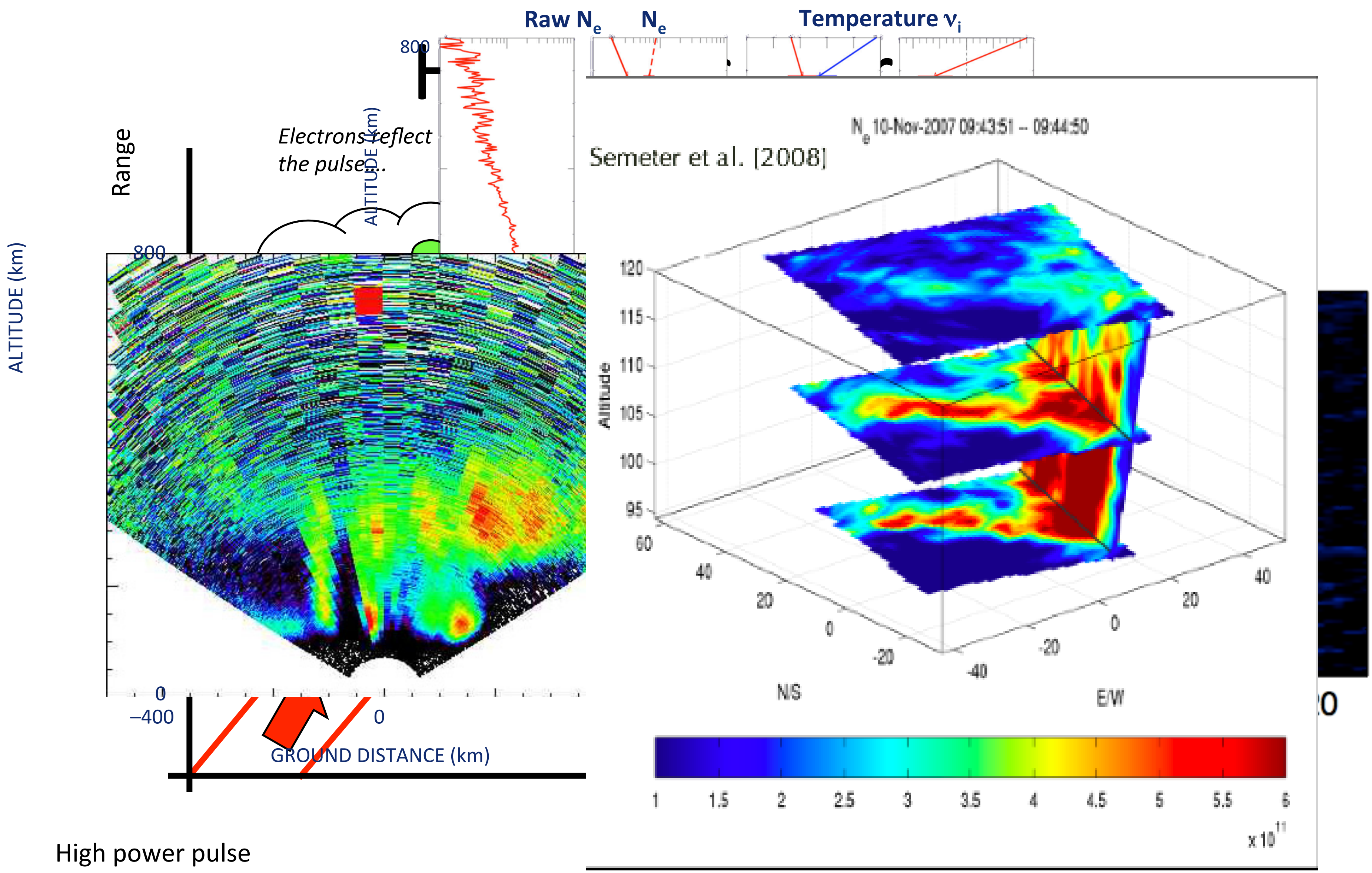

electron
k
E sin(ω t – k x)
ion
$\frac{\sigma_{ion}}{\sigma_{ele}} = \left(\frac{m_{ele}}{m_{ion}}\right)^2$

With incoherent Scatter Radars we can determine statistical properties of the charged particle distributions

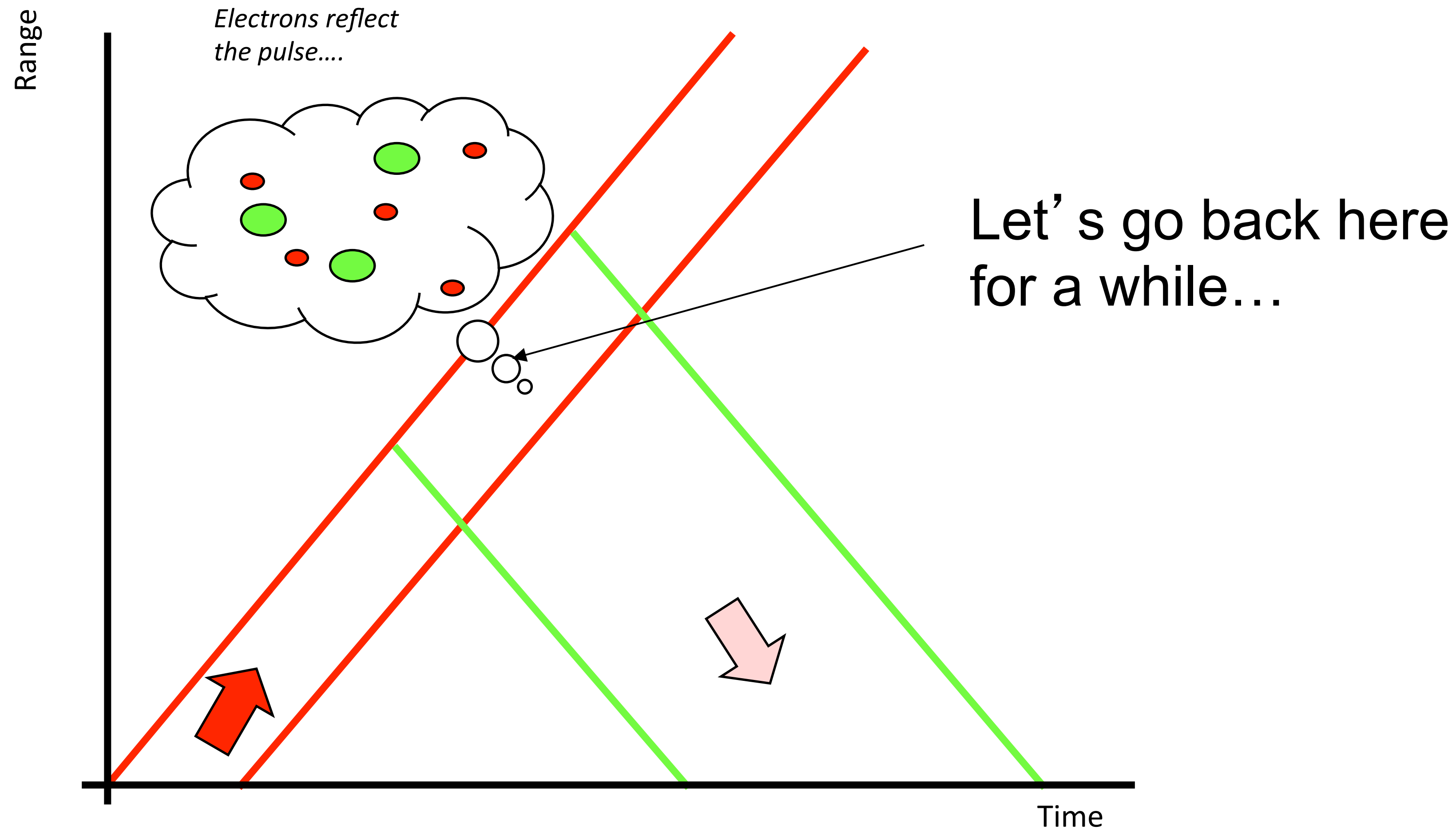

i+5
i+4
i+3
i+2
i+1
i
Σ i.(i+n)*
n
Fourier
Transform



High power pulse

Only ~0.0000000000000000001% of the transmitted power is returned!

How ISRs work…

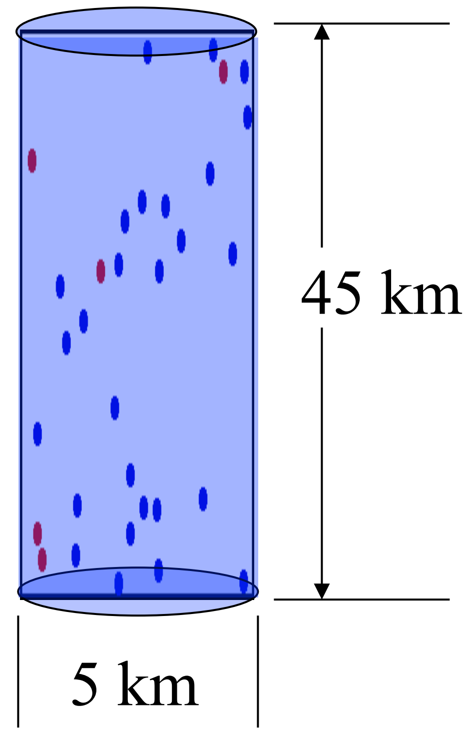


High power pulse

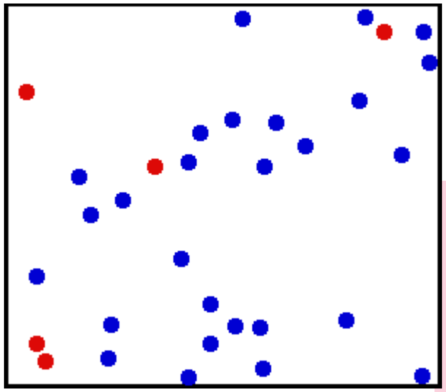
Very sensitive receiver

Total cross section estimate:

Consider an antenna with a 1-degree beam measuring the ionospheric plasma at 300 km range and using a 300 microsecond pulse.
If the electron density is 10^{12} m^{-3}, the total number of electrons scattering into a given measurement is ~8.8×10^{23}. This yields a total cross-section of 88 mm^2 – we need a big radar!



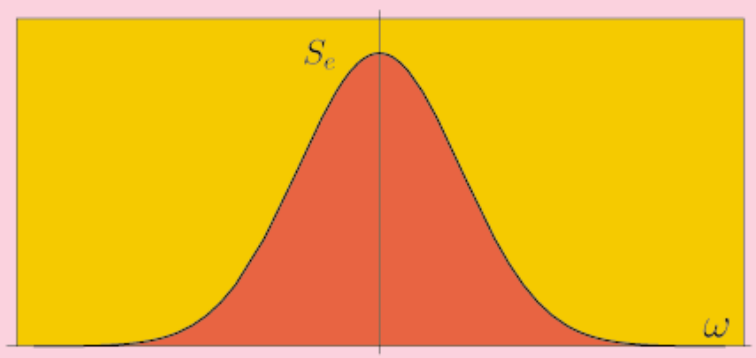
For TRUE incoherent scatter…



no collective interactions

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

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



Incoherent scattering - the short story

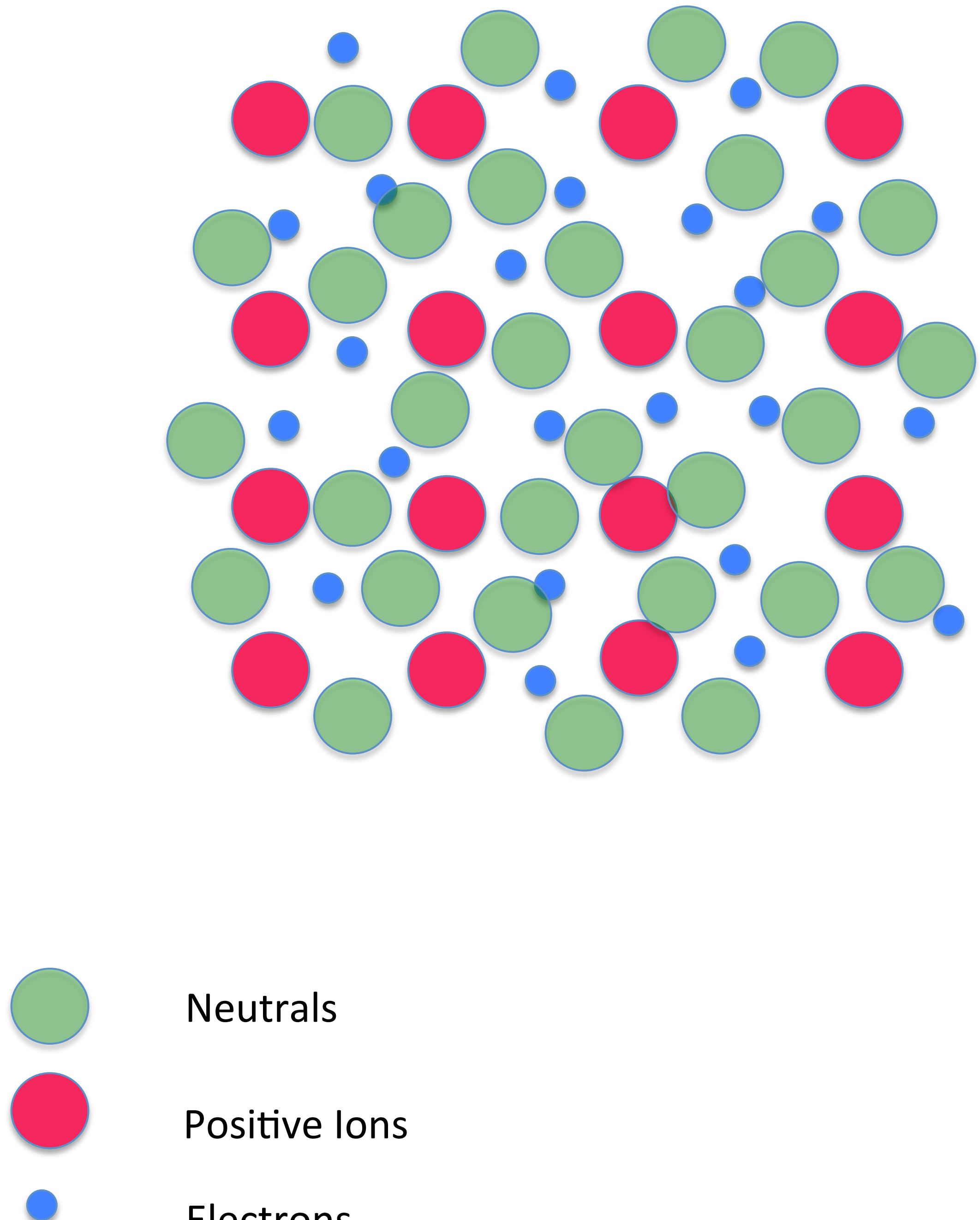
Incoherent scattering - the short story

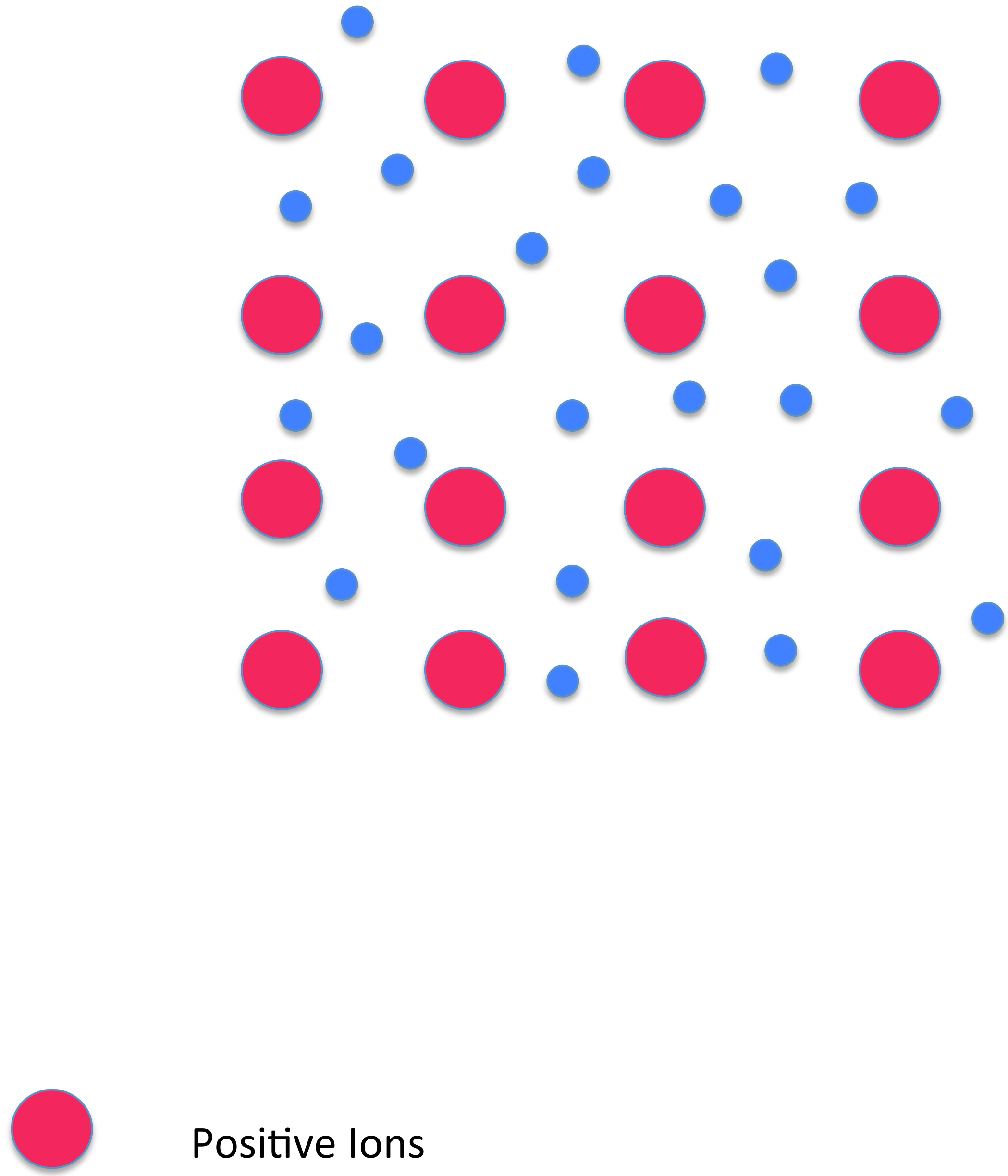
- We only see scattering from the electrons

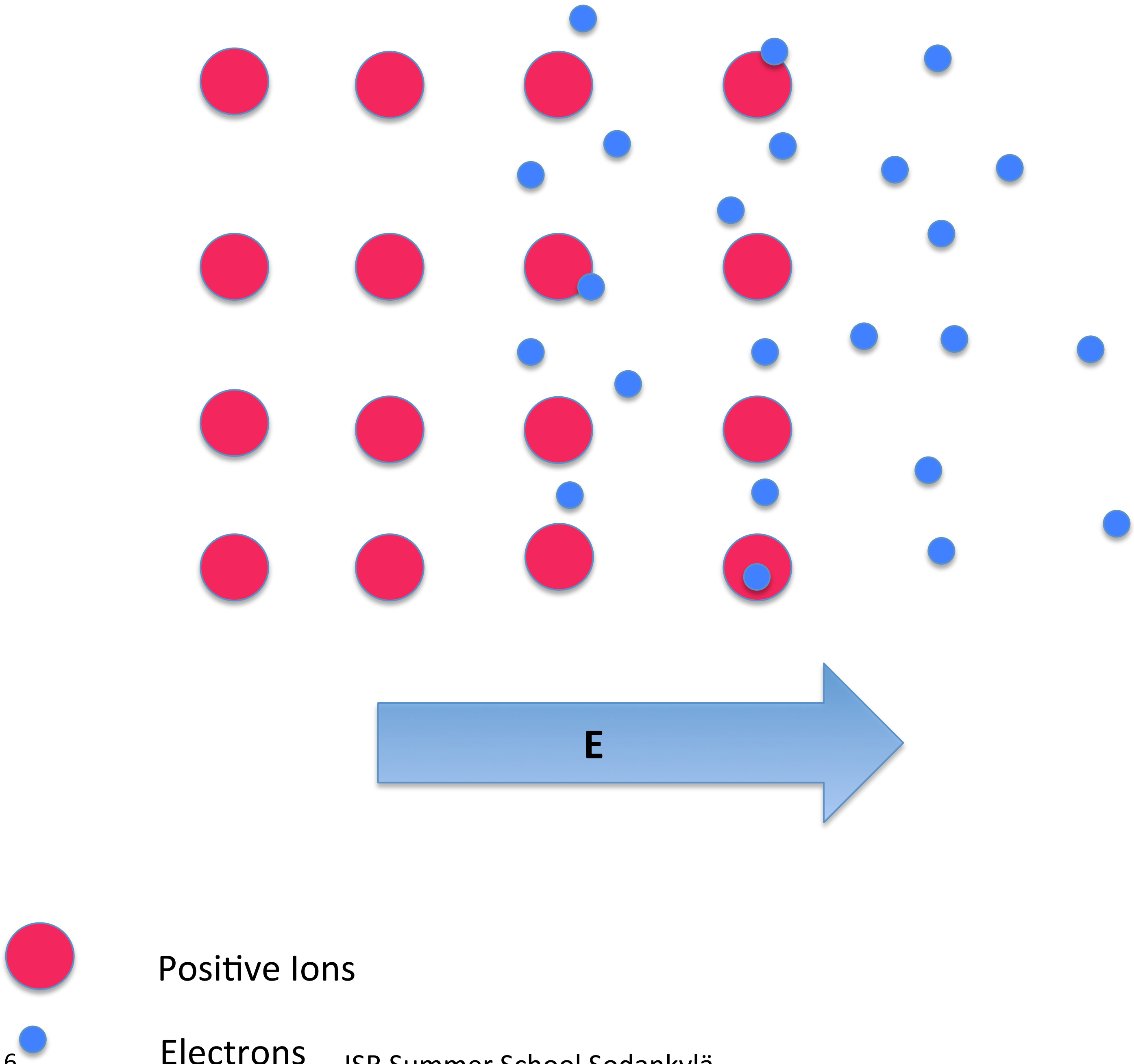
  …but they also tell the story about the ion dynamics…

