Introduction to Incoherent Scatter 1

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SRI International

Incoherent Scatter Radar

- Incoherent
- Scatter
- Radar

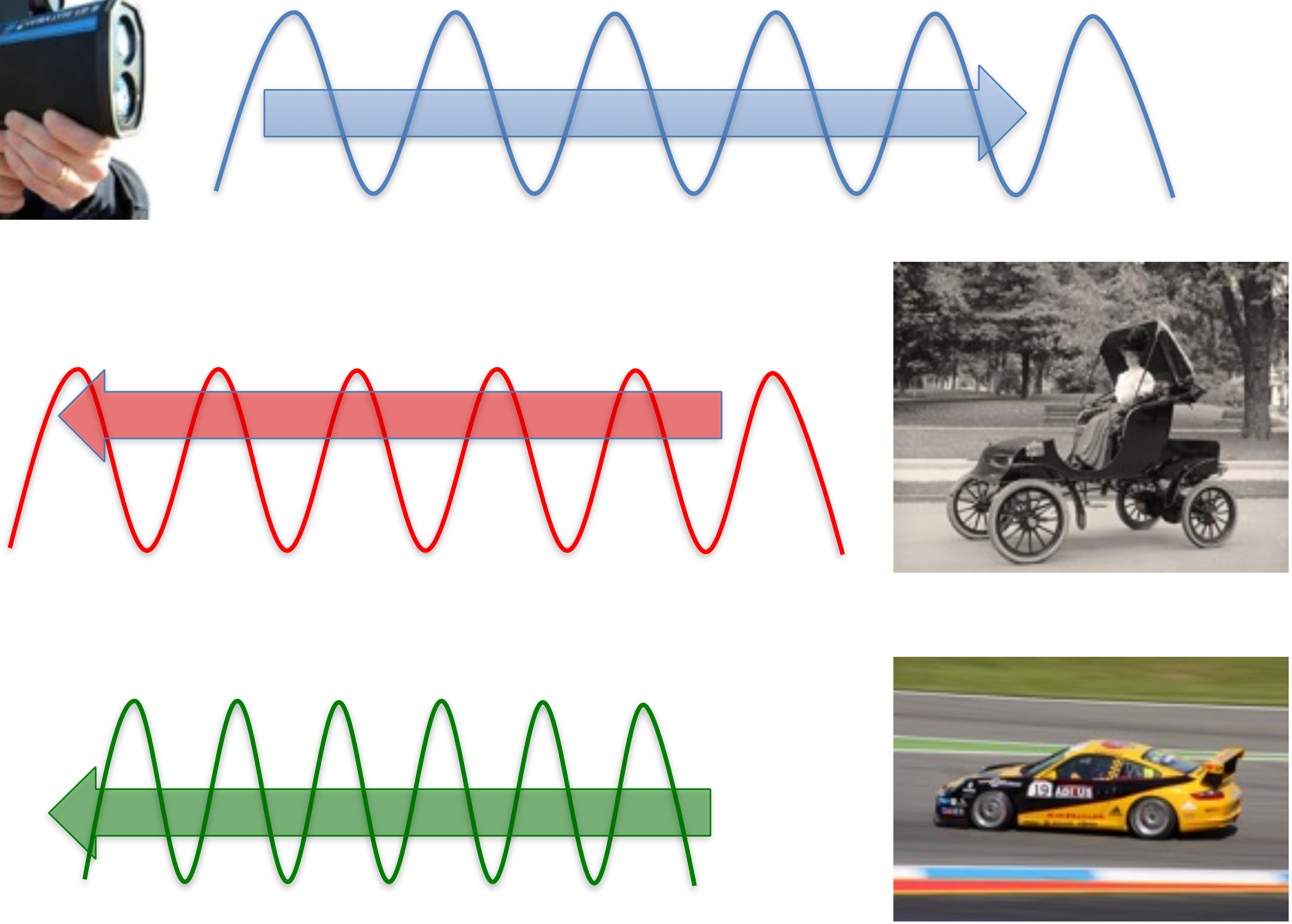
Incoherent Scatter Radar

- Radar
- Scatter
- Incoherent

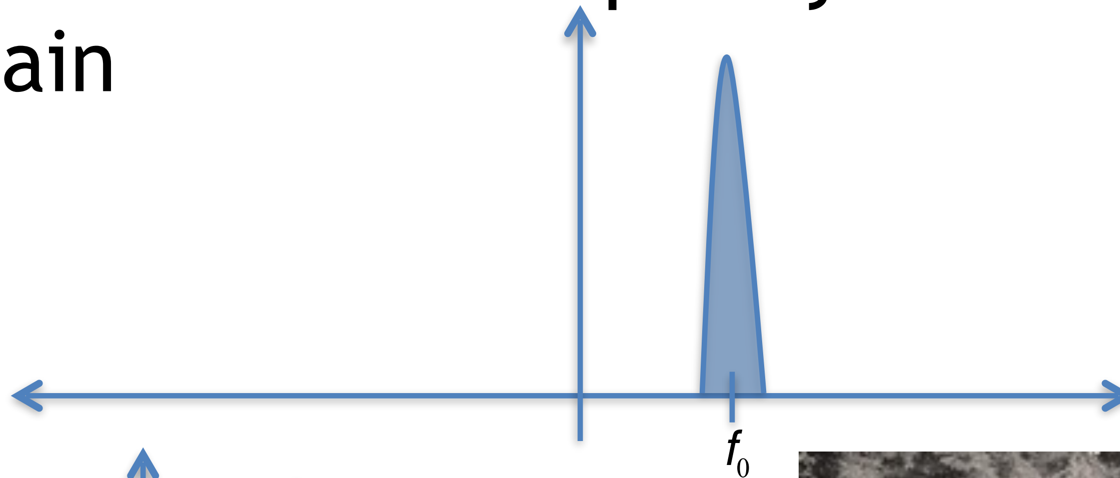
Radar

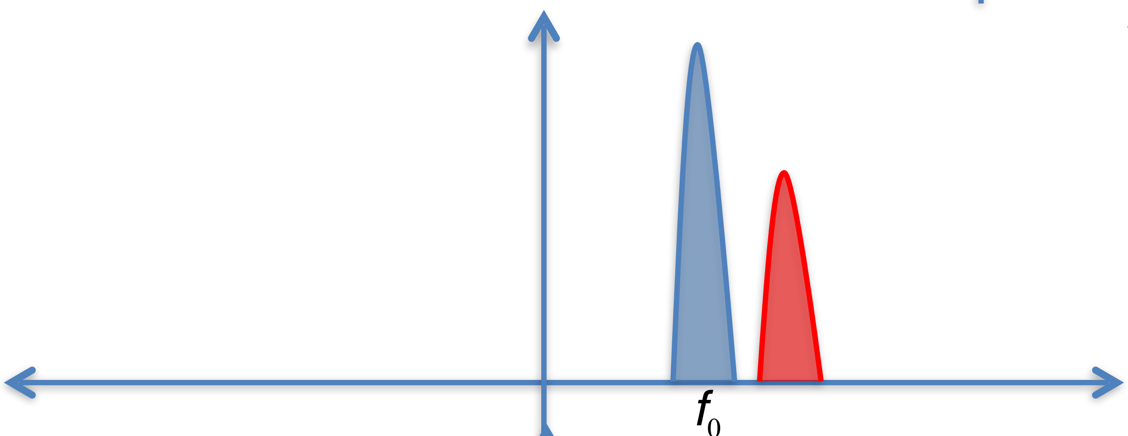
- RADAR (RAdio Detection And Ranging)
  - is a technique for detecting and studying remote targets by transmitting a radio wave in the direction of the target and observing the reflection of the wave.
  - **Radar** is an object detection system which uses radio waves to determine the range, altitude,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