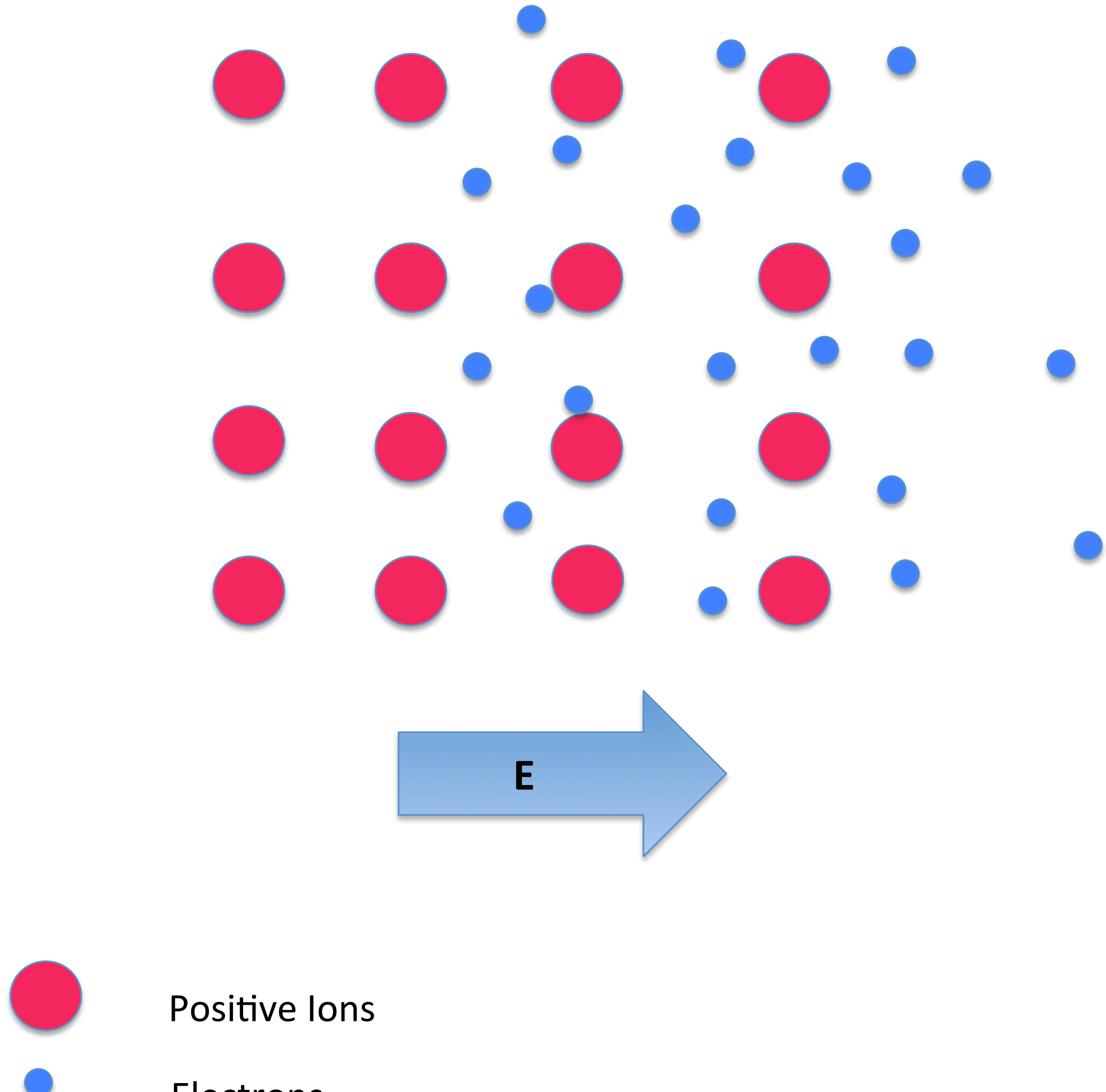
Collective behavior…

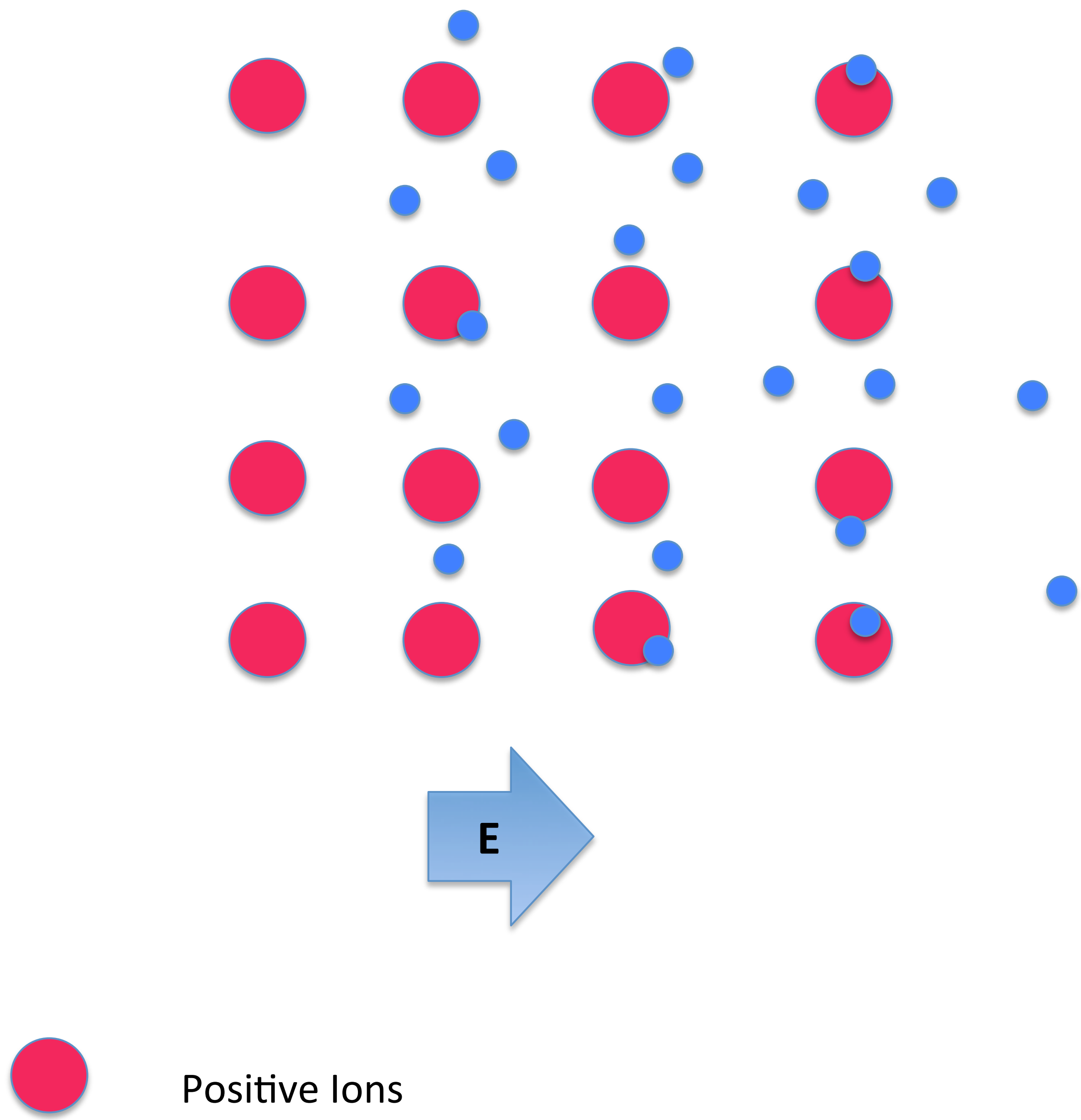
- There are a number of wave modes existing inherently in the ionospheric plasma…


Neutrals
Positive Ions
Electrons


Positive Ions
Electrons


E
Positive Ions
Electrons


E
Positive Ions
Electrons



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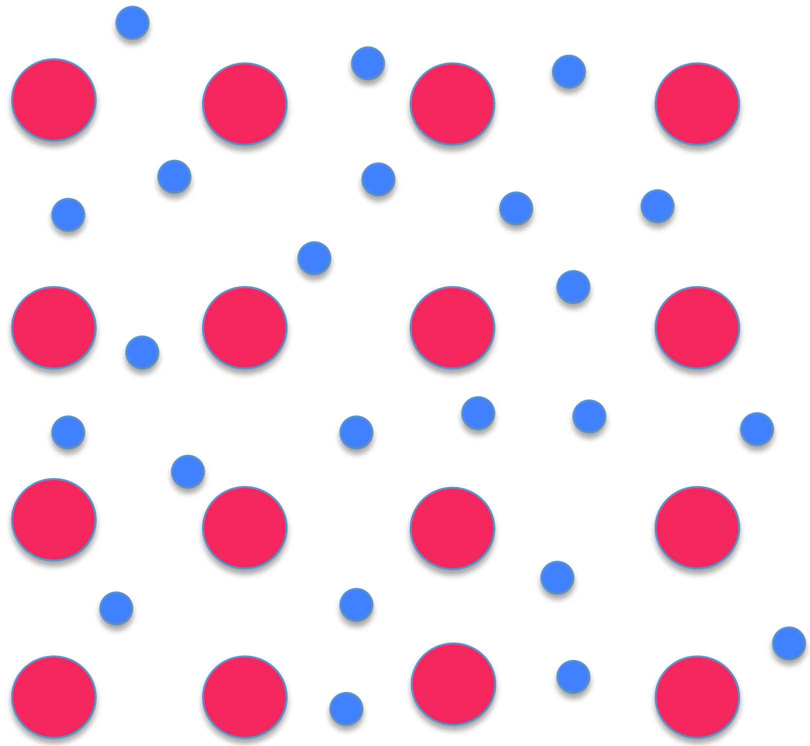
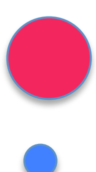
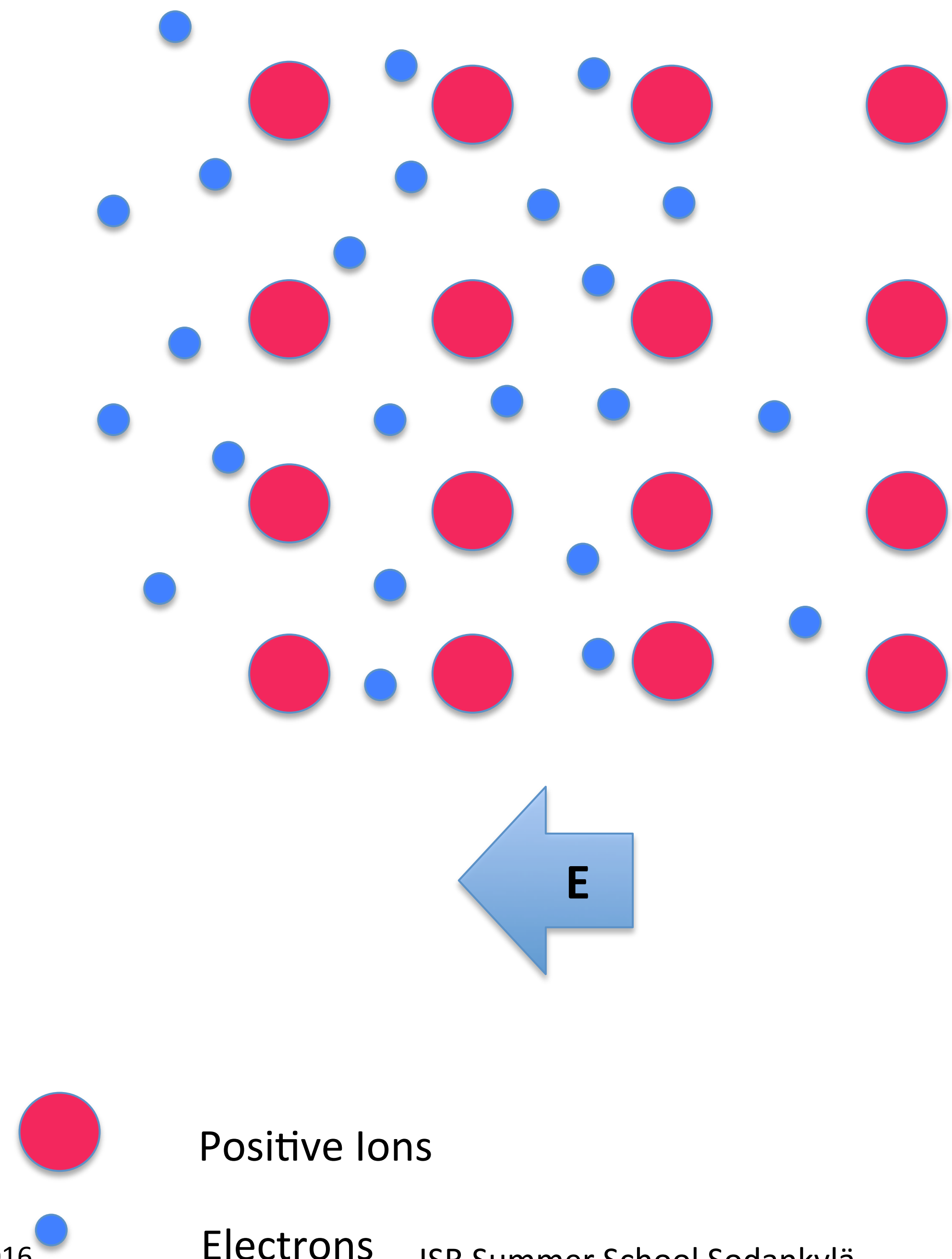
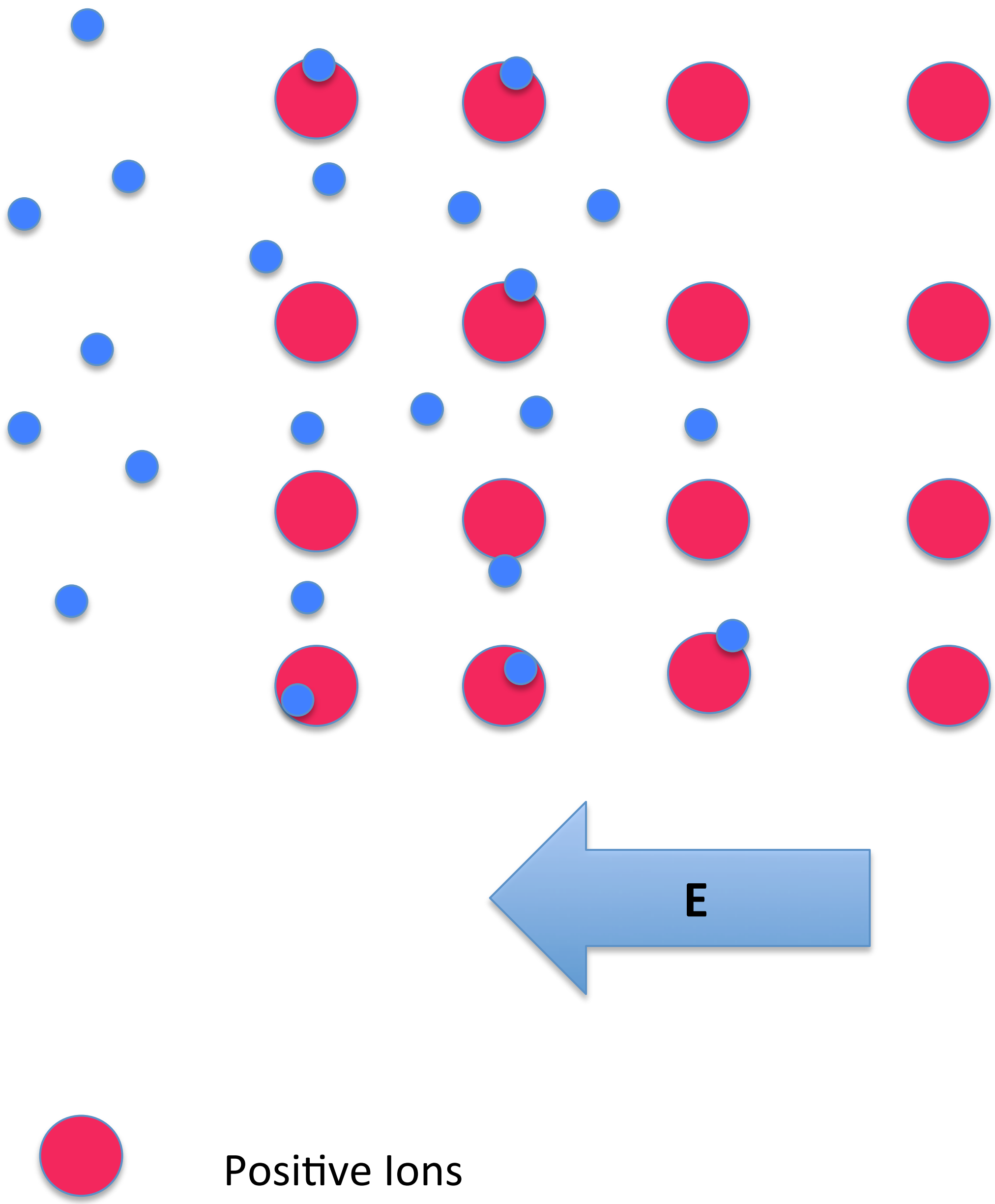
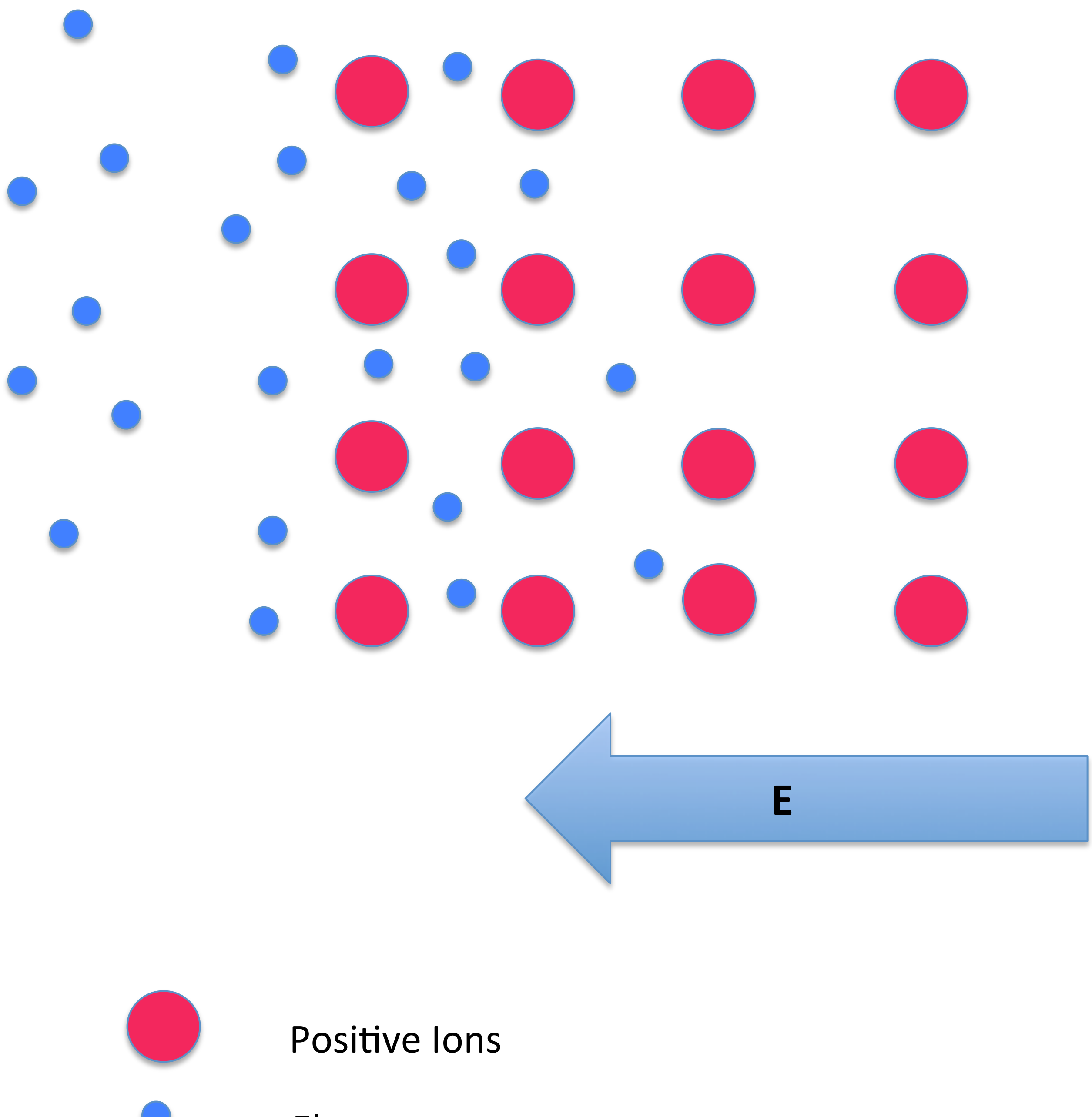
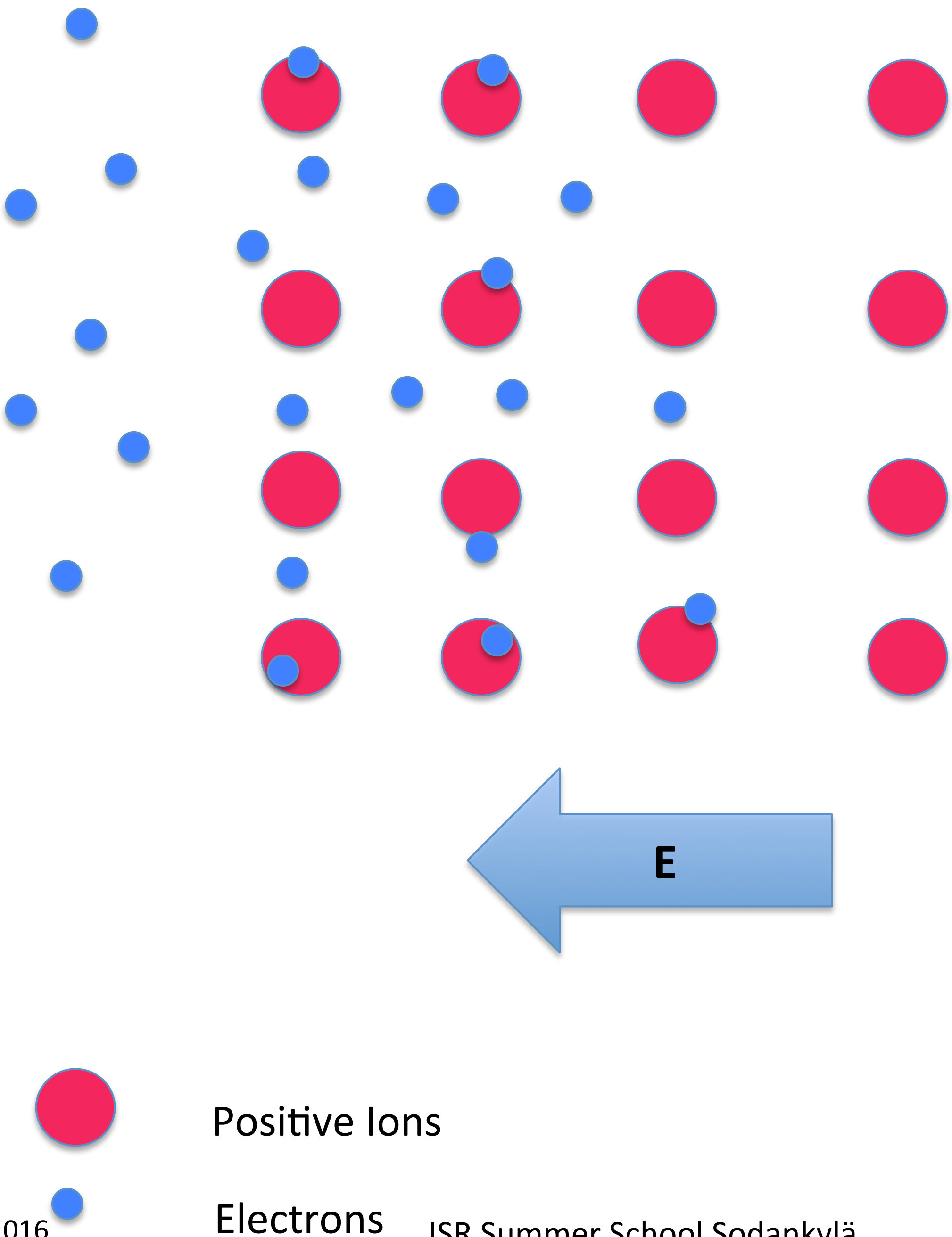


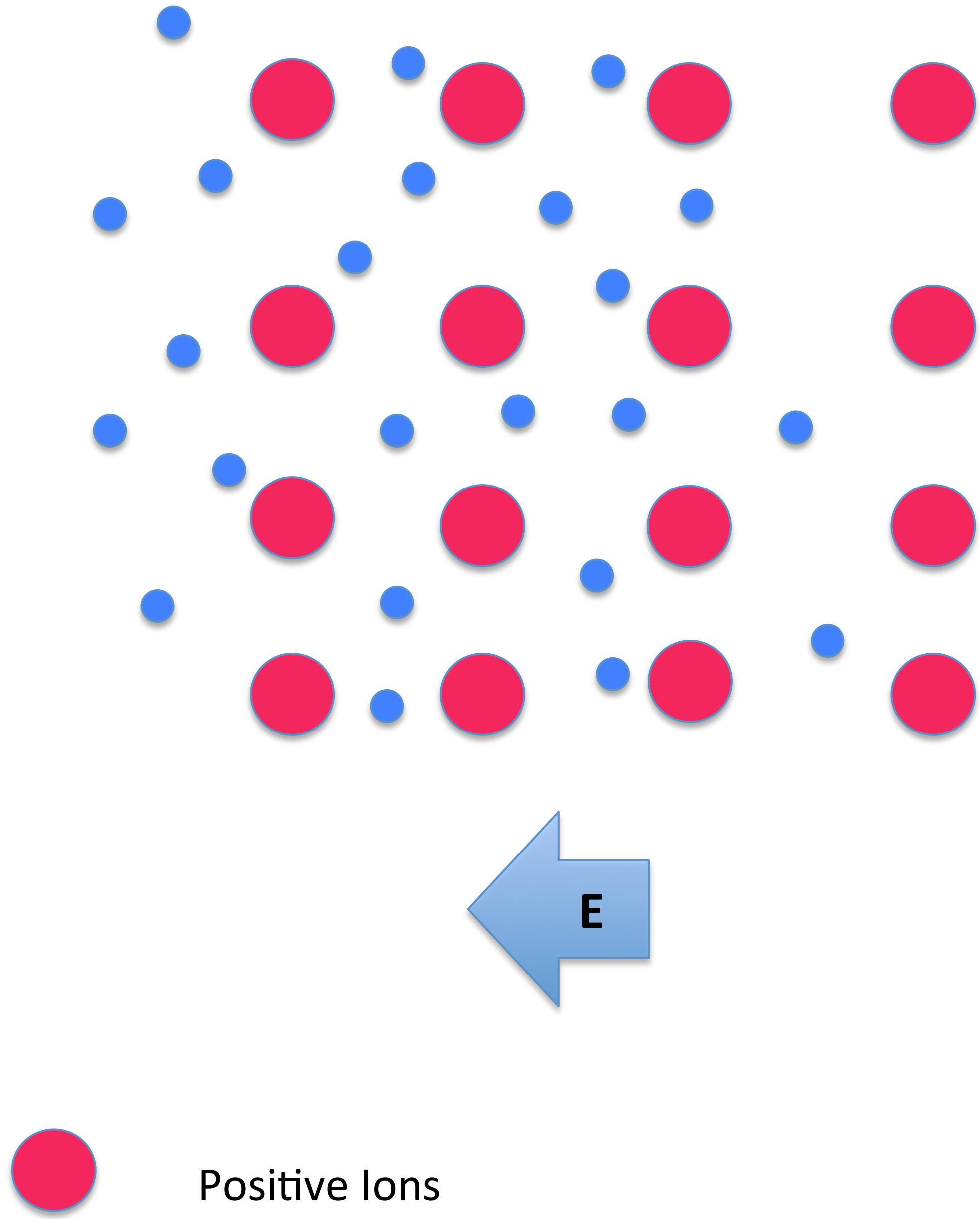

Positive Ions
Electrons


E
Positive Ions
Electrons


E
Positive Ions
Electrons


E
Positive Ions
Electrons


E
Positive Ions
Electrons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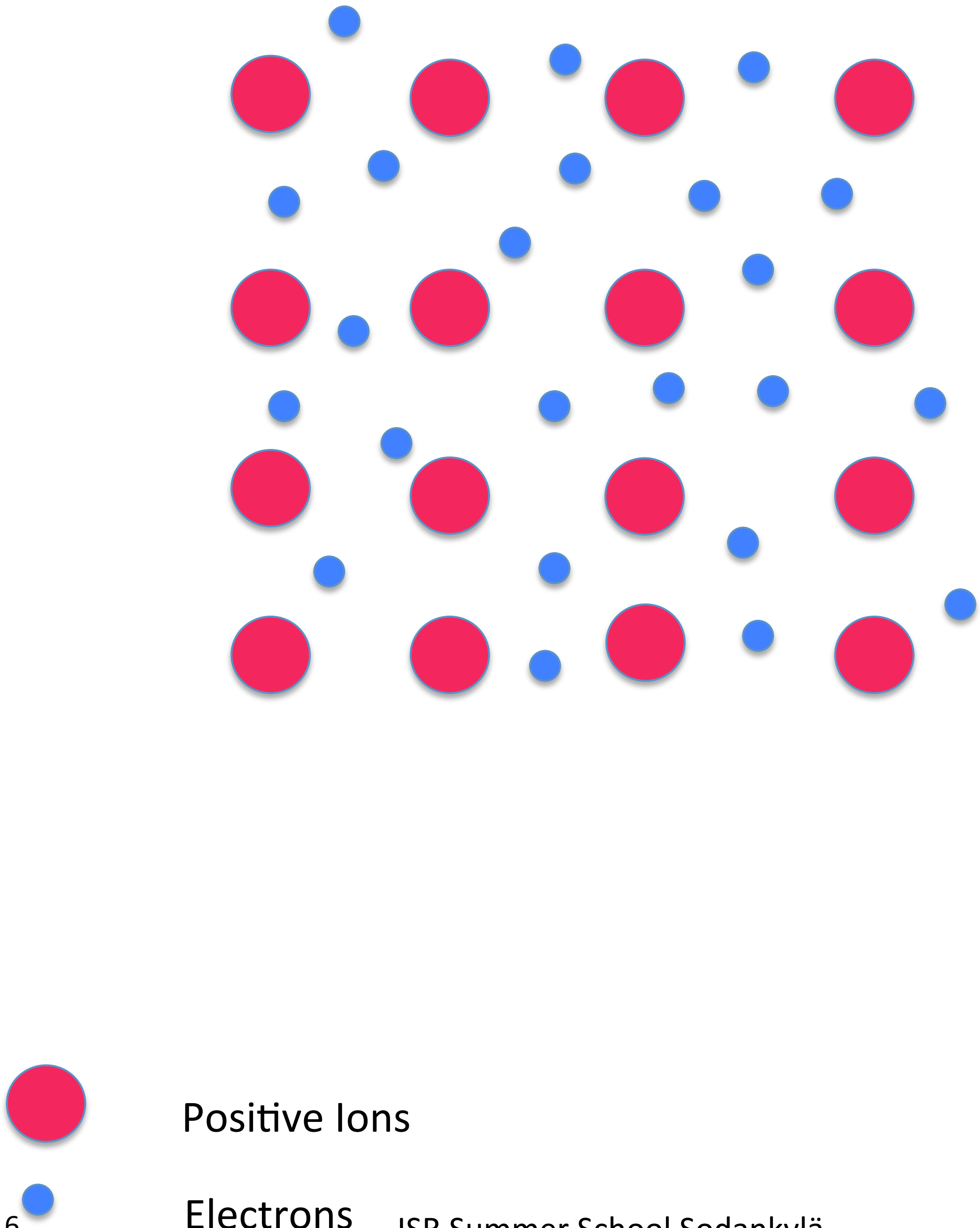
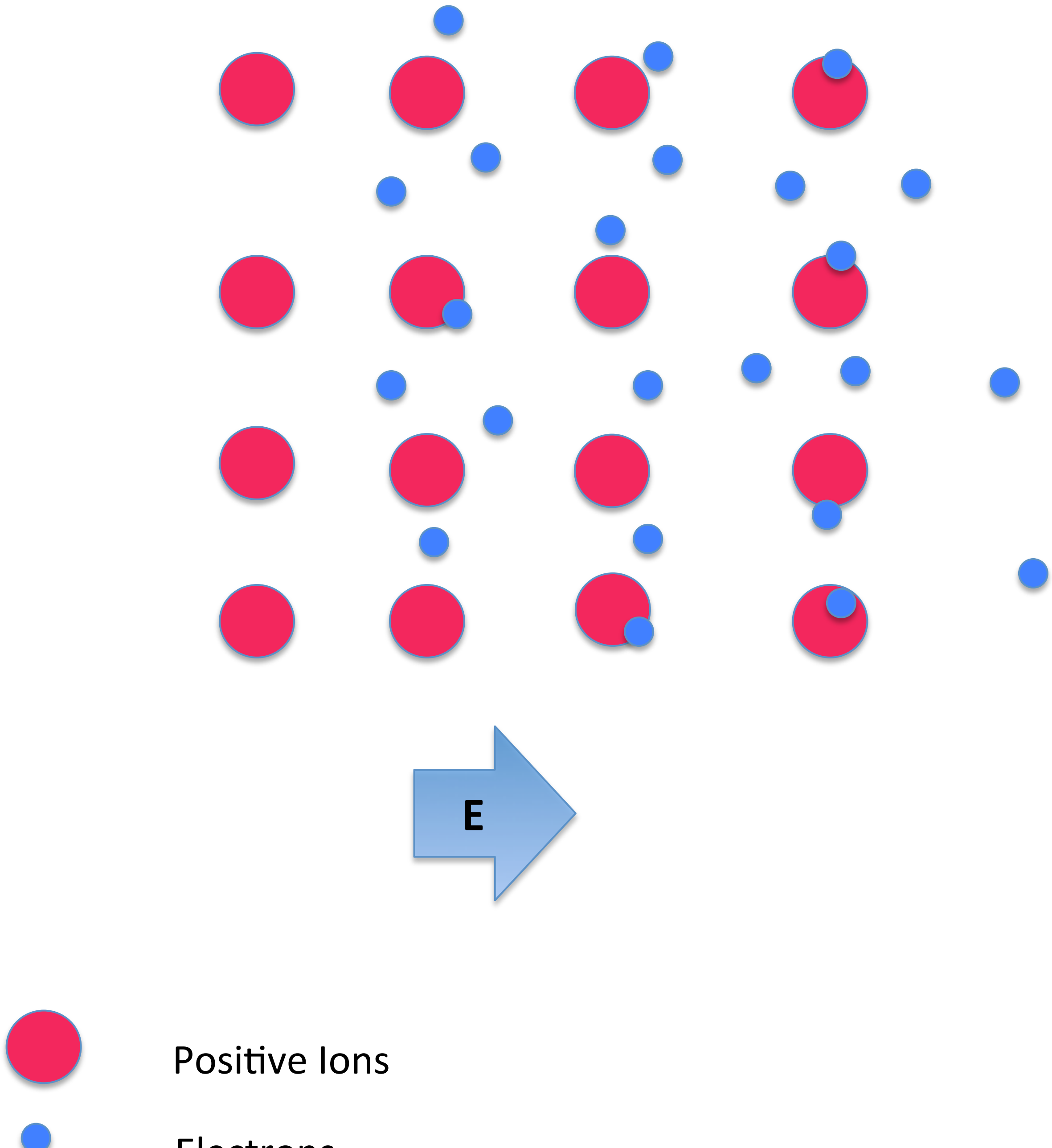
Positive Ions
Electrons


Positive Ions
Electrons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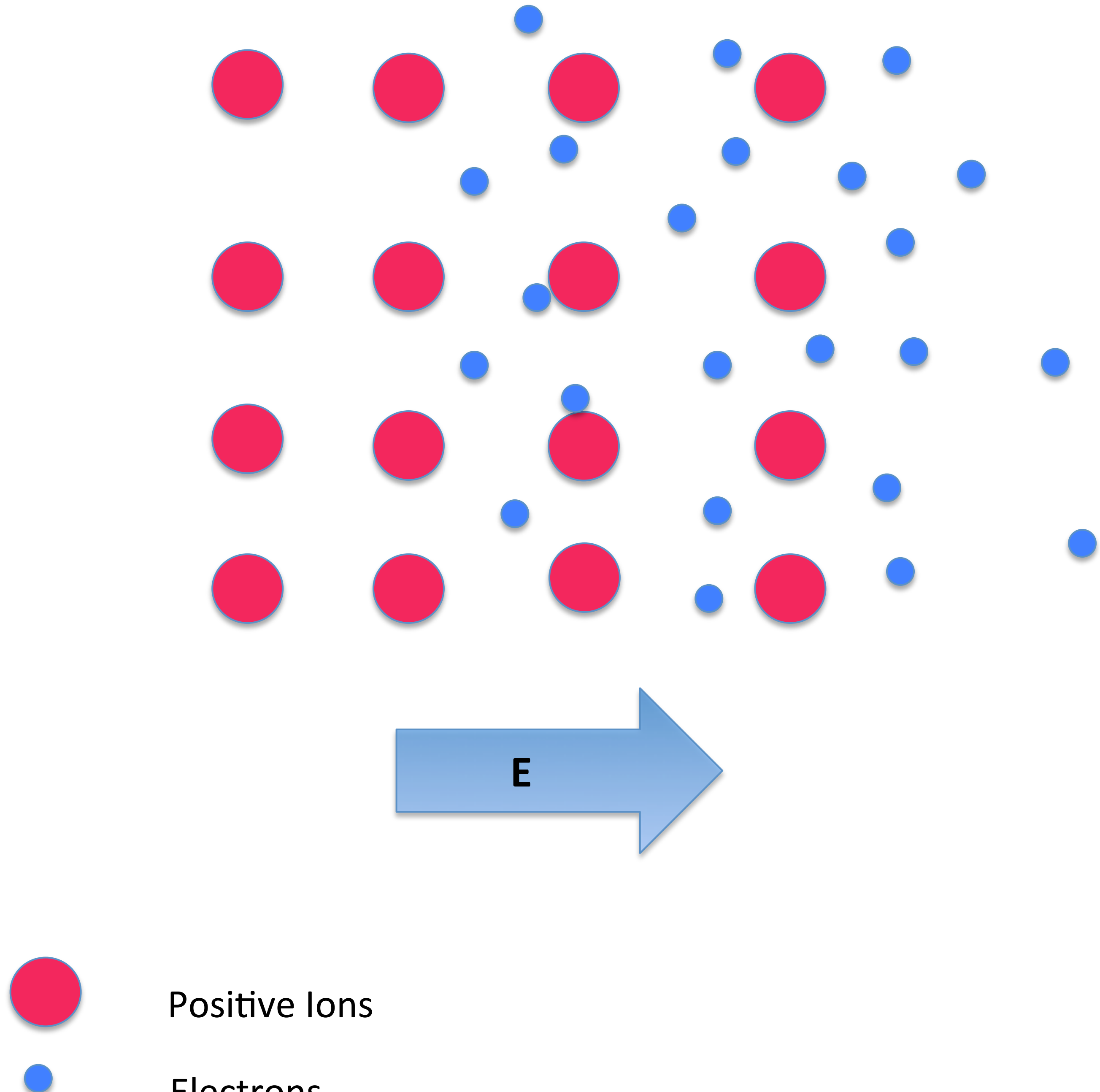
Positive Ions
Electrons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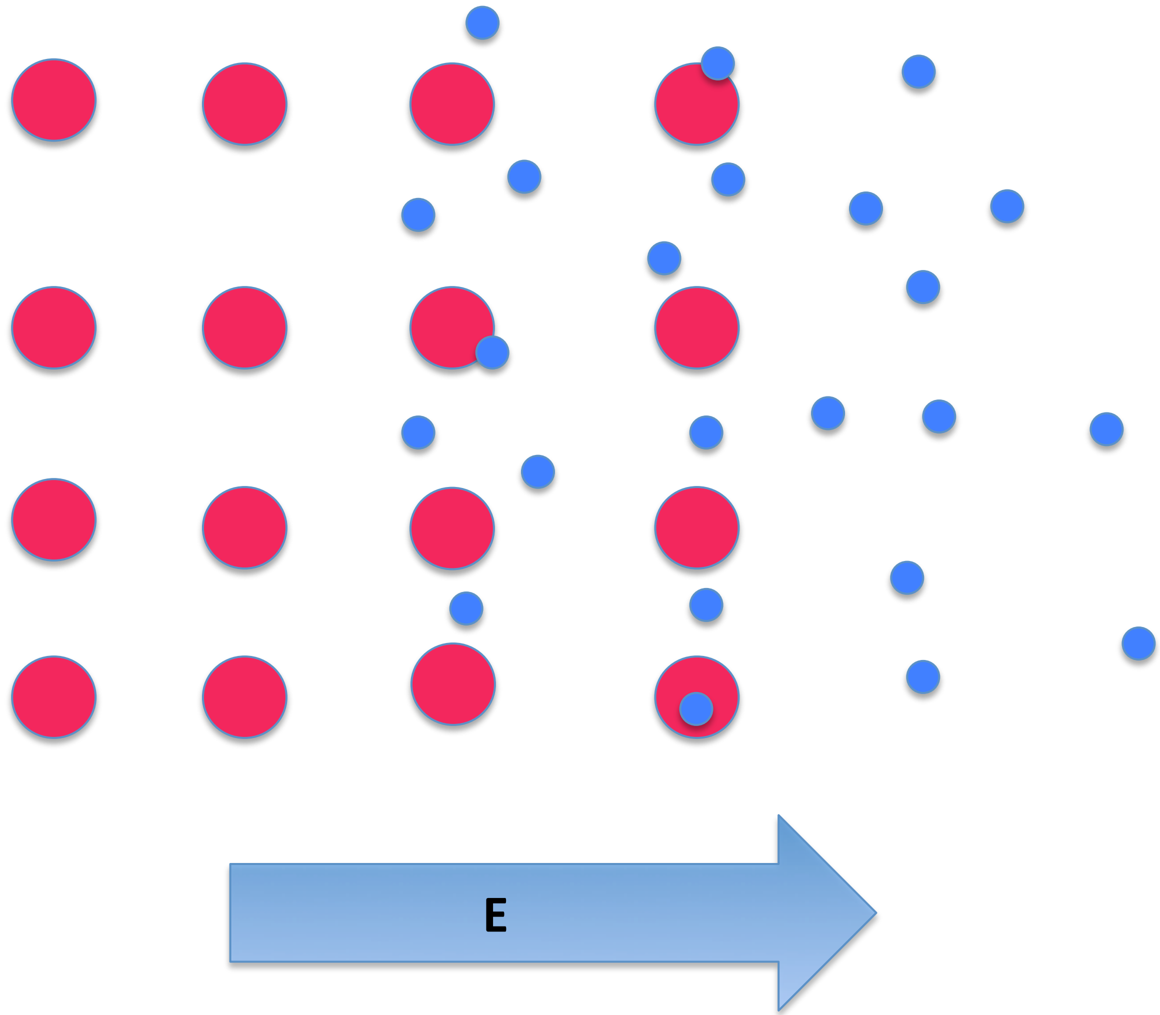
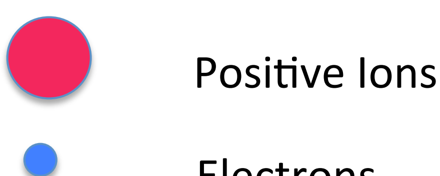
Positive Ions
Electrons



E



Positive Ions
Electrons

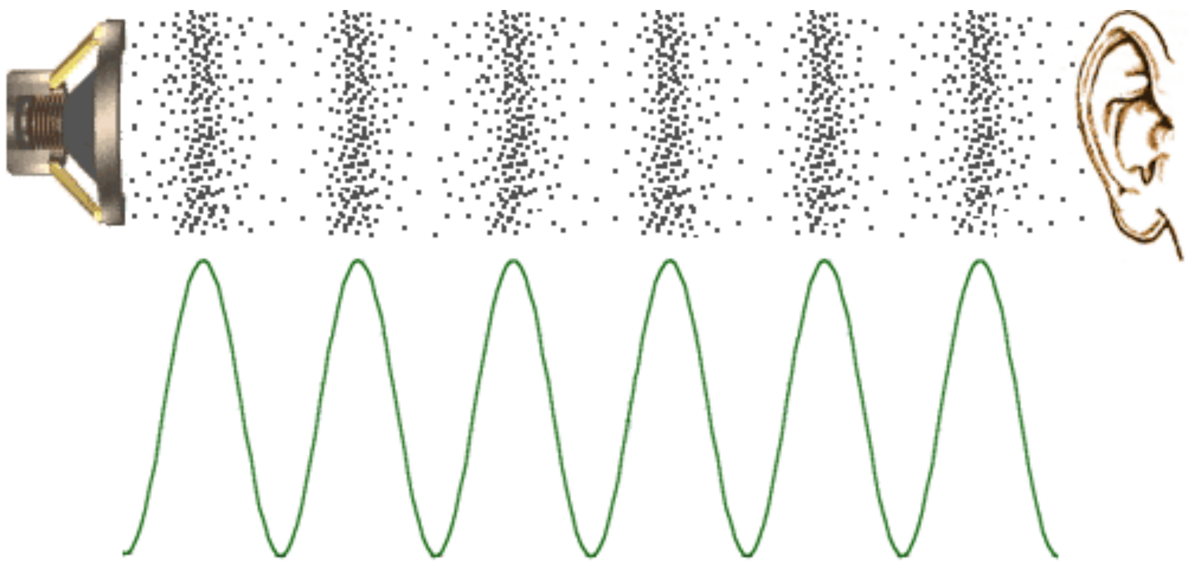
Langmuir waves

- High frequency electrostatic waves
- Dispersion relation:

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

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

Ion Acoustic Waves…



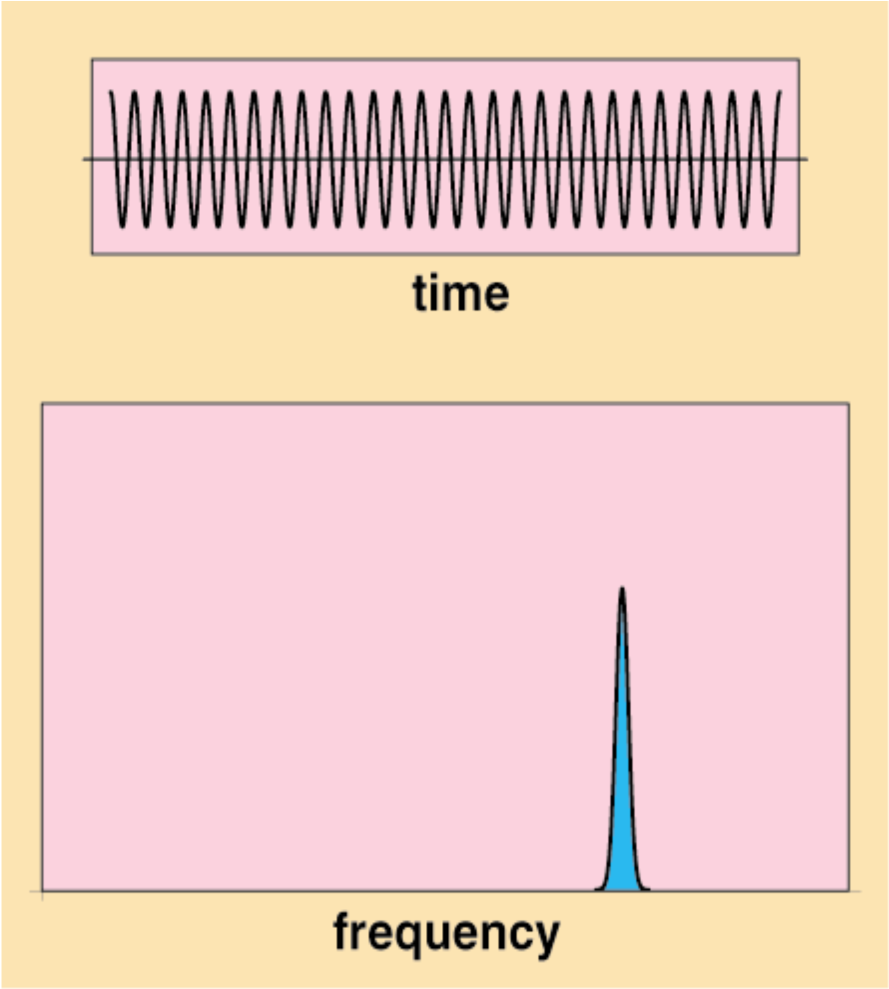
"Pressure" waves in the ion density.

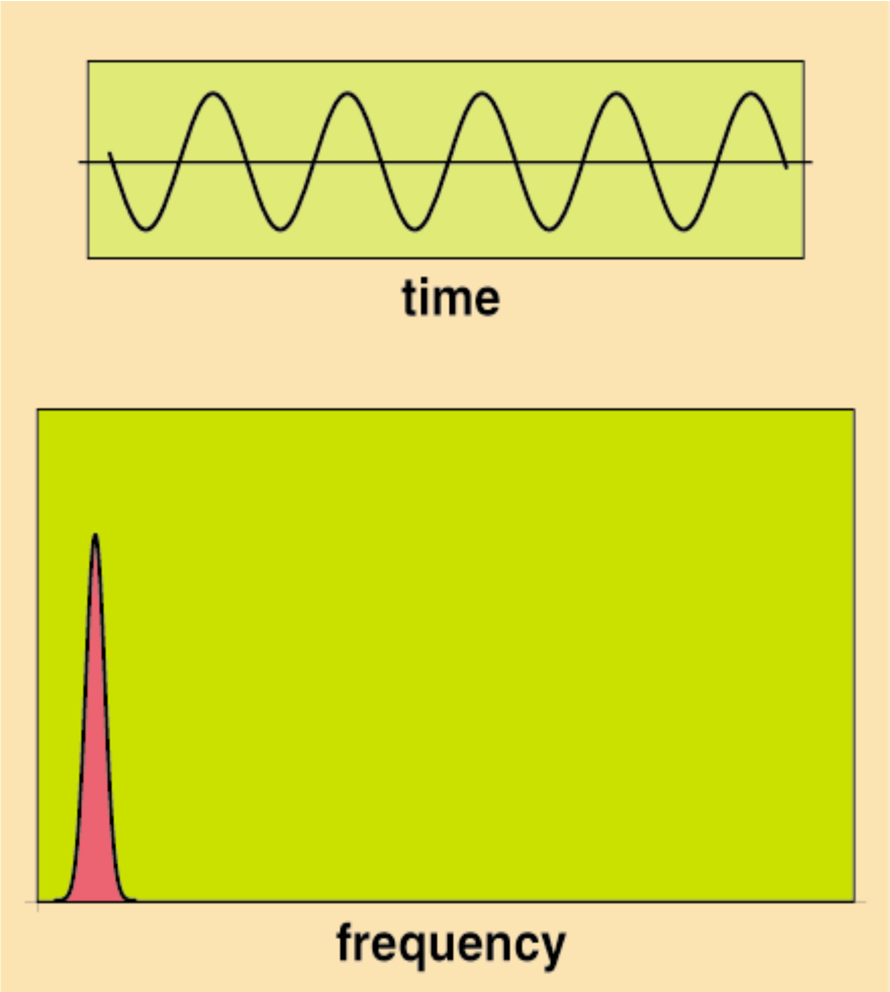
Ion acoustic waves

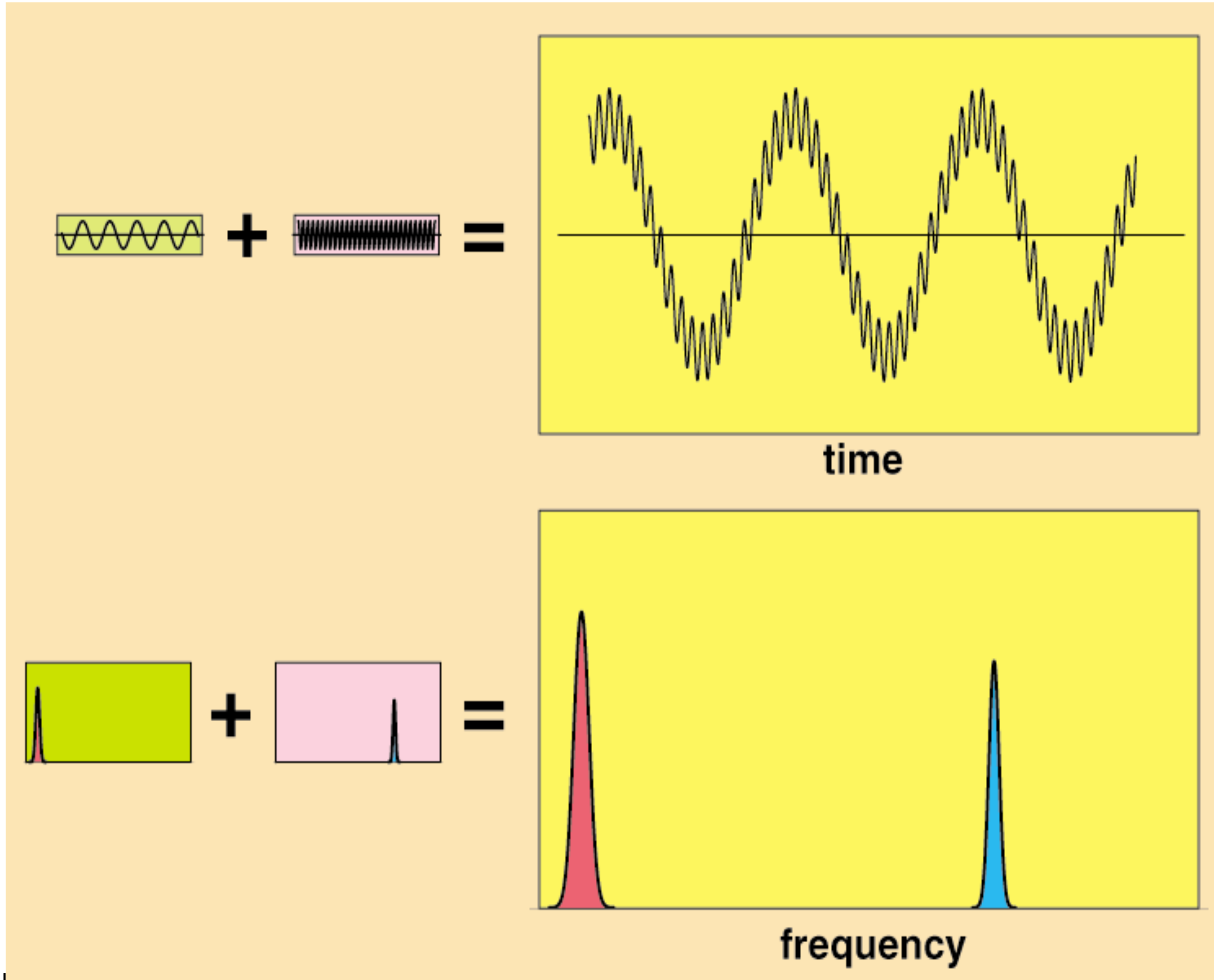
* Ion acoustic waves:

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

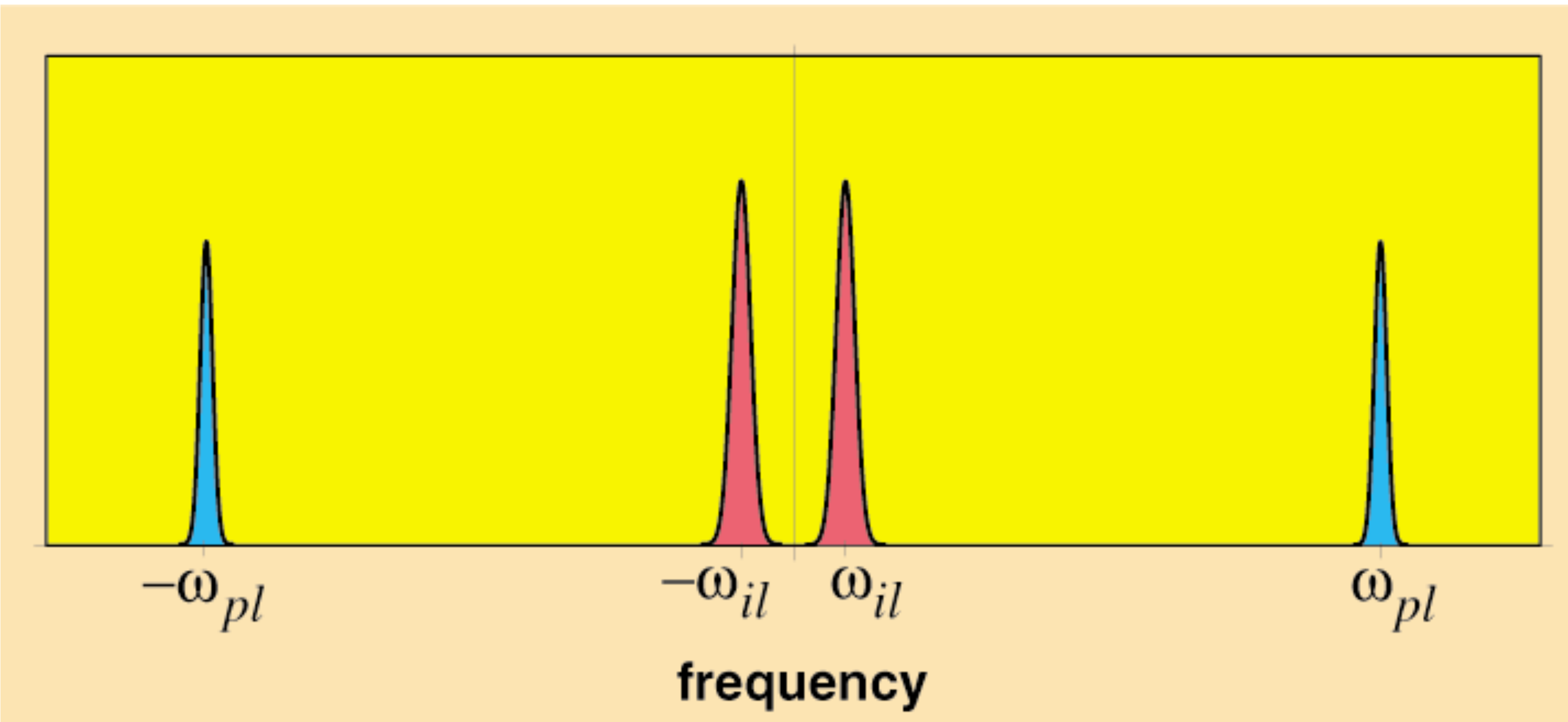
$$\omega_i = -\sqrt{\frac{\pi}{8}} \frac{\omega_r}{(1 + k^2 \lambda_{De}^2)^{3/2}} \left[\left(\frac{T_e}{T_i} \right)^{3/2} \exp\left(-\frac{T_e/T_i}{2(1 + k^2 \lambda_{De}^2)} \right) + \sqrt{\frac{m_e}{m_i}} \right] \tag{64}$$

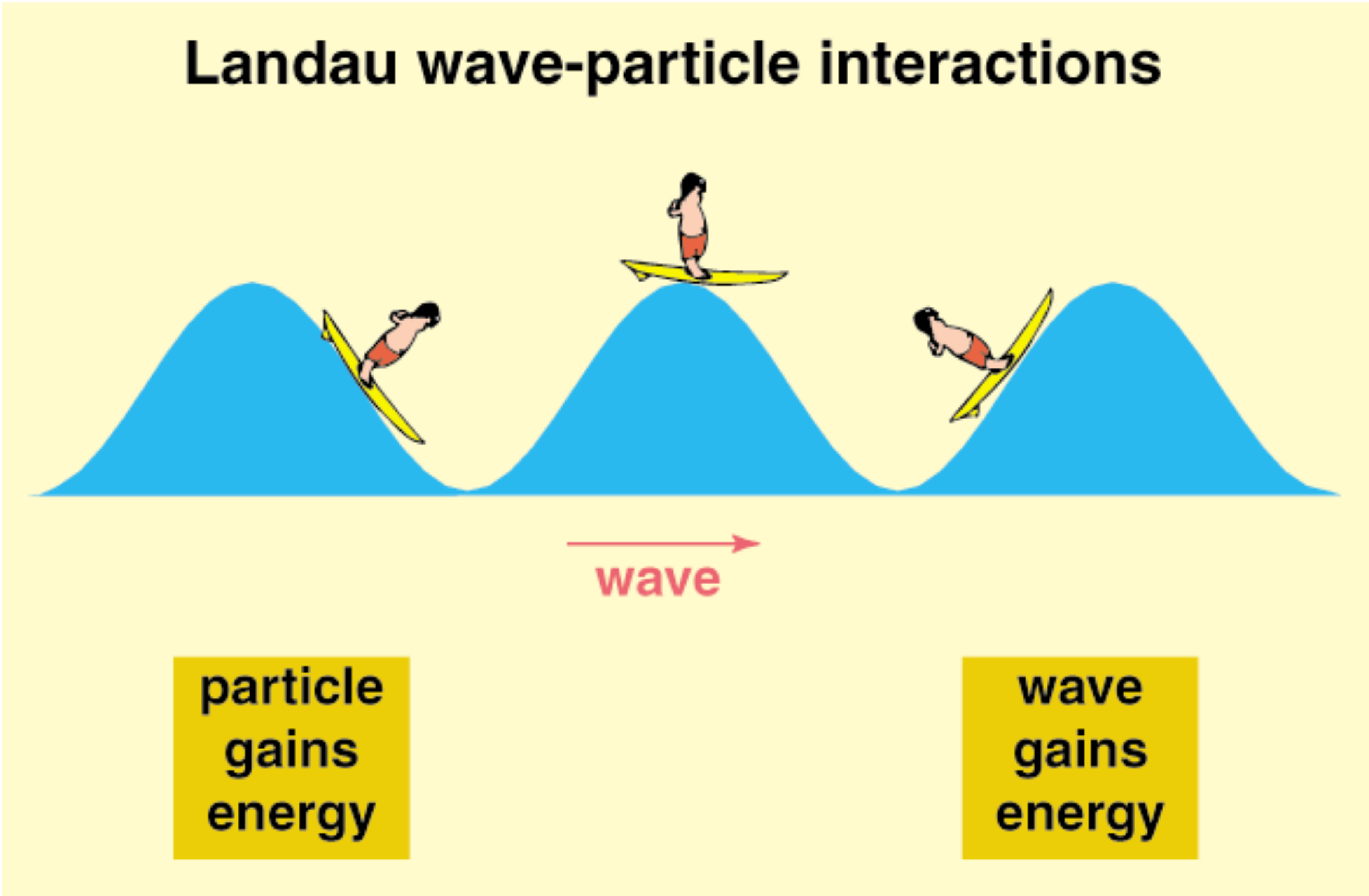

time
frequency

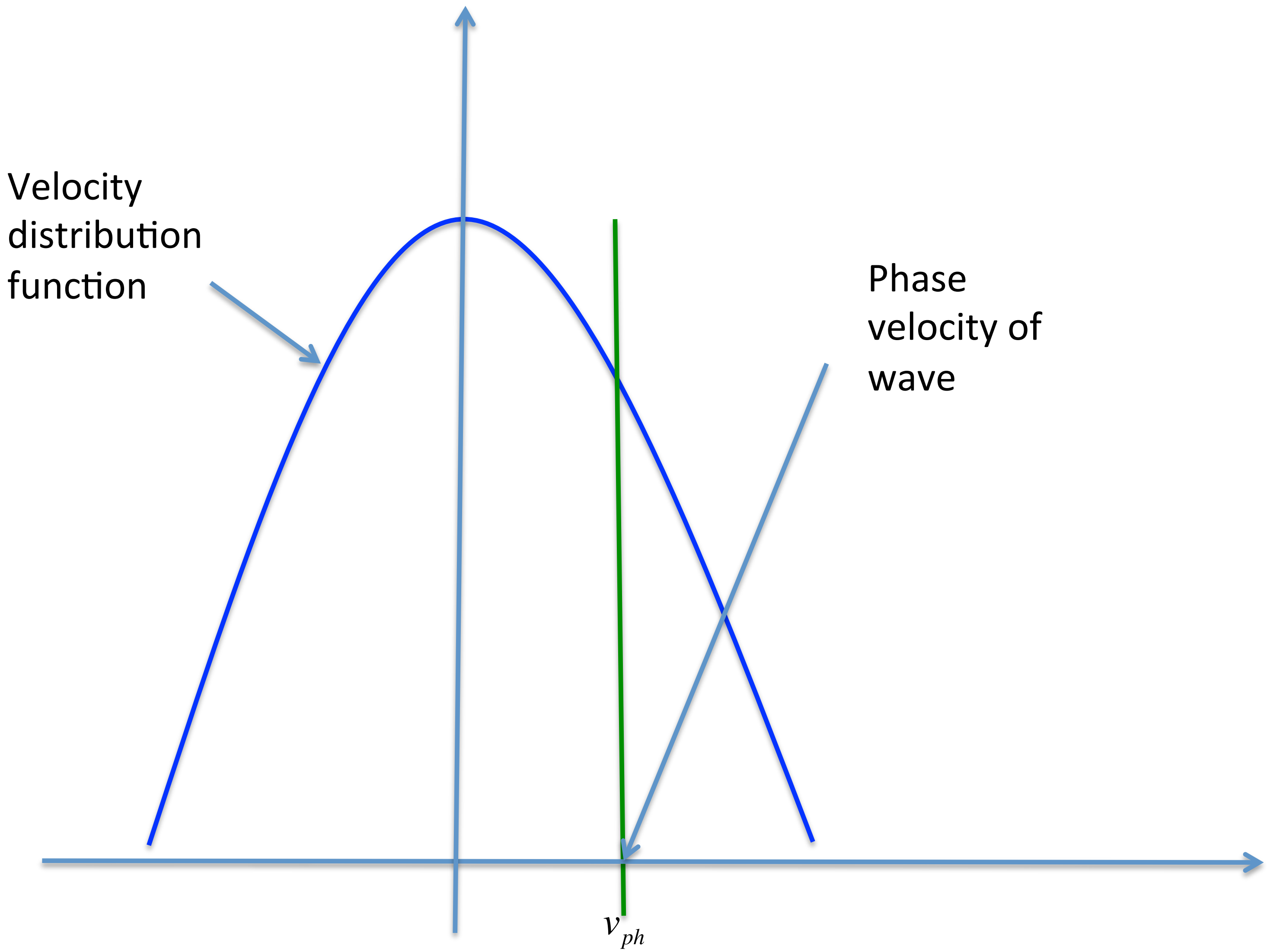

time
frequency

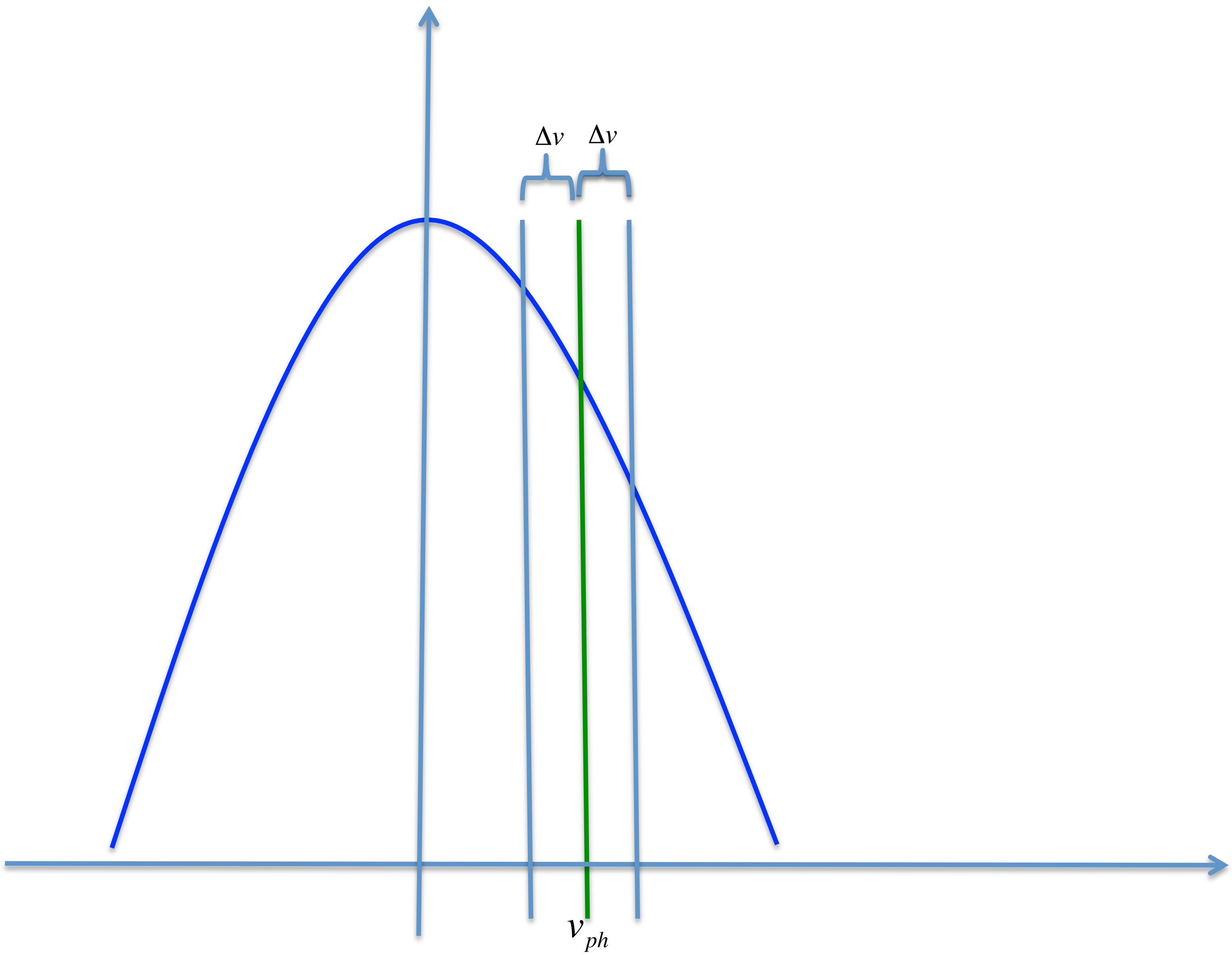

time
frequency

Plasma Wave Approach (cont'd)