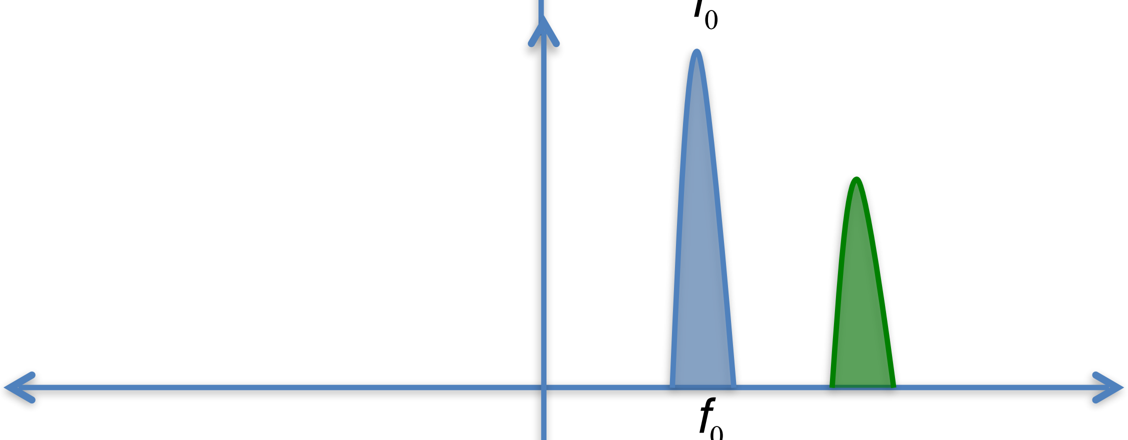
Doppler Radar – time domain

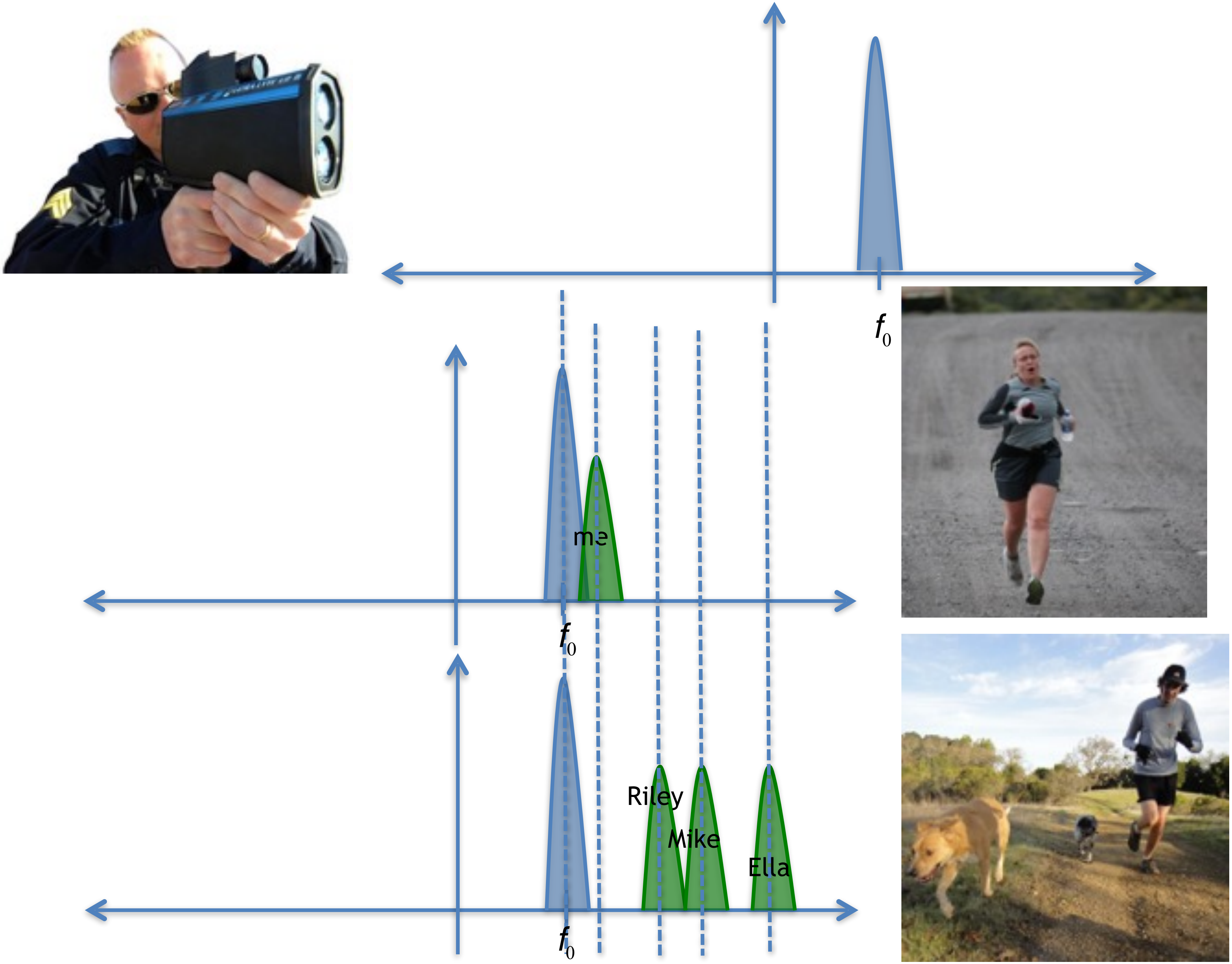


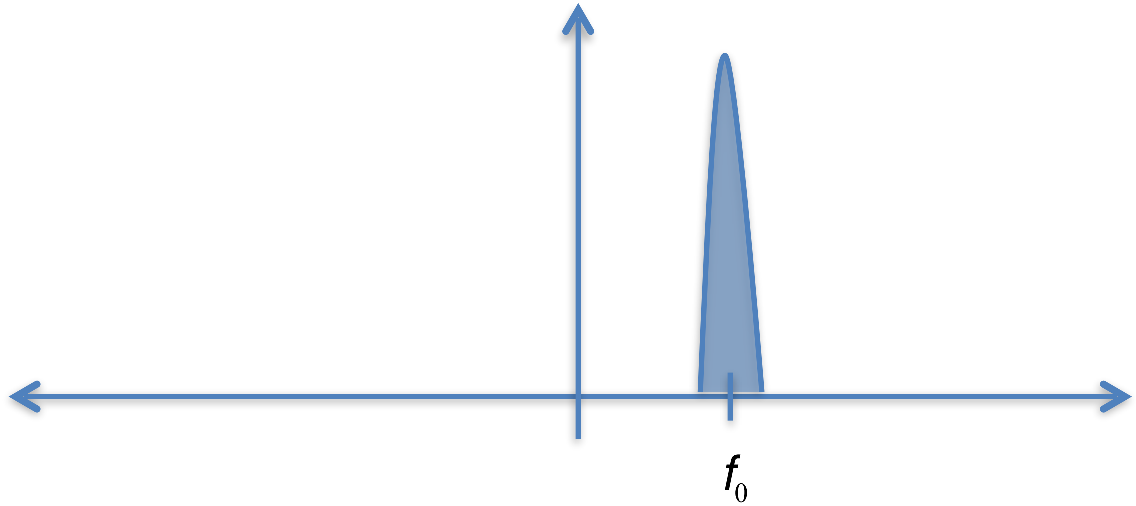