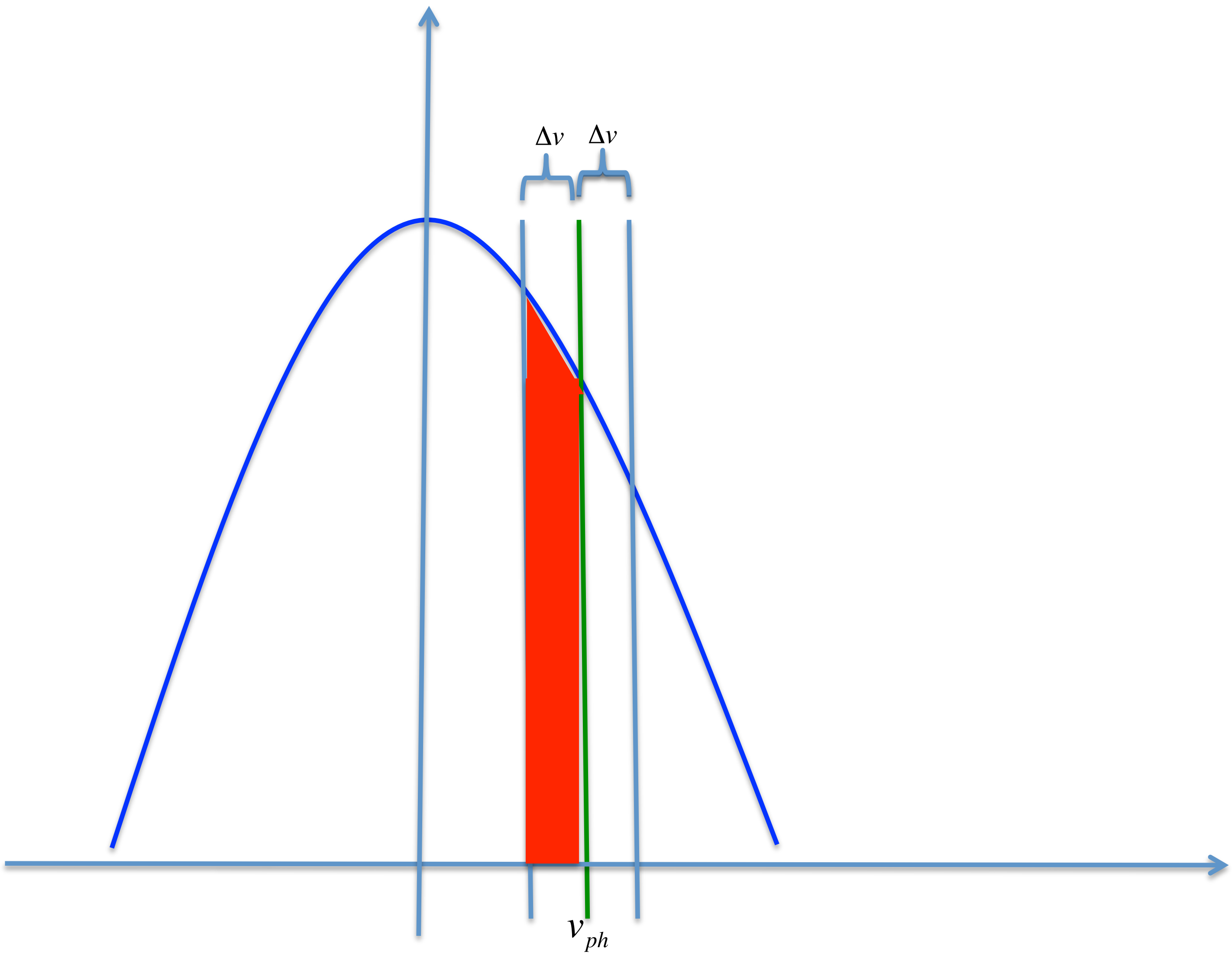



Landau wave-particle interactions
wave
particle gains energy
wave gains energy

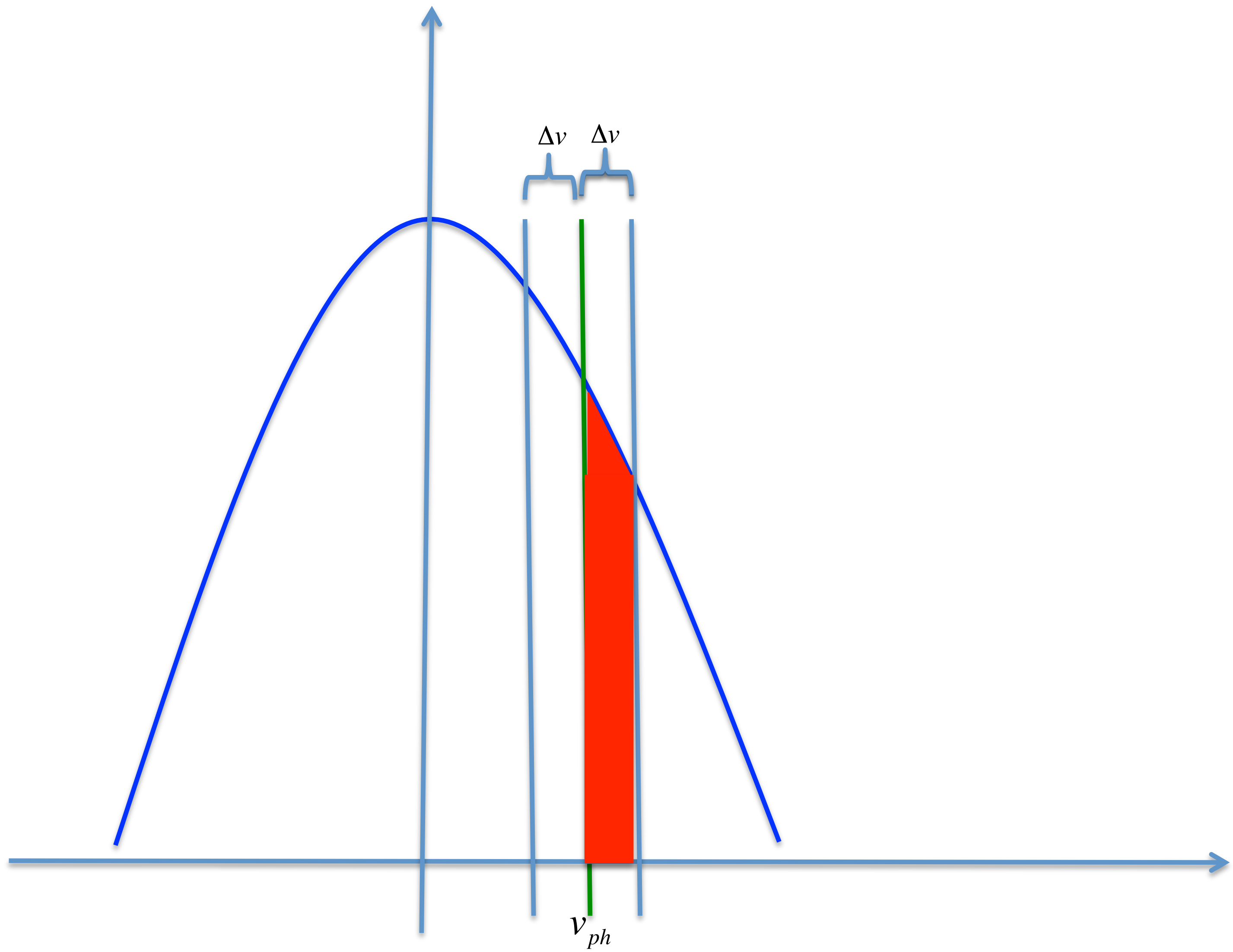

Velocity distribution function
Phase velocity of wave
v_{ph}



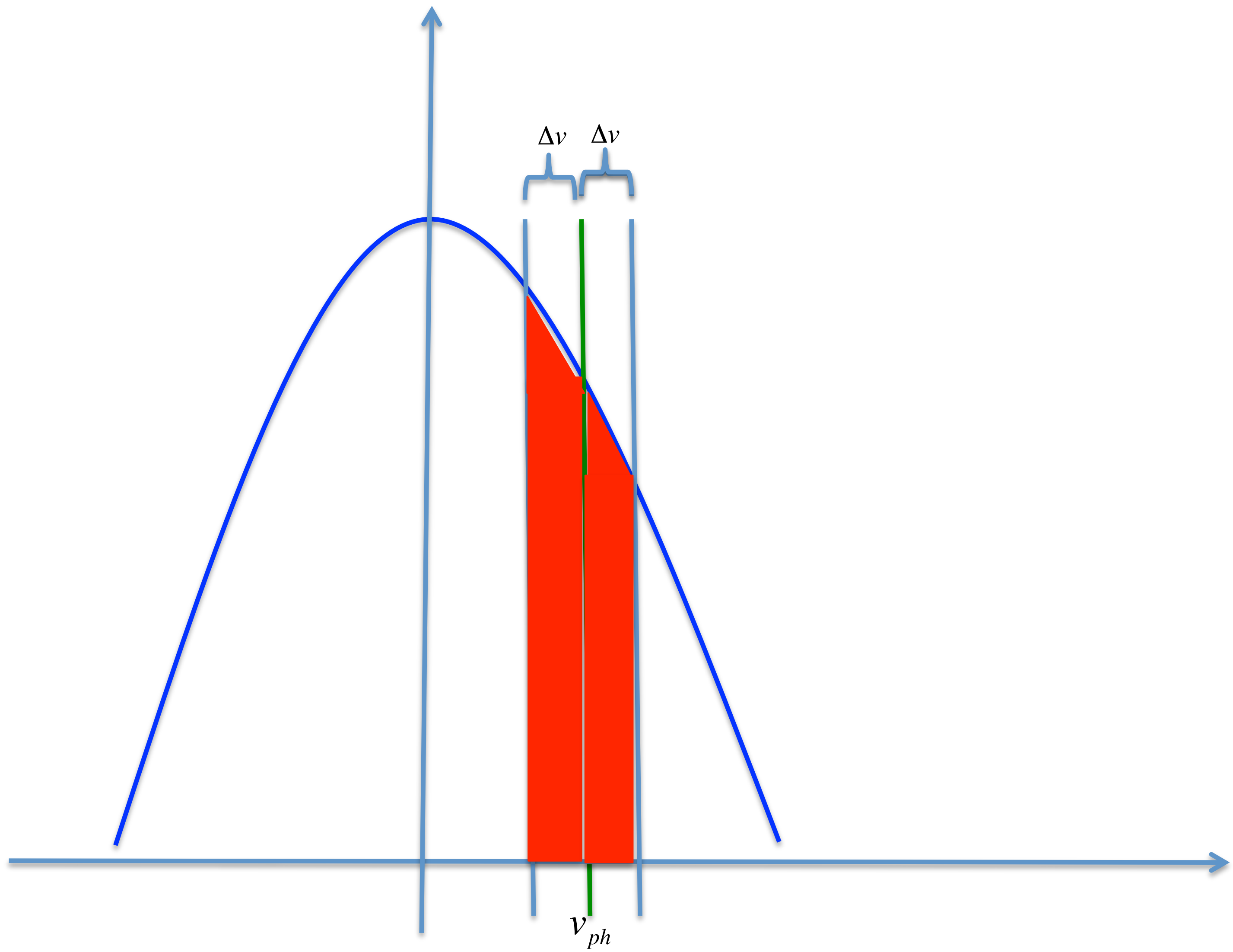
Δv
Δv
v_{ph}



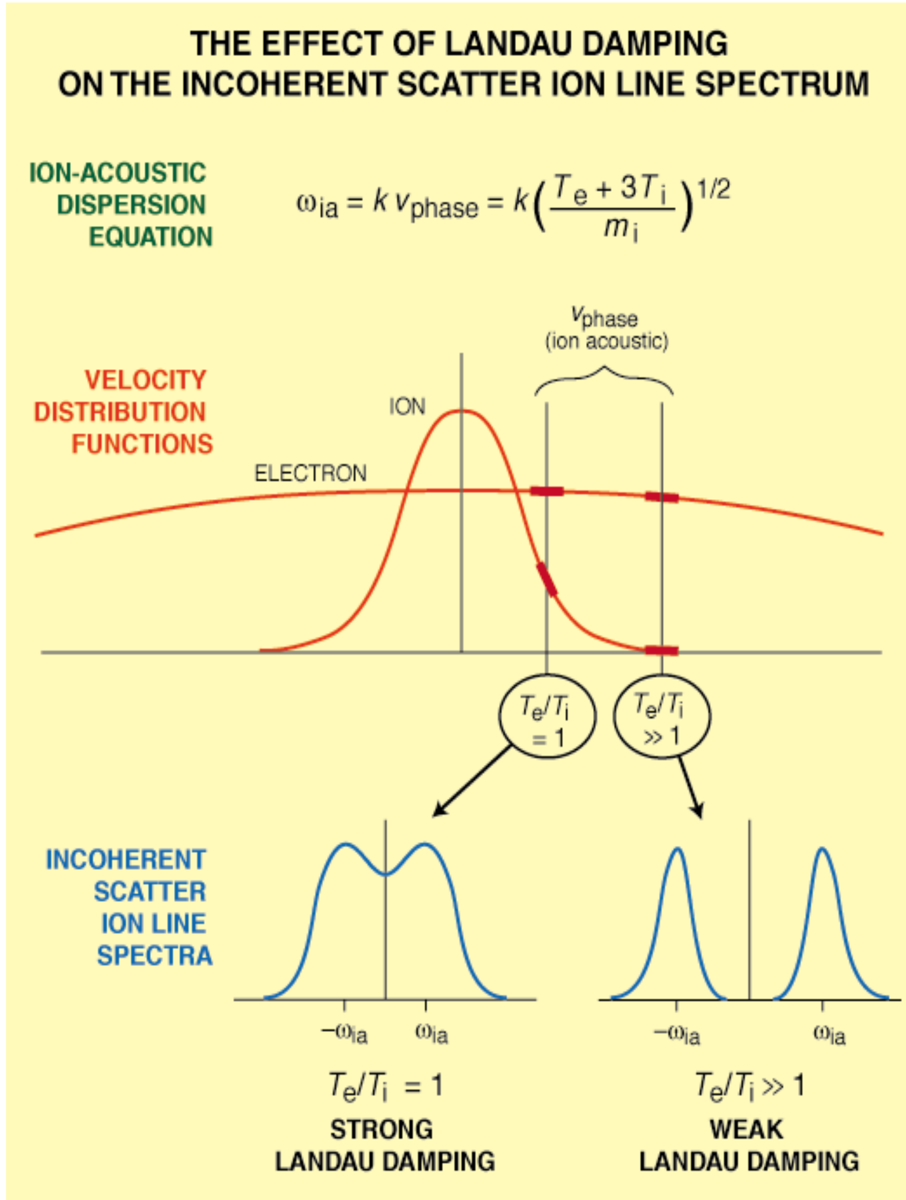
Δv
Δv
v_{ph}

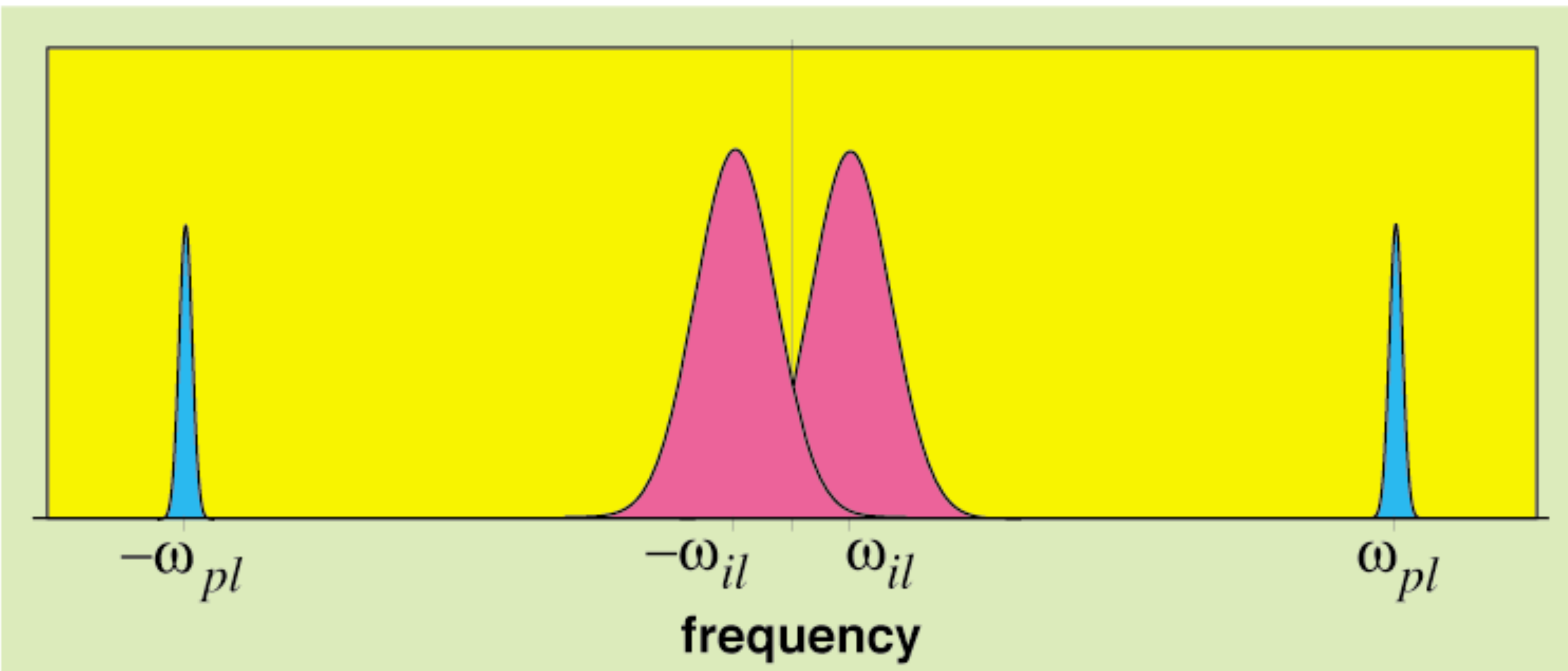


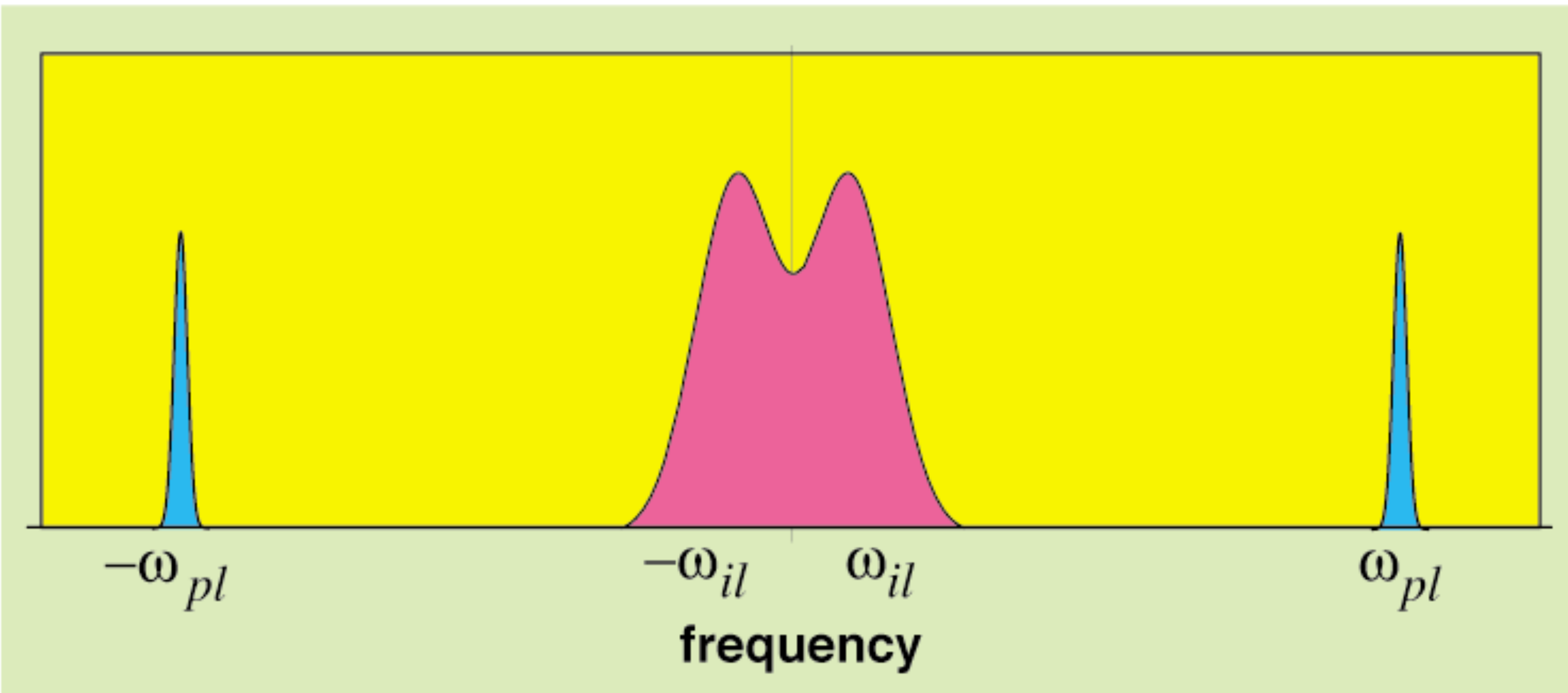
Δv
Δv
v_{ph}



Δv
Δv
v_ph


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
v_{phase} (ion acoustic)
ION
ELECTRON
$T_e/T_i = 1$
$T_e/T_i \gg 1$
INCOHERENT SCATTER ION LINE SPECTRA
$-\omega_{ia}$
ω_{ia}
$-\omega_{ia}$
ω_{ia}
$T_e/T_i = 1$
STRONG LANDAU DAMPING
$T_e/T_i \gg 1$
WEAK LANDAU DAMPING


$-\omega_{pl}$
$-\omega_{il}$
ω_{il}
ω_{pl}
frequency



$-\omega_{pl}$
$-\omega_{il}$
ω_{il}
ω_{pl}
frequency

Incoherent Scattering Spectrum

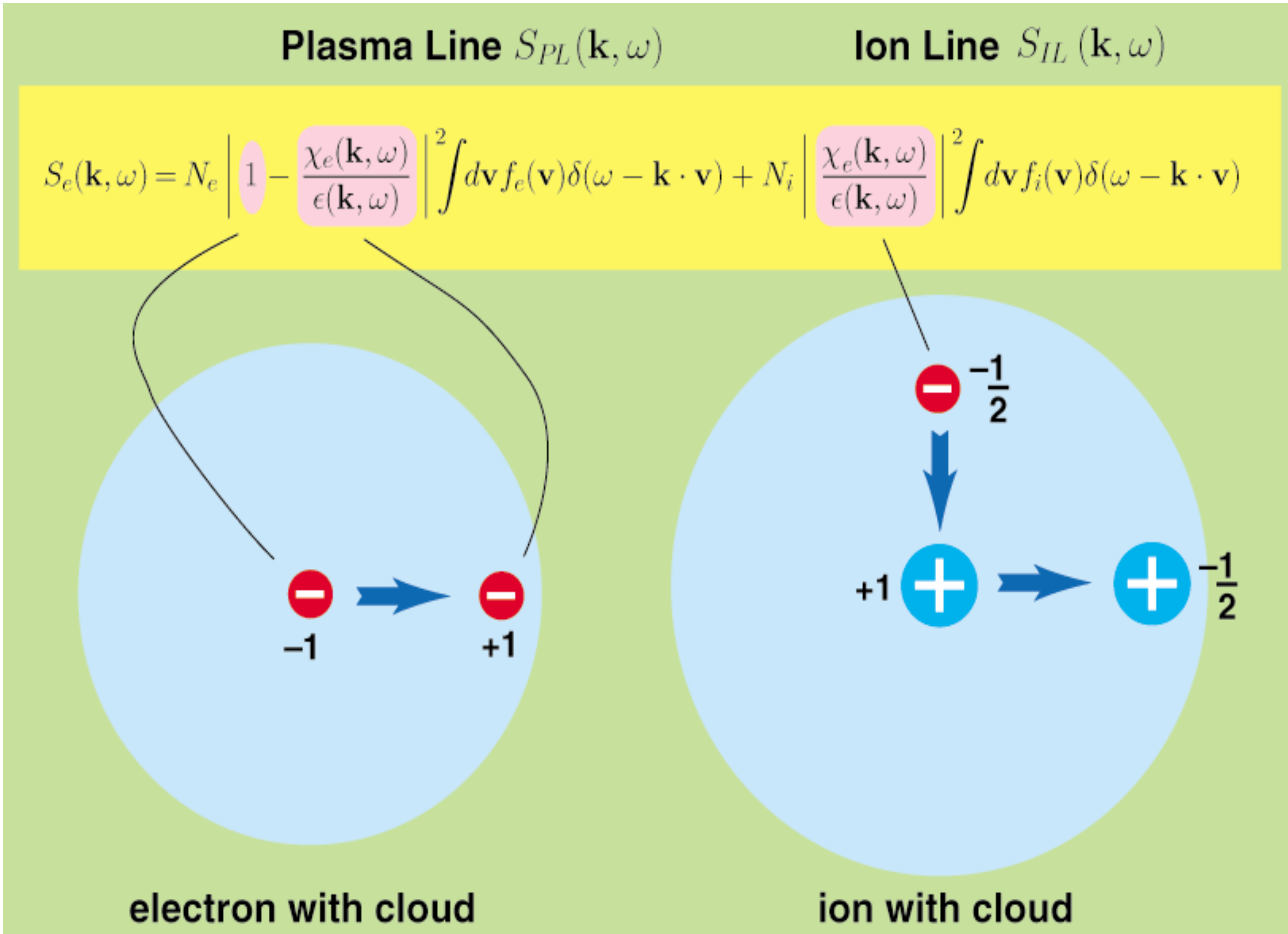
$$S_e(\mathbf{k},\omega) = N_e \left|1 - \frac{\chi_e(\mathbf{k},\omega)}{\epsilon(\mathbf{k},\omega)}\right|^2 \int d\mathbf{v}\, f_e(\mathbf{v})\, \delta(\omega - \mathbf{k}\cdot\mathbf{v}) + N_i \left|\frac{\chi_e(\mathbf{k},\omega)}{\epsilon(\mathbf{k},\omega)}\right|^2 \int d\mathbf{v}\, f_i(\mathbf{v})\,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

Plasma line　　　　Ion line

electric susceptibility $\chi_{e,i}(\mathbf{k},\omega)$

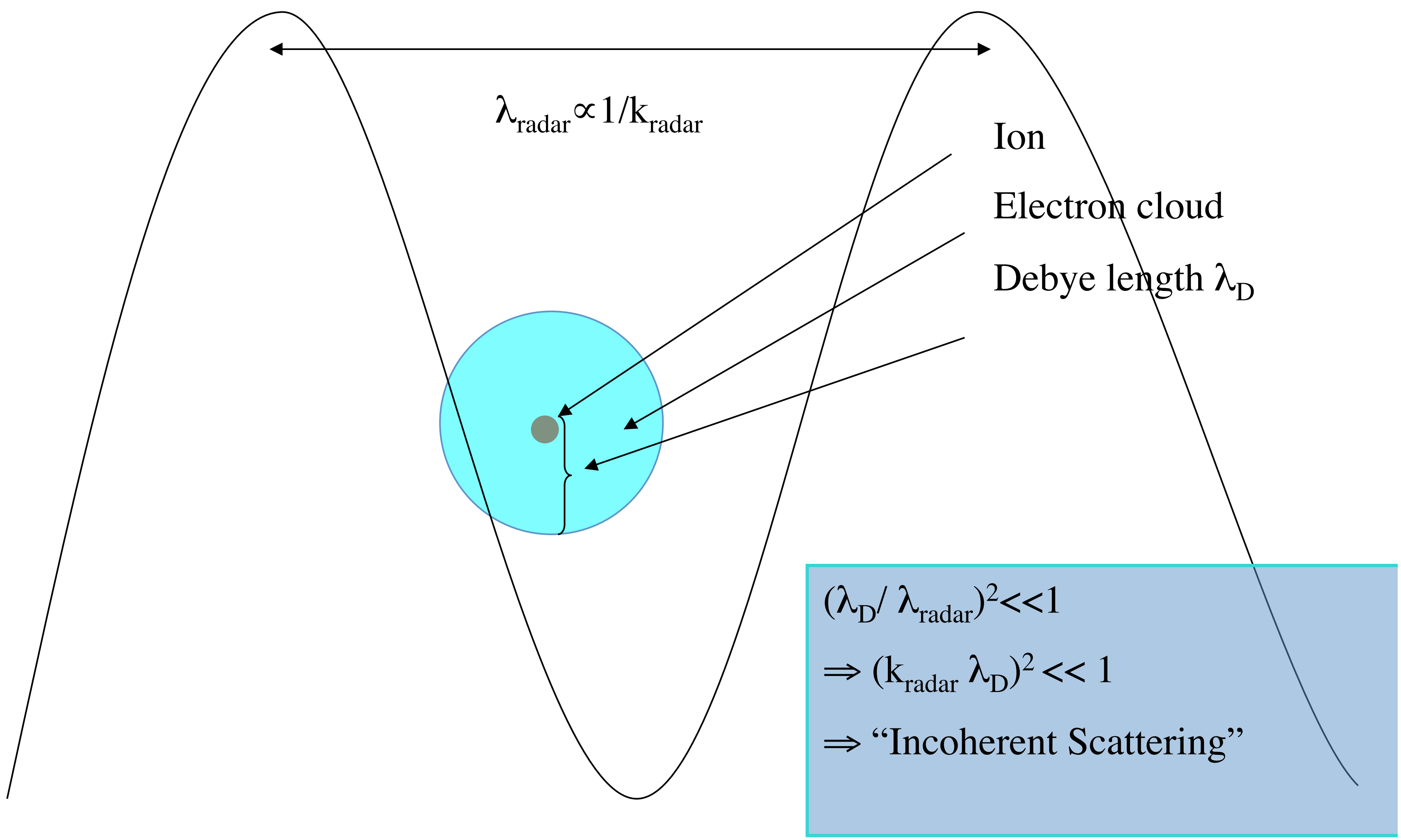
dielectric constant function $\epsilon(\mathbf{k},\omega)$

velocity distribution function $f_{e,i}(\mathbf{v})$



Plasma Line $S_{PL}(\mathbf{k},\omega)$
Ion Line $S_{IL}(\mathbf{k},\omega)$
$S_e(\mathbf{k},\omega) = N_e \left|1 - \frac{\chi_e(\mathbf{k},\omega)}{\epsilon(\mathbf{k},\omega)}\right|^2 \int d\mathbf{v}\, f_e(\mathbf{v})\delta(\omega - \mathbf{k}\cdot\mathbf{v}) + N_i \left|\frac{\chi_e(\mathbf{k},\omega)}{\epsilon(\mathbf{k},\omega)}\right|^2 \int d\mathbf{v}\, f_i(\mathbf{v})\delta(\omega - \mathbf{k}\cdot\mathbf{v})$
−1
+1
$-\frac{1}{2}$
+1
$-\frac{1}{2}$
electron with cloud
ion with cloud

Debye length dependence



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

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

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

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

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

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

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

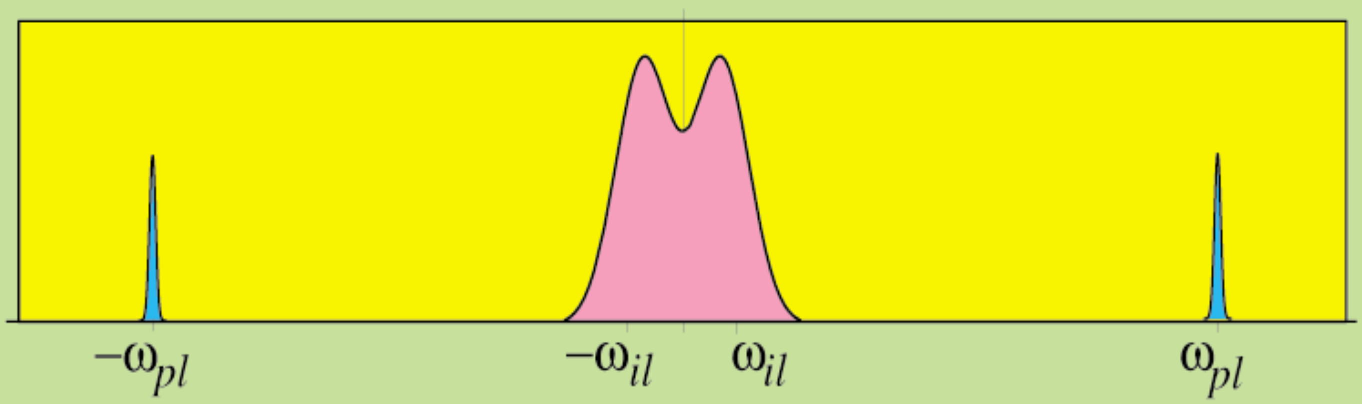
Plasma Line $S_{PL}(\mathbf{k},\omega)$ **Ion Line** $S_{IL}(\mathbf{k},\omega)$

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

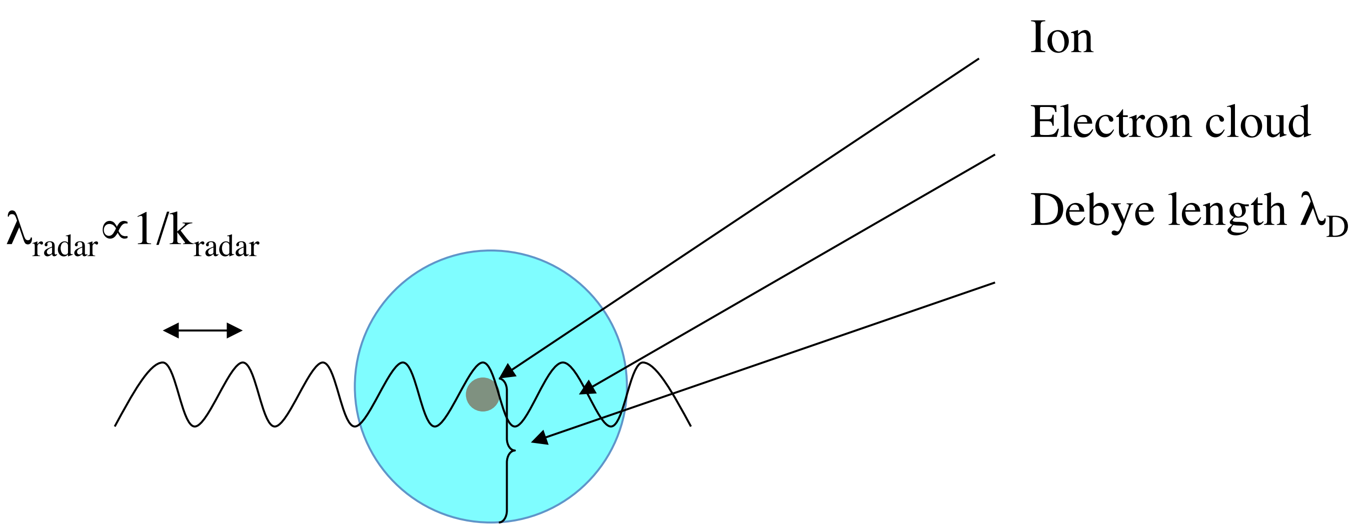
$$\epsilon(\mathbf{k},\omega)=\mathbf{0}$$

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

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



Debye length dependence



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

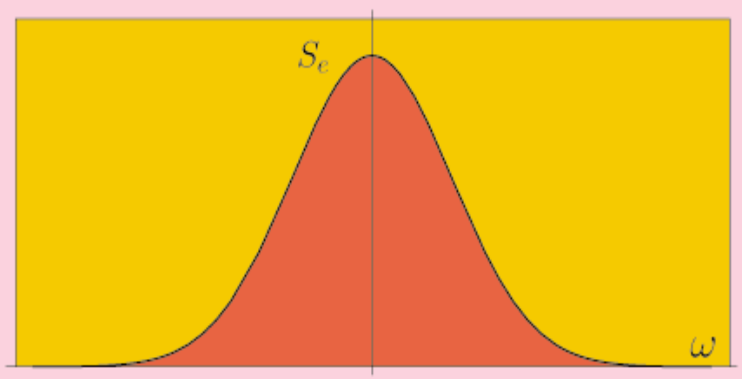
$\Rightarrow (k_{radar}\, \lambda_D)^2 > 1$

$\Rightarrow$ No collective interactions

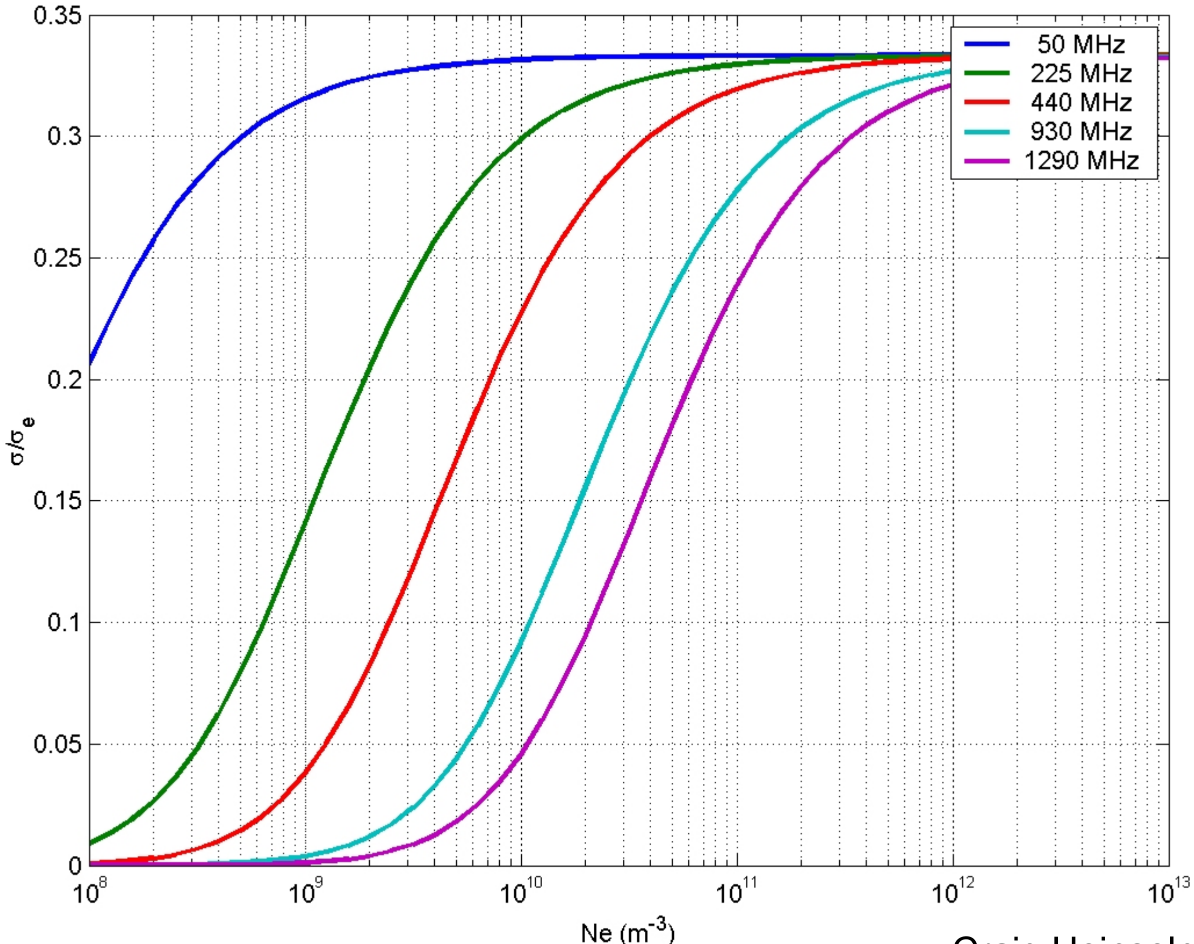
no collective interactions

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

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



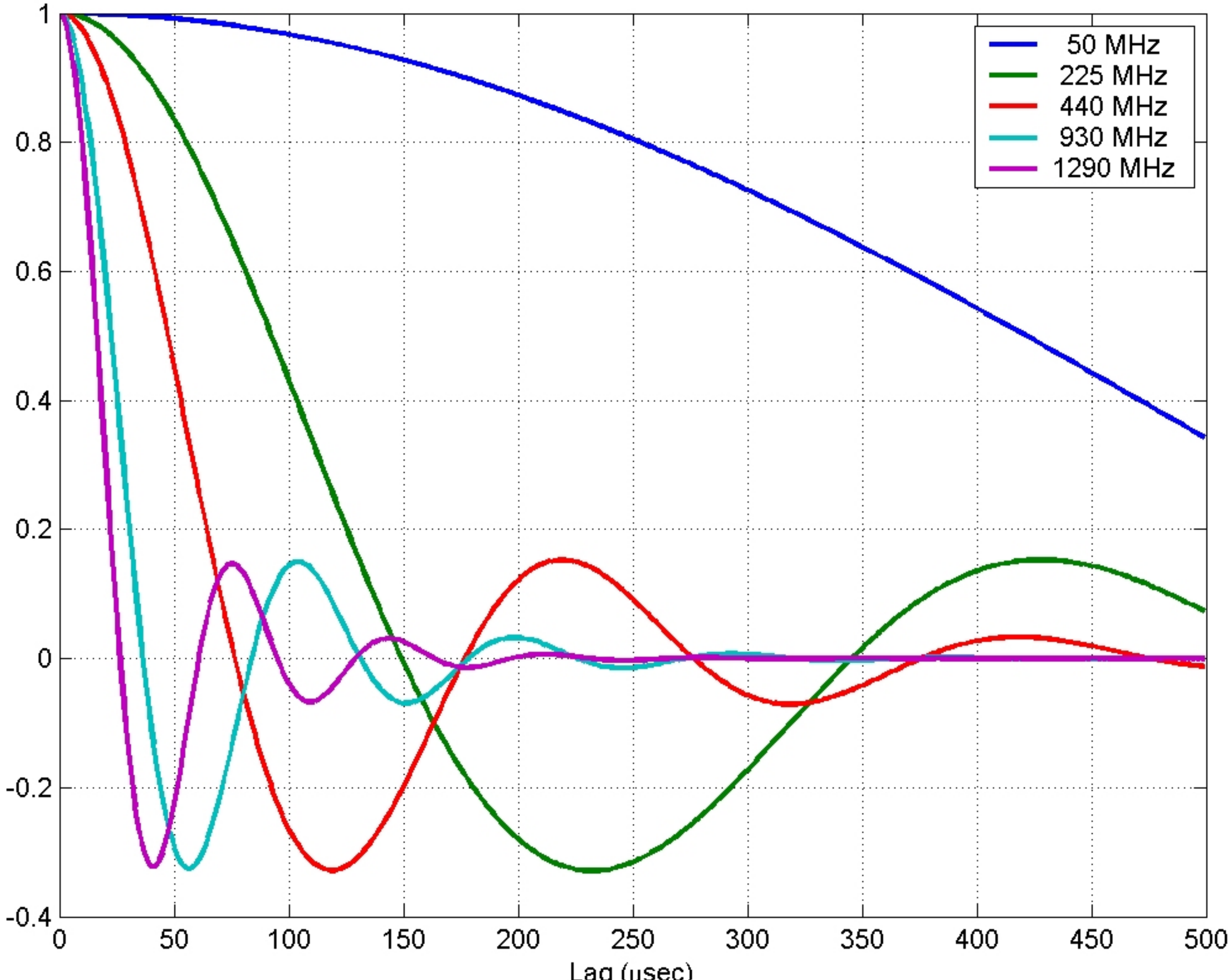
Debye Length Dependencies



<u>Parameters</u>
Ti: 1000 K
Te: 2000 K

Craig Heinselman

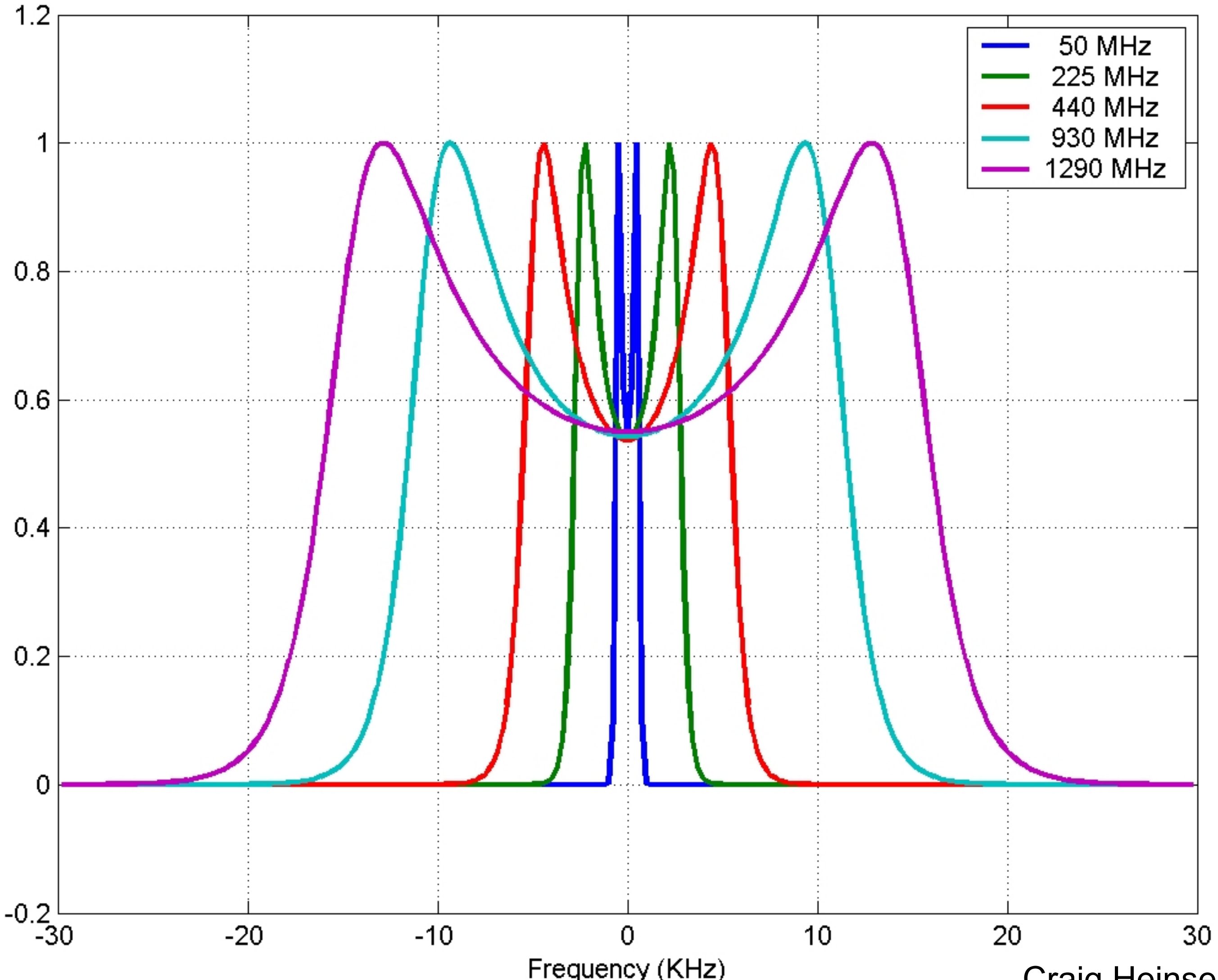
Radar Frequency Dependencies



Parameters
Ne: 10^{12} m^{-3}
Ti: 1000 K
Te: 2000 K
Comp: 100% O^+
ν_{in}: 10^{-6} KHz

Craig Heinselman

Radar Frequency Dependencies



Parameters
Ne: 10^{12} m^{-3}
Ti: 1000 K
Te: 2000 K
Comp: 100% O^{+}
ν_{in}: 10^{-6} KHz

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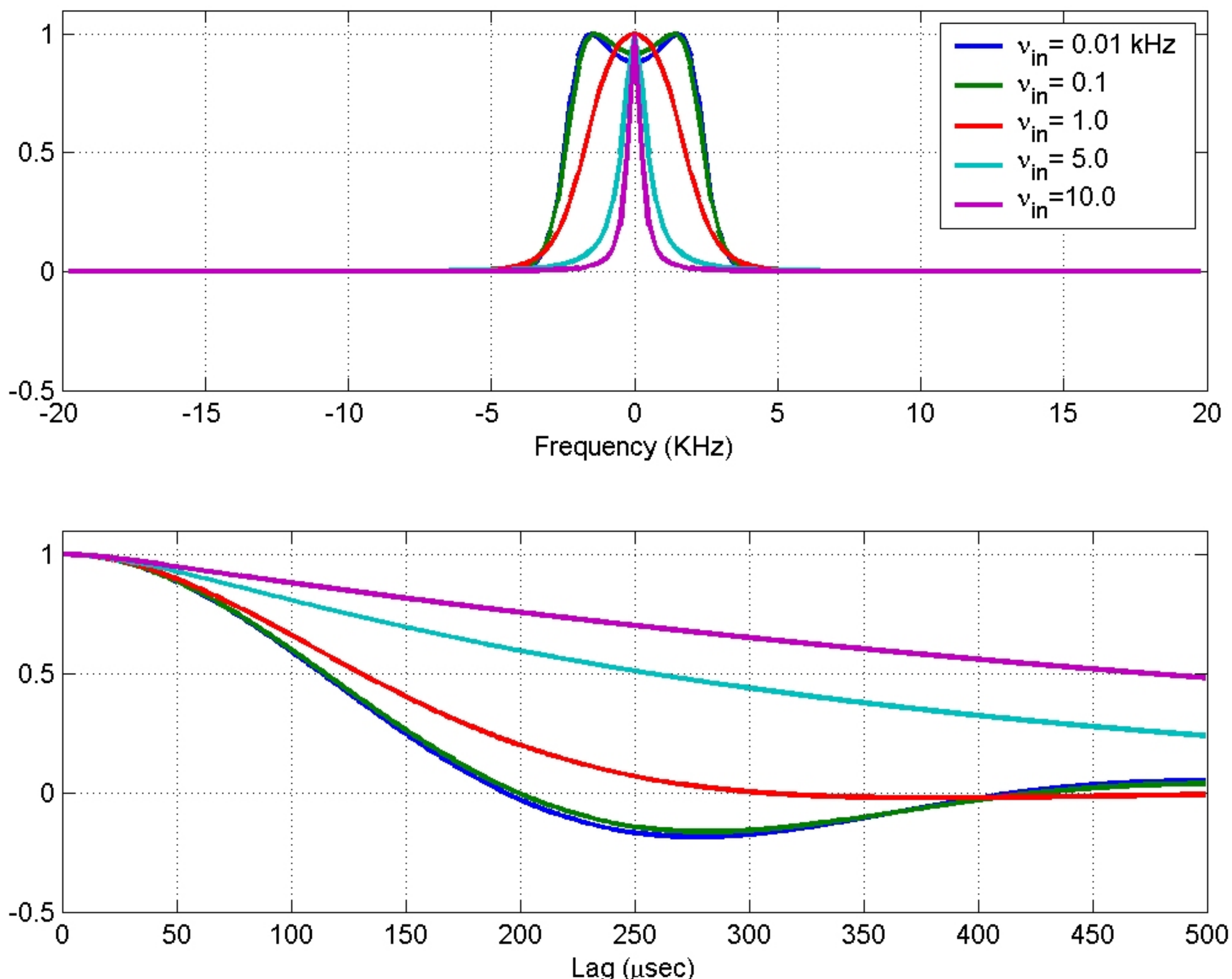
With the frequency of the radar chosen (which is a one time thing!), how does the spectra depend on geophysical parameters?

Ion-Neutral Collision Frequency



Parameters
Freq: 449 MHz
Ne: 10^{12} m^{-3}
Ti: 500 K
Te: 500 K
Comp: 100% NO^{+}

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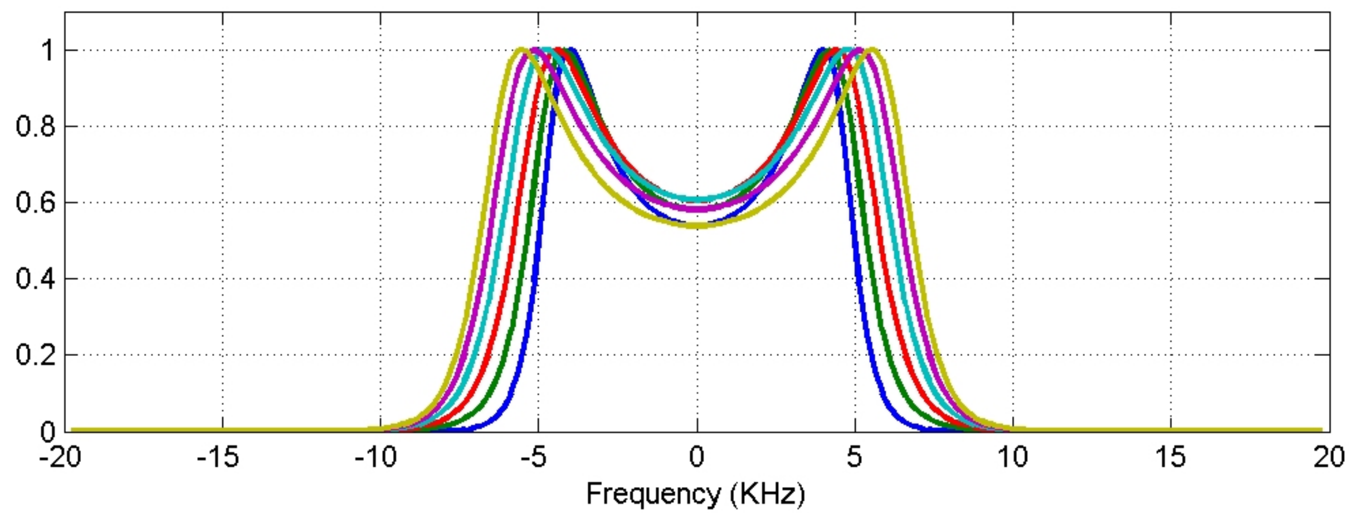
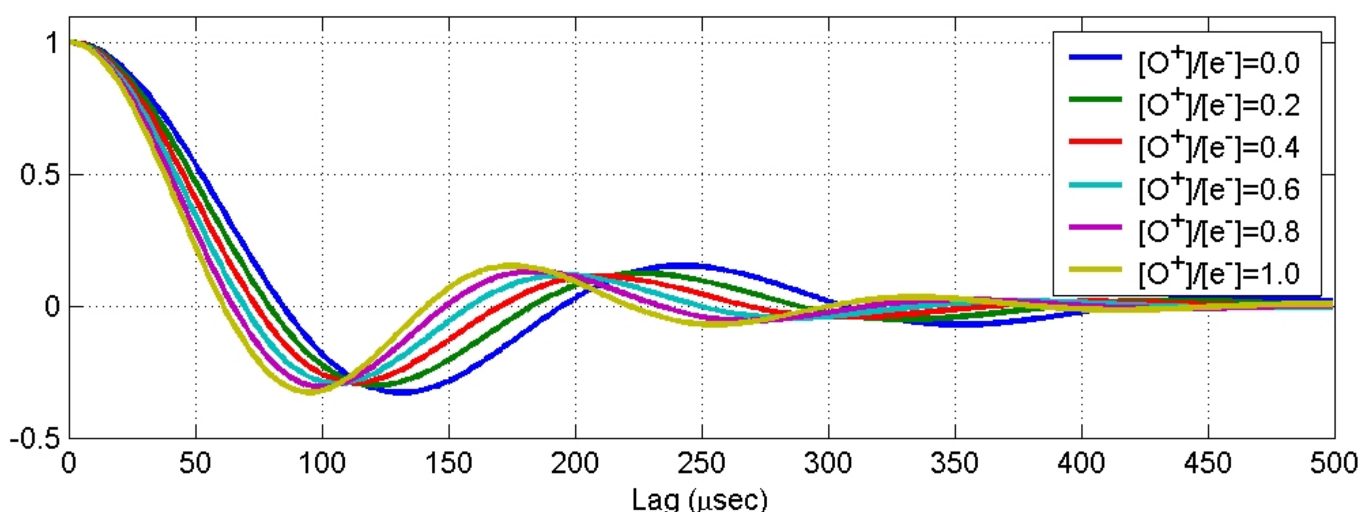
Ion Composition (O^+ vs. NO^+)



<u>Parameters</u>
Freq: 449 MHz
Ne: 10^{12} m^{-3}
Ti: 1500 K
Te: 3000 K
ν_{in}: 10^{-6} KHz