Doppler Radar – frequency domain

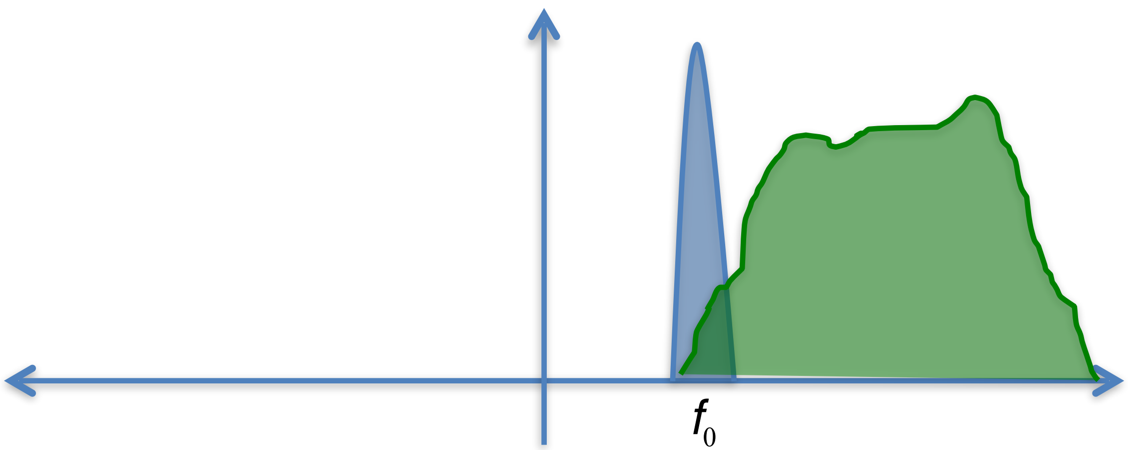







f_0
me
f_0
Riley
Mike
Ella
f_0


f_0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