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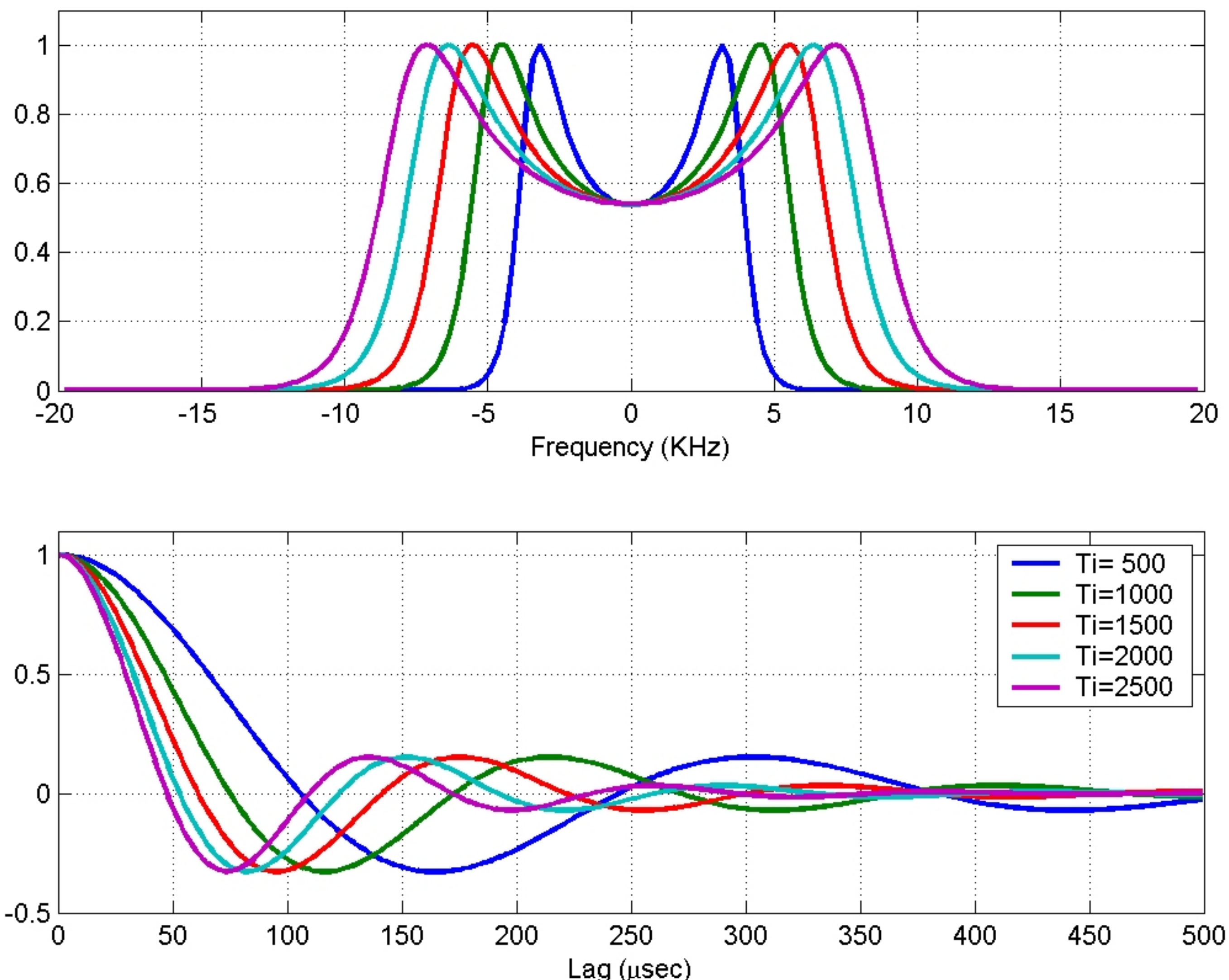
Ion Temperature



<u>Parameters</u>
Freq: 449 MHz
Ne: 10^{12} m^{-3}
Te: 2*Ti
Comp: 100% O^{+}
ν_{in}: 10^{-6} KHz

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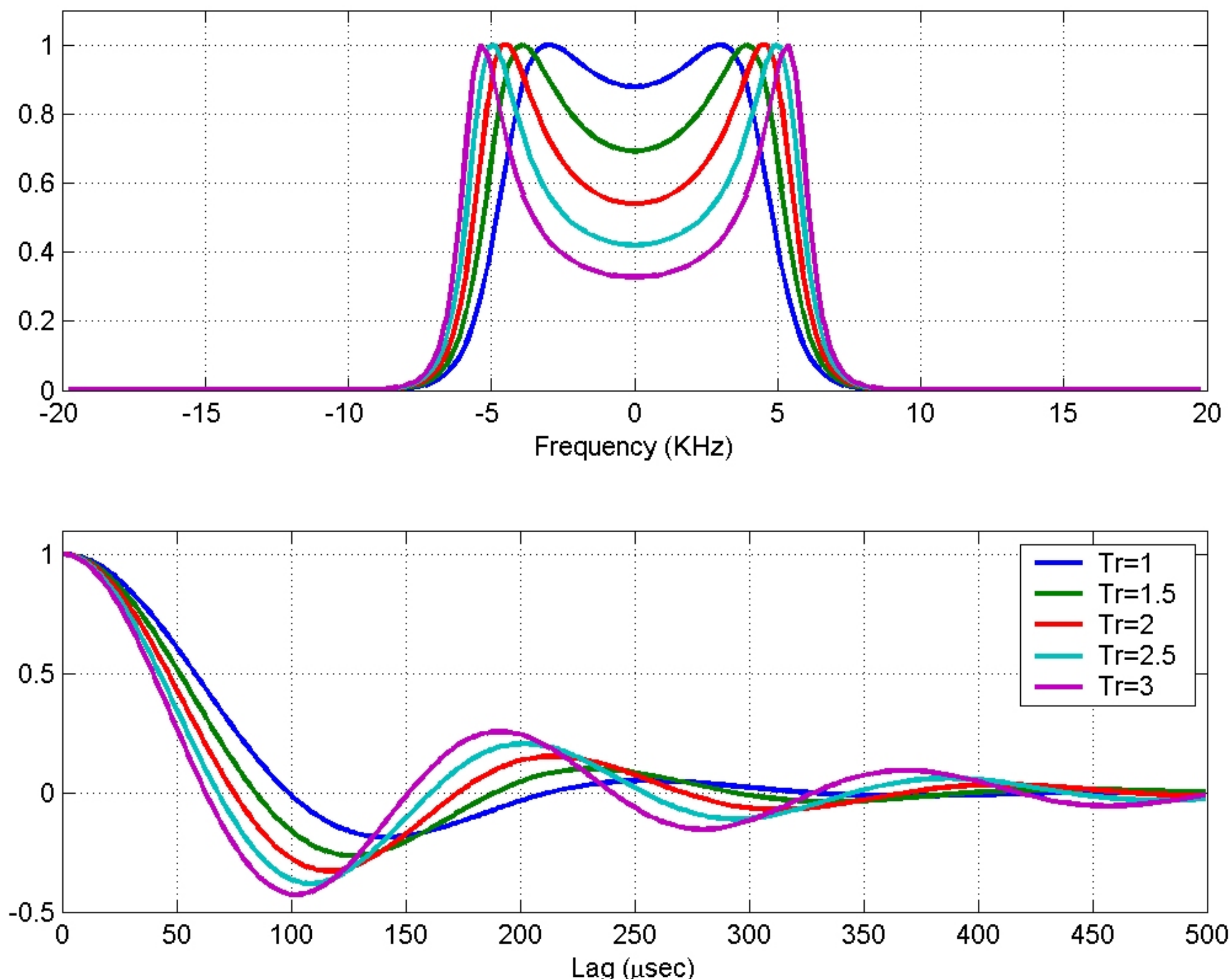
Electron/Ion Temperature Ratio



<u>Parameters</u>
Freq: 449 MHz
Ne: 10^{12} m^{-3}
Ti: 1000 K
Comp: 100% O^+
ν_{in}: 10^{-6} KHz

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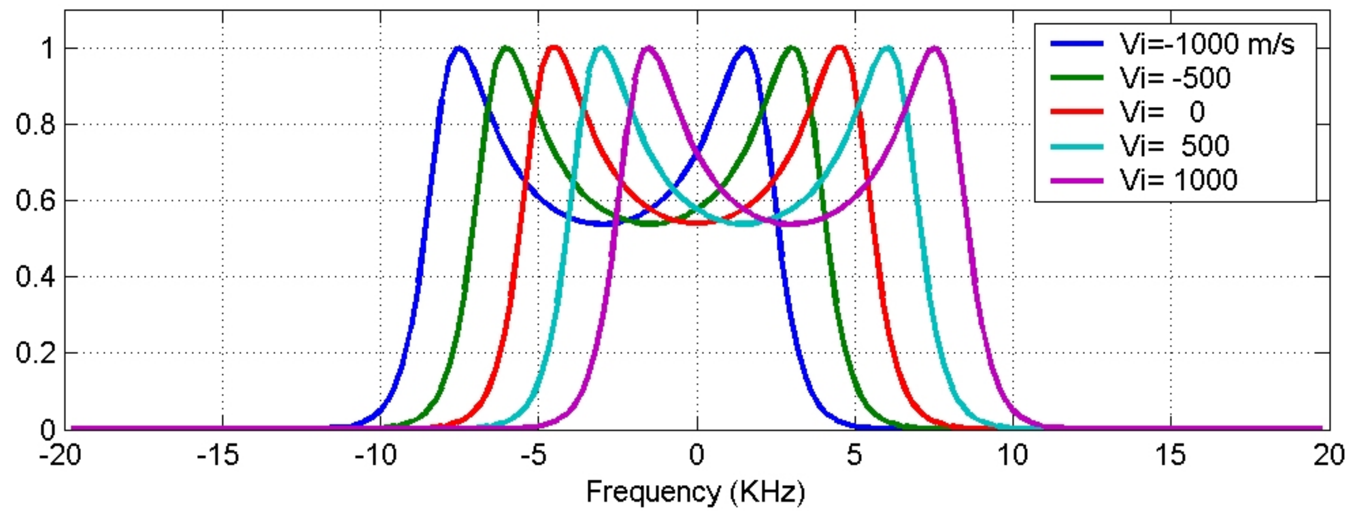
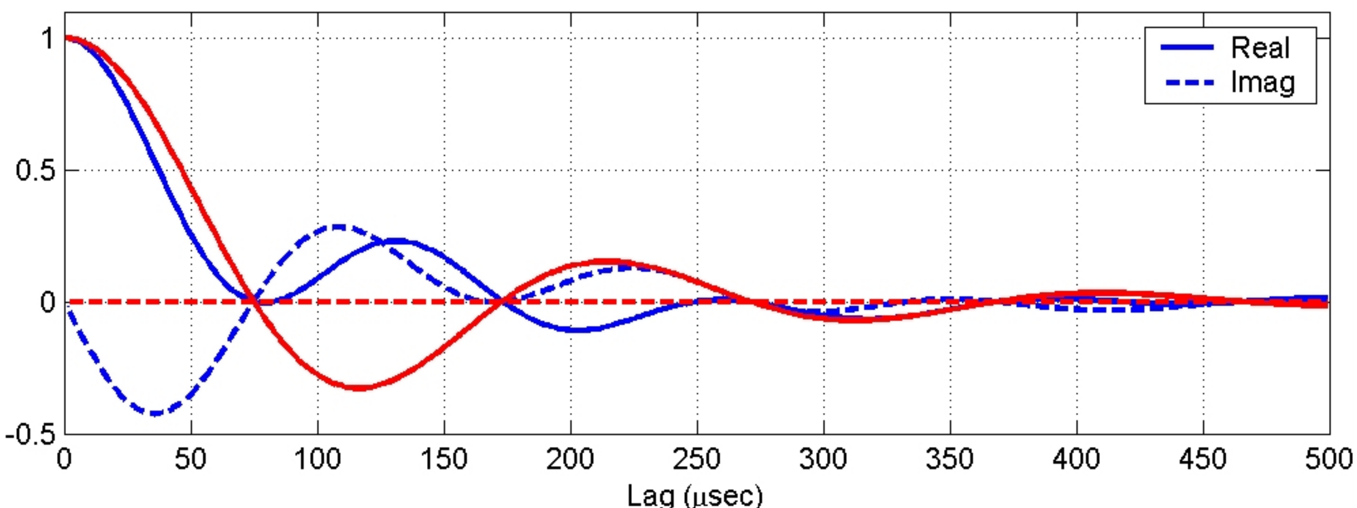
Ion Velocity





<u>Parameters</u>
Freq: 449 MHz
Ne: 10^{12} m^{-3}
Ti: 1000 K
Te: 2000 K
Comp: 100% O^+
ν_{in}: 10^{-6} KHz

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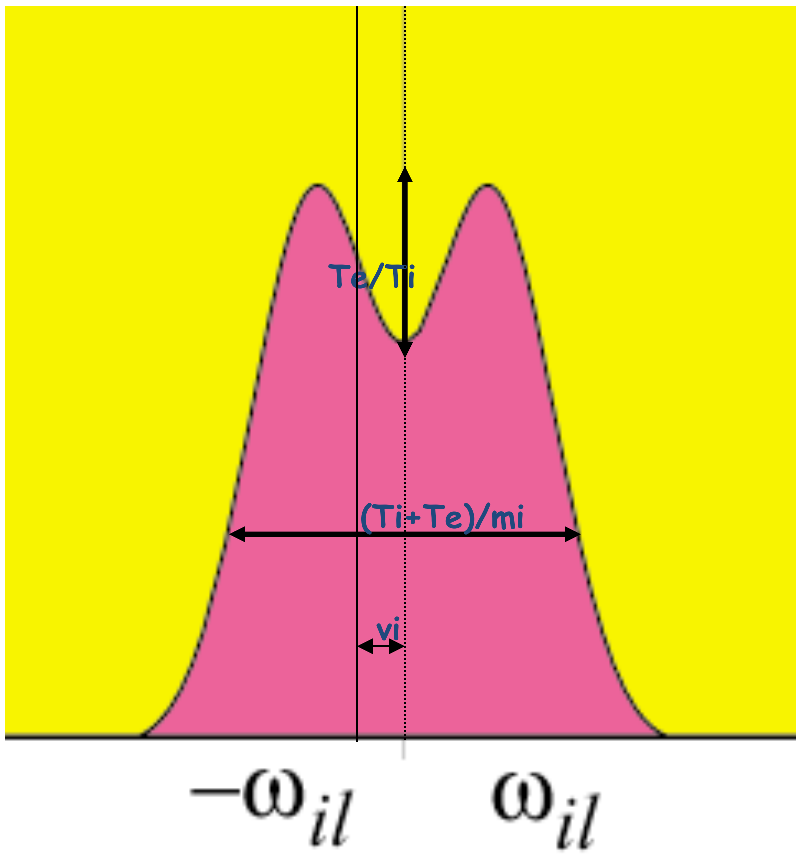
…or to sum up…



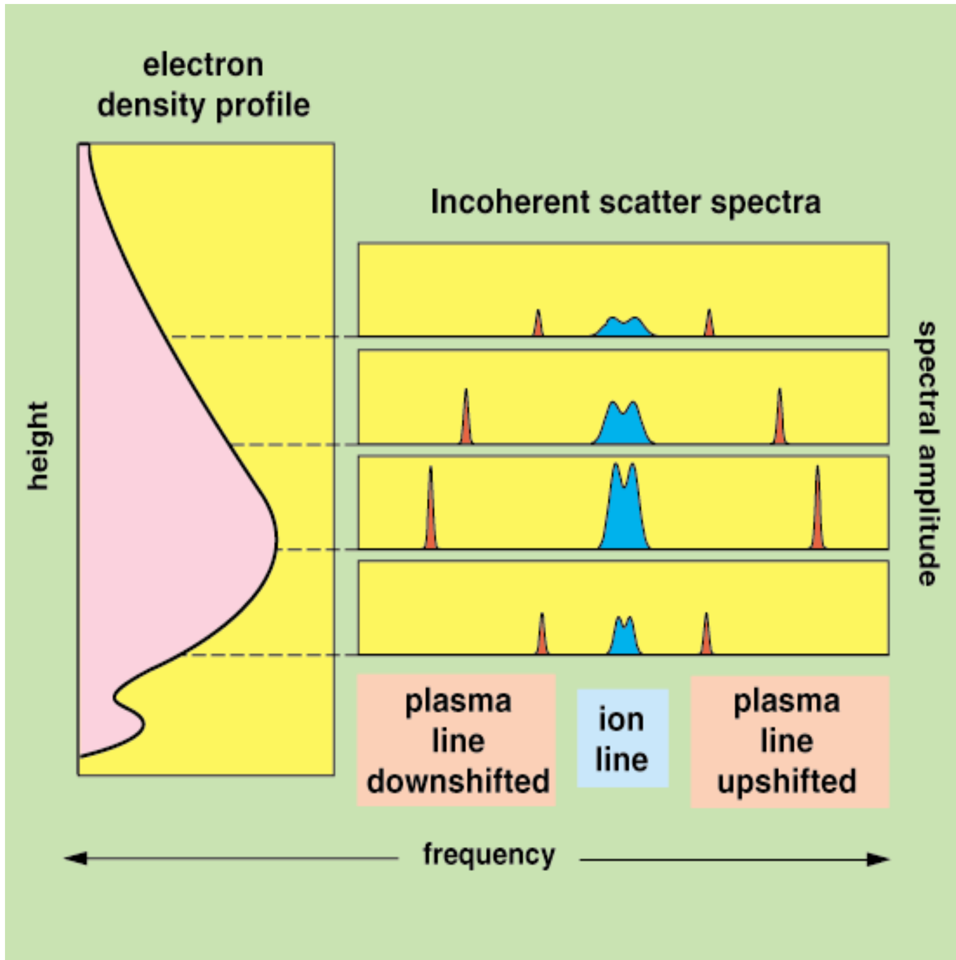
•Ion (and electron) temperature (Ti and Te) to ion mass (mi) ratio from the width of the spectra

•Electron to ion temperature ratio (Te/Ti) from "peak_to_valley" ratio

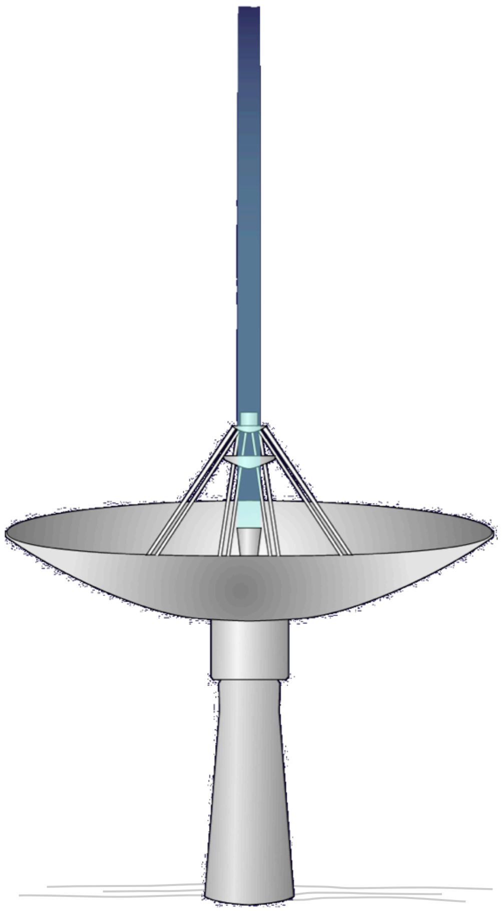
•Electron (= ion) density from total area (corrected for temperatures)

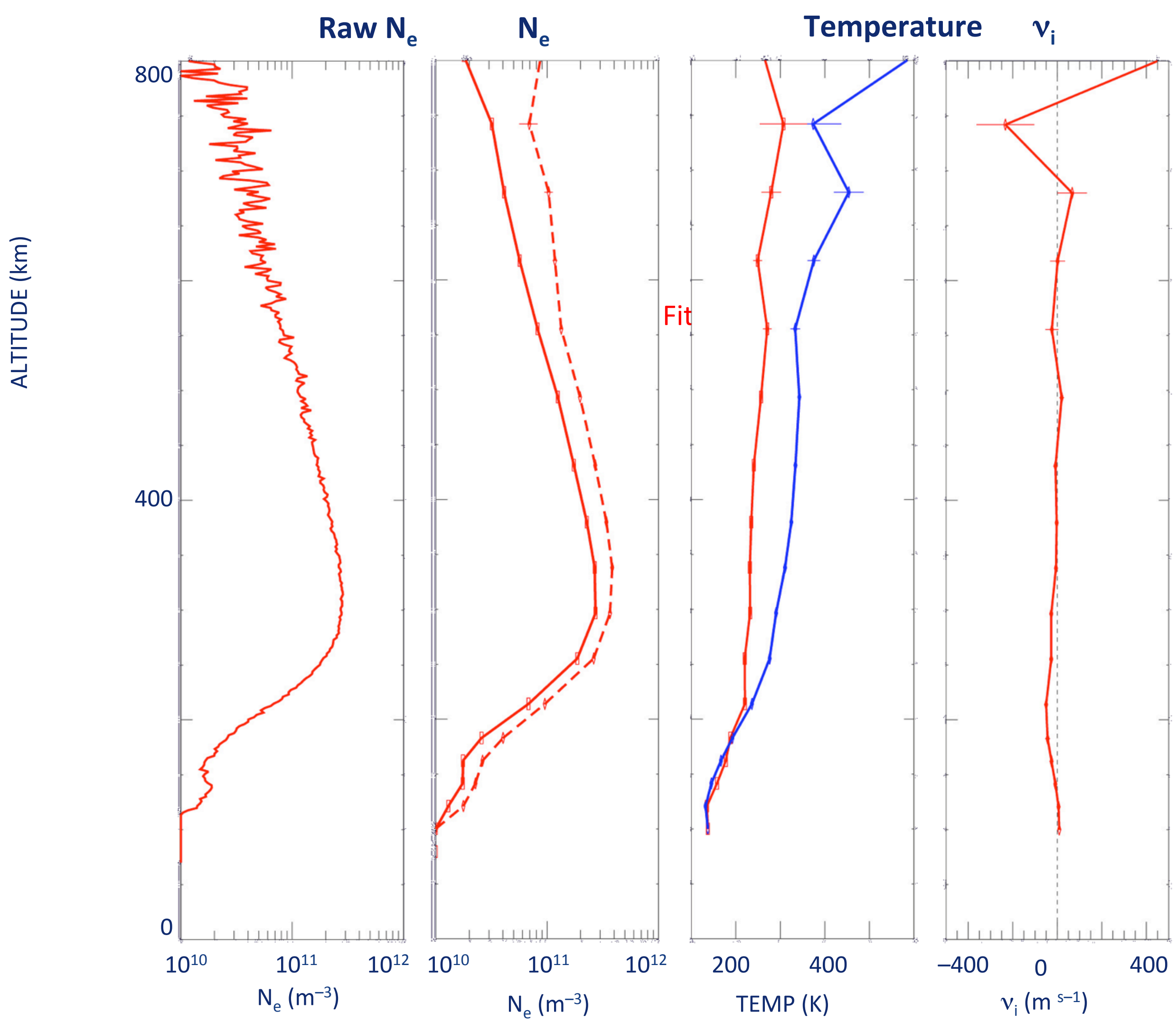
•Ion velocity (vi) from the Doppler shift