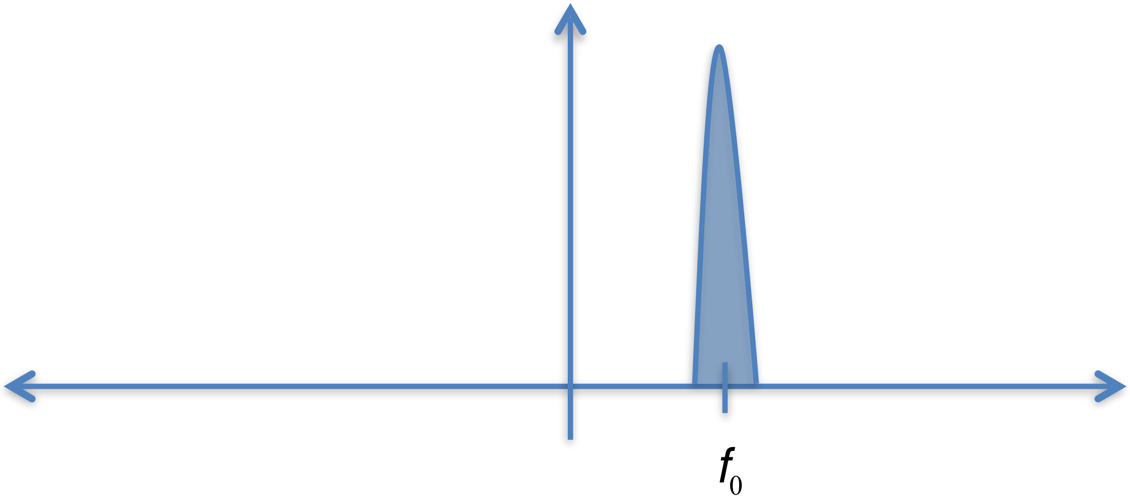
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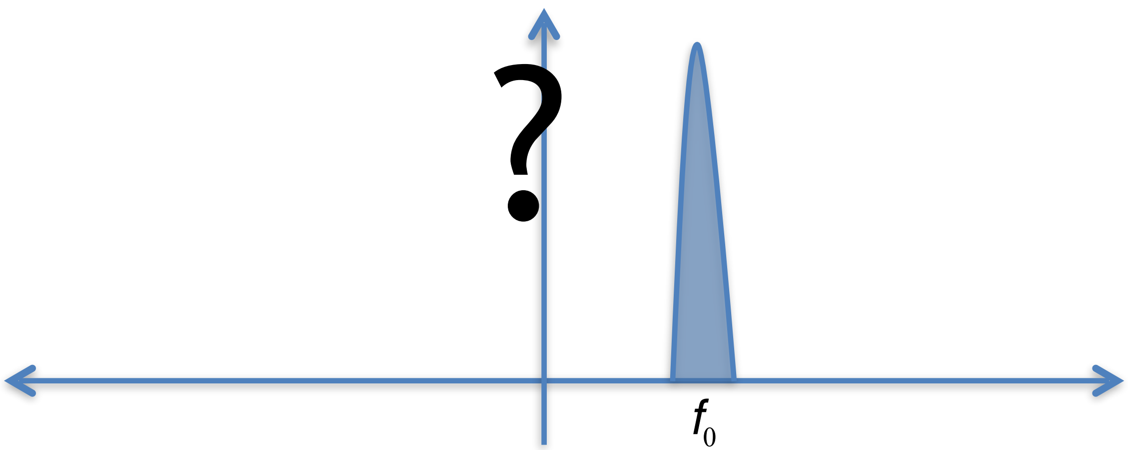
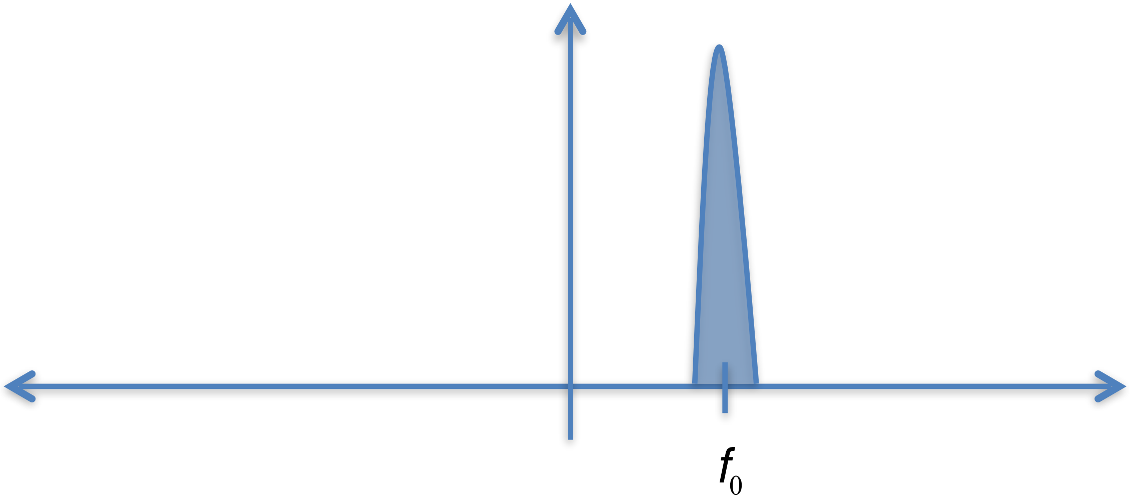