Spectral space as a function of altitude

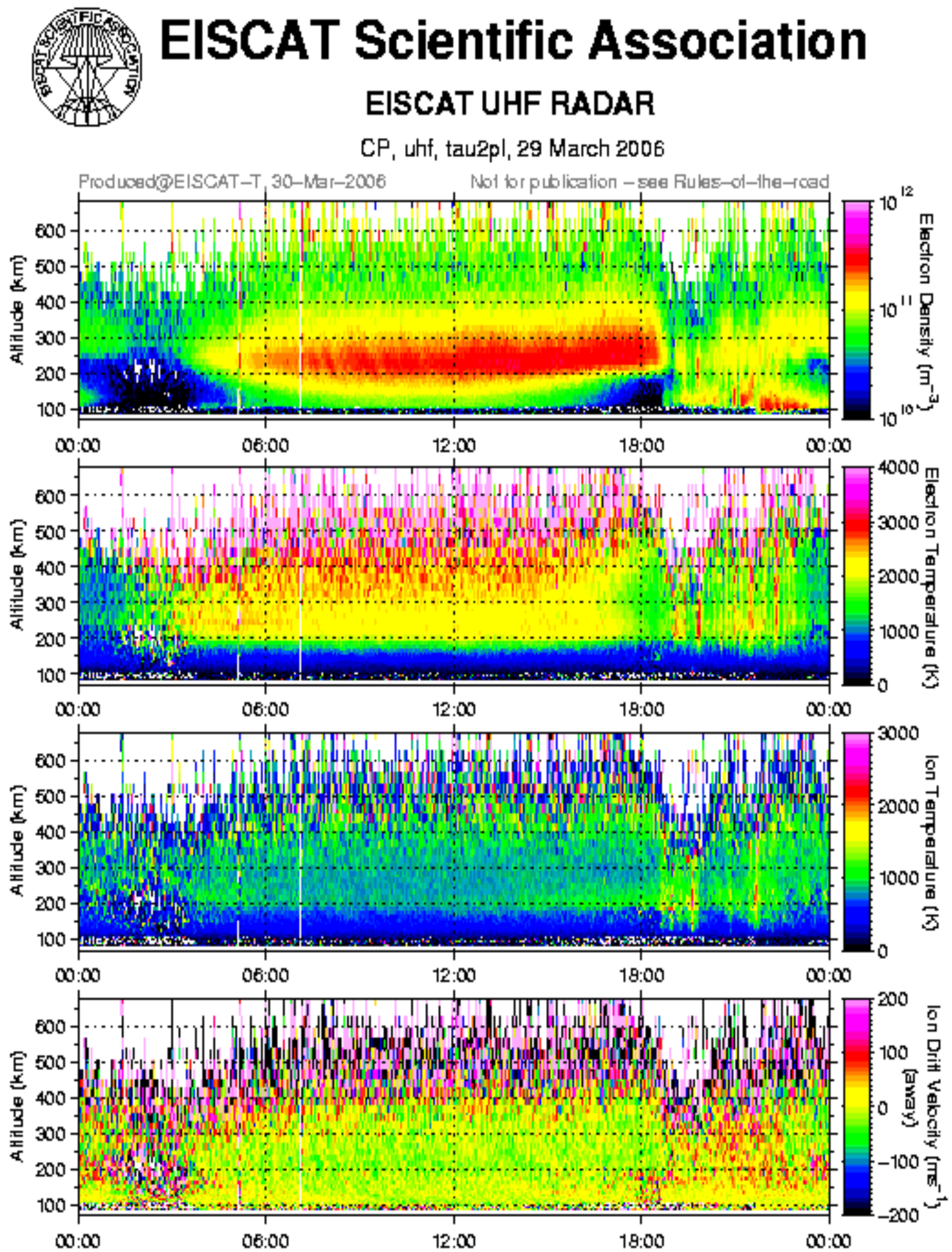


Plasma Parameter Profile





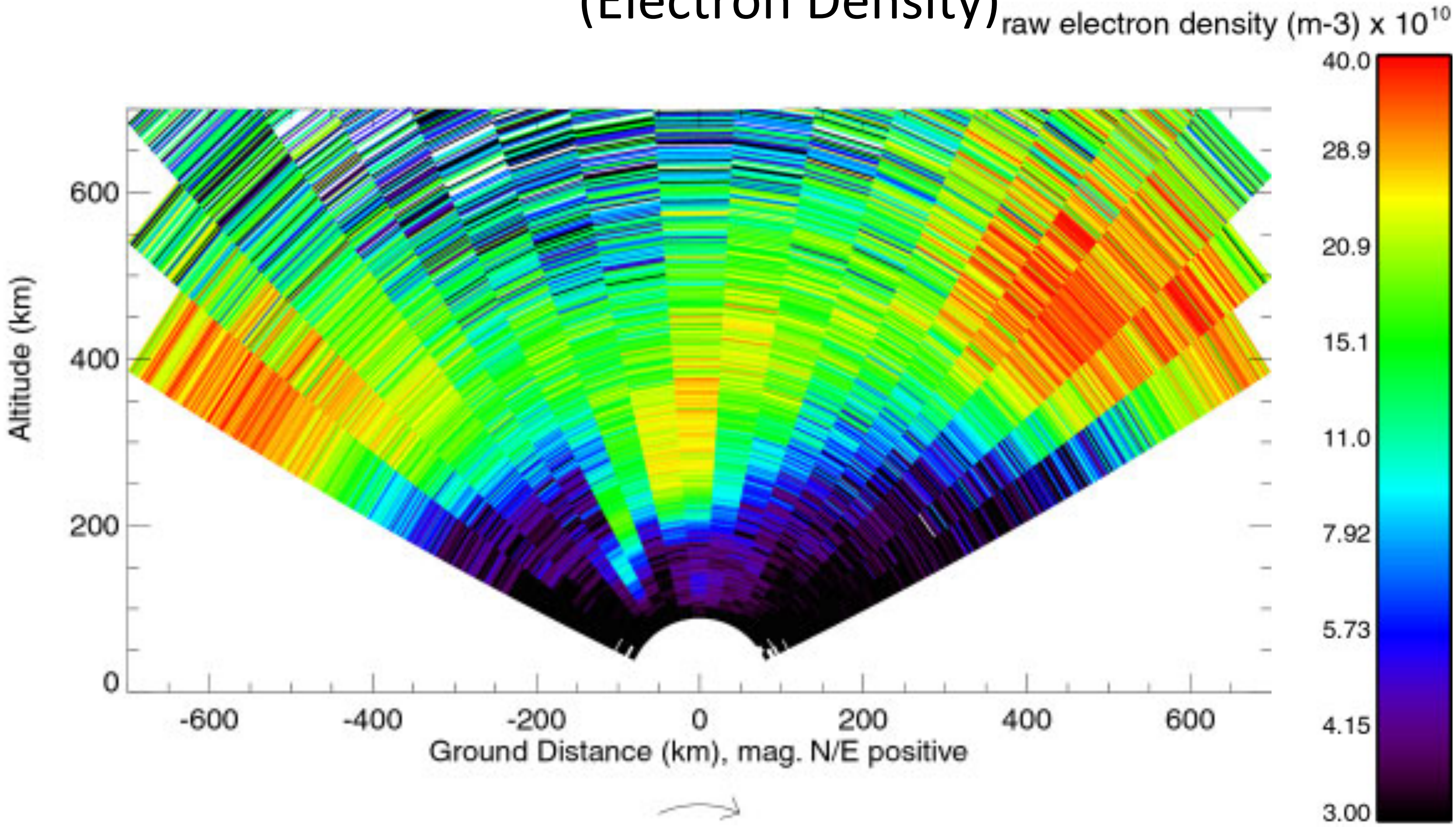
v6



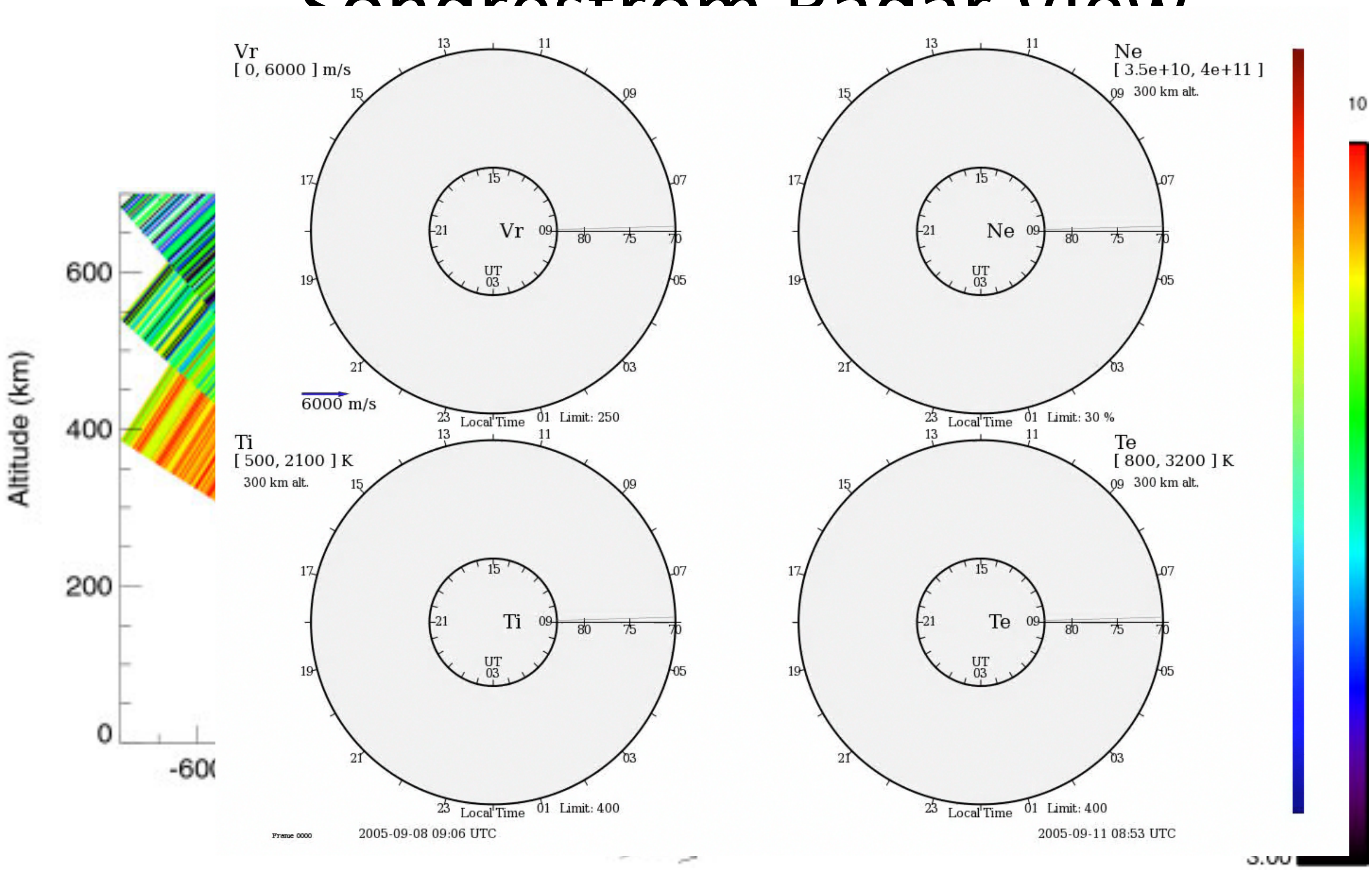
EISCAT Scientific Association
EISCAT UHF RADAR
CP, uhf, tau2pl, 29 March 2006
Produced@EISCAT-T, 30-Mar-2006
Not for publication – see Rules-of-the-road
Altitude (km)
Electron Density (m^{-3})
Electron Temperature (K)
Ion Temperature (K)
Ion Drift Velocity (ms^{-1}) (away)
00:00
06:00
12:00
18:00

Sondrestrom Radar View

(Electron Density)

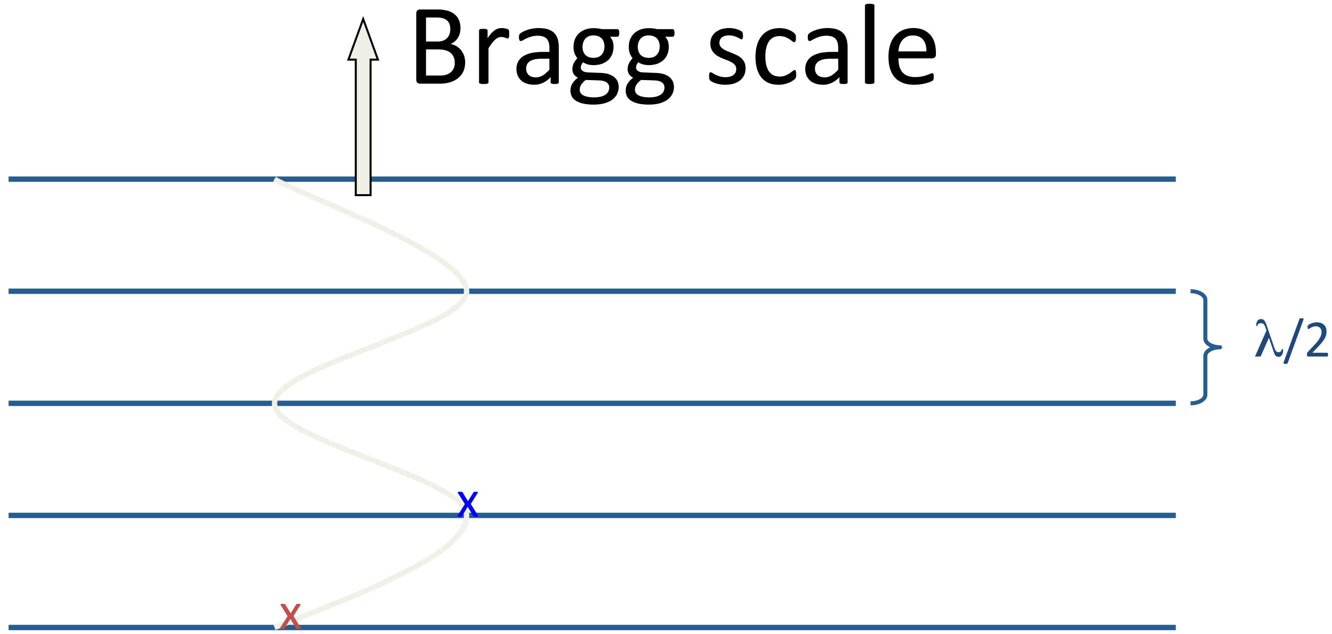


Sondrestrom Radar View

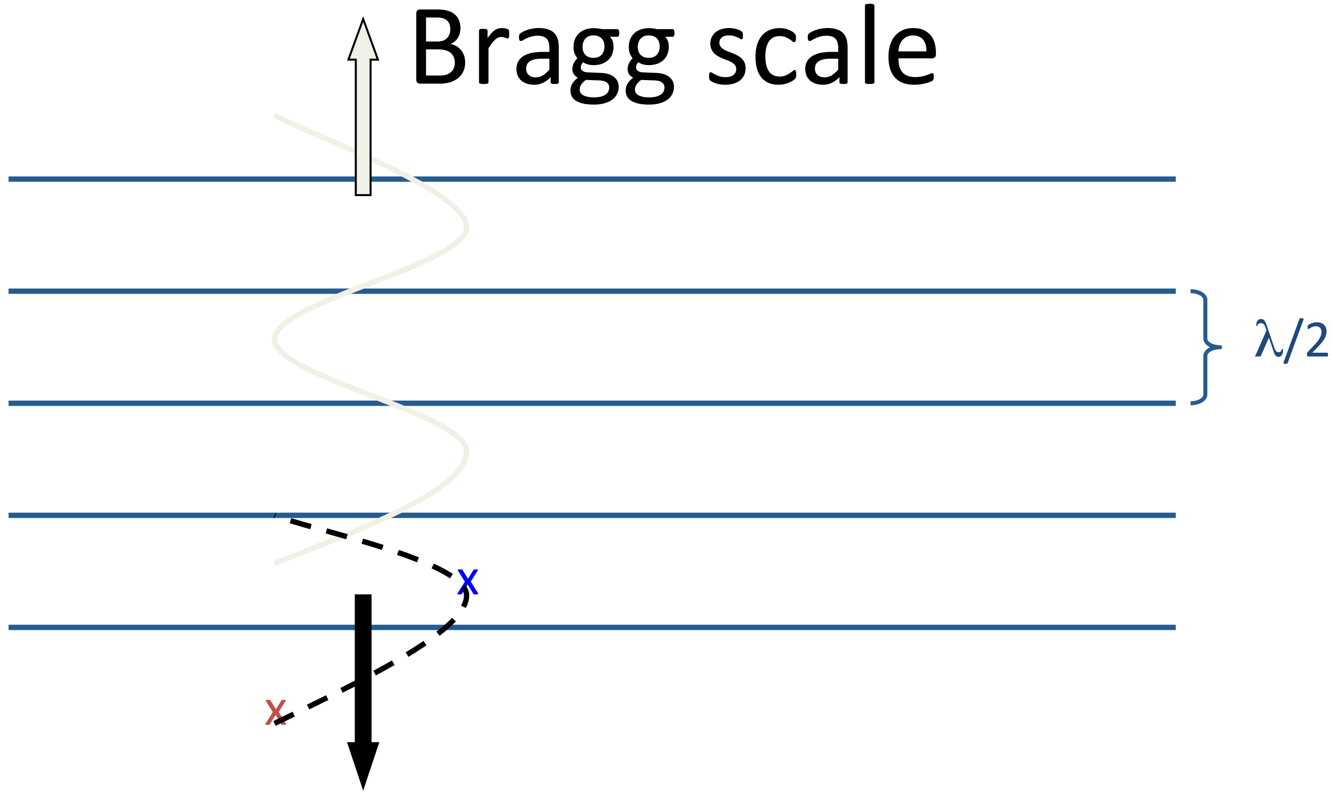


And this is the level data we will work on in the MADRIGAL session…

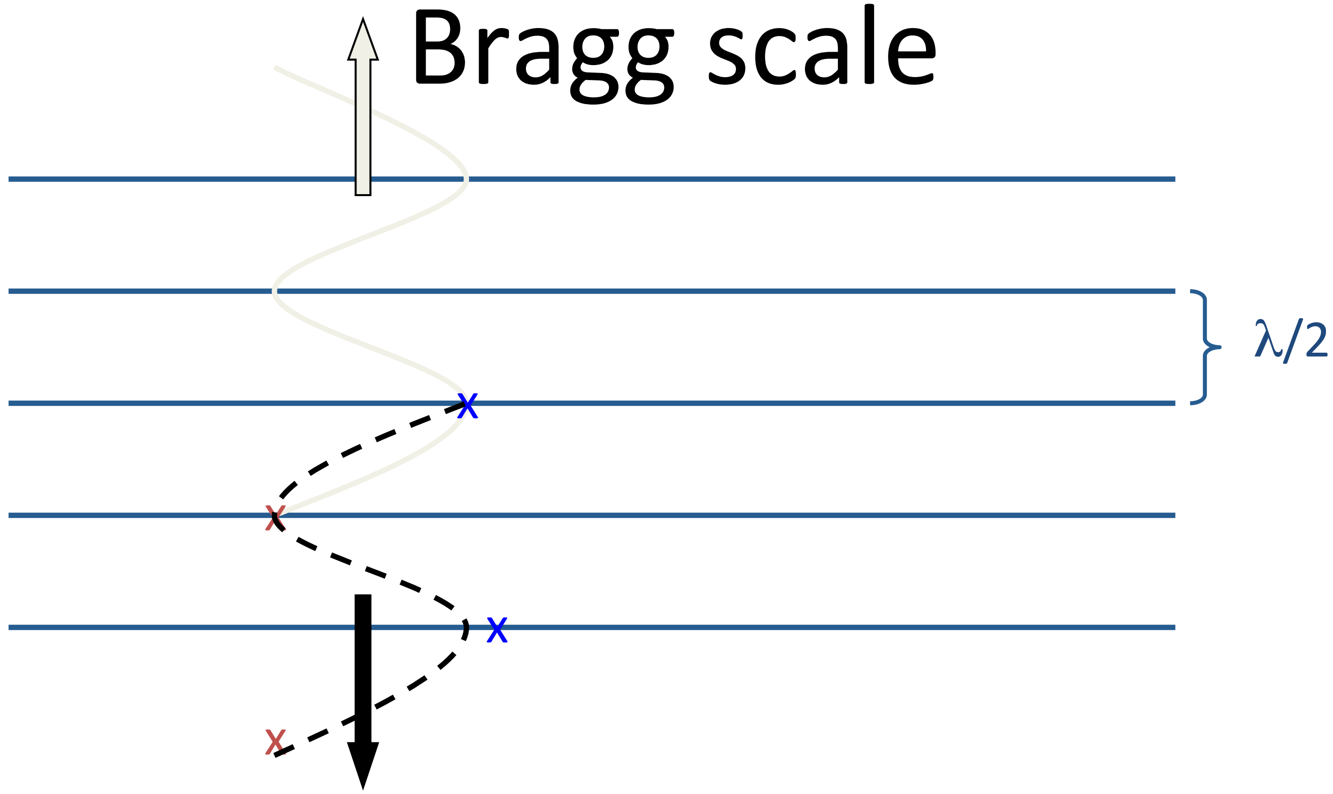
Bragg scale



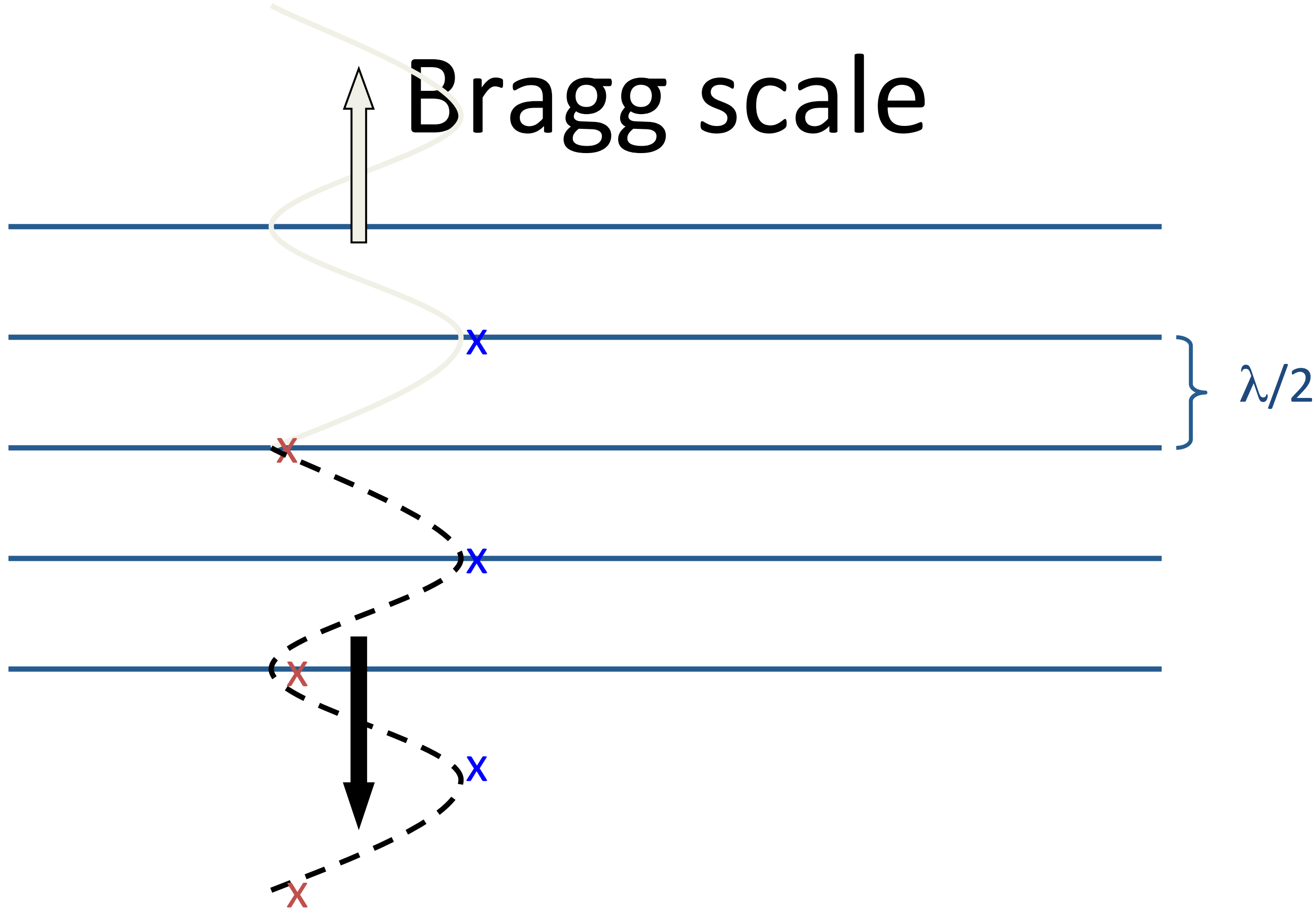
Bragg scale



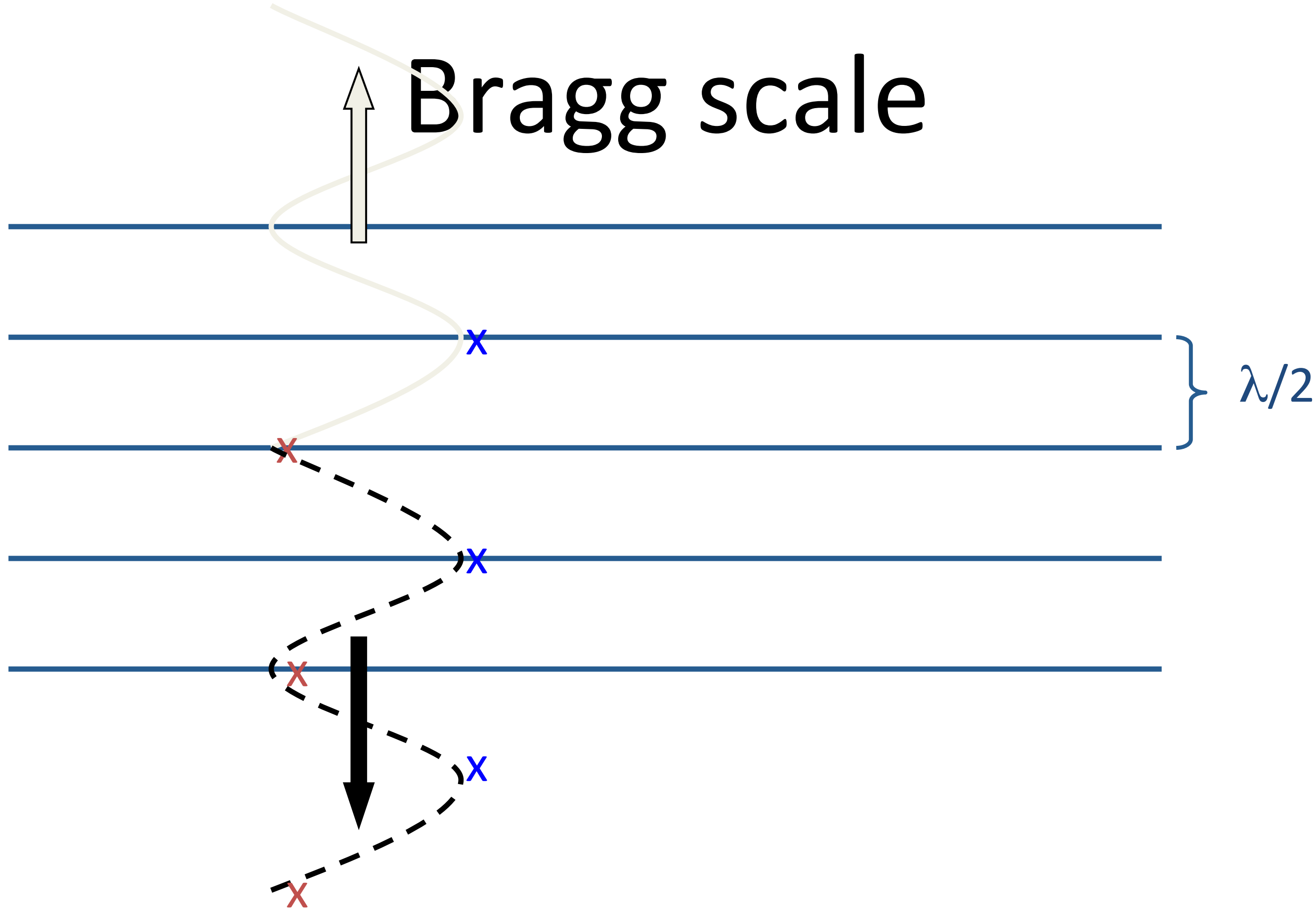
Bragg scale



Bragg scale



Bragg scale



The Bragg condition for backscatter means that a radar can only observe structures in the refractive index with size close to the half radar wavelength.