?
f_0


START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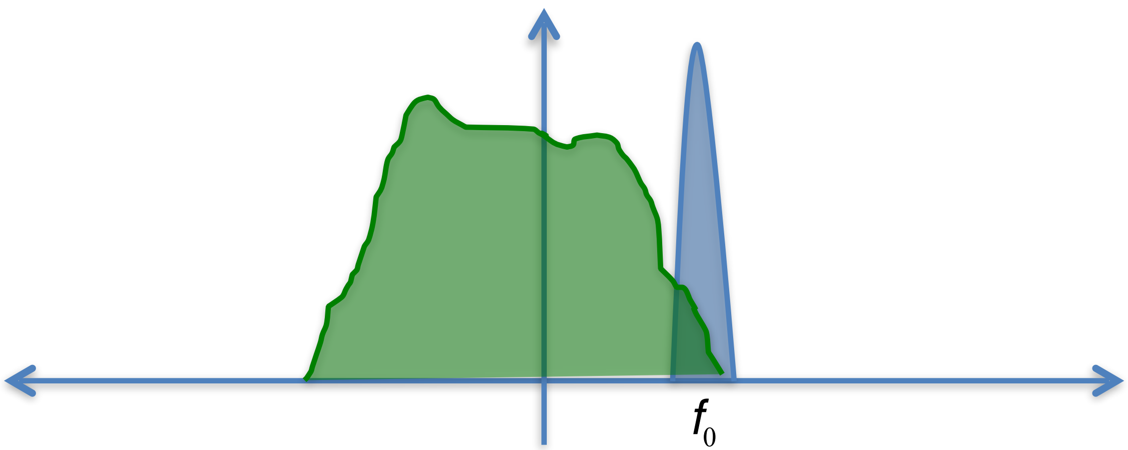

f_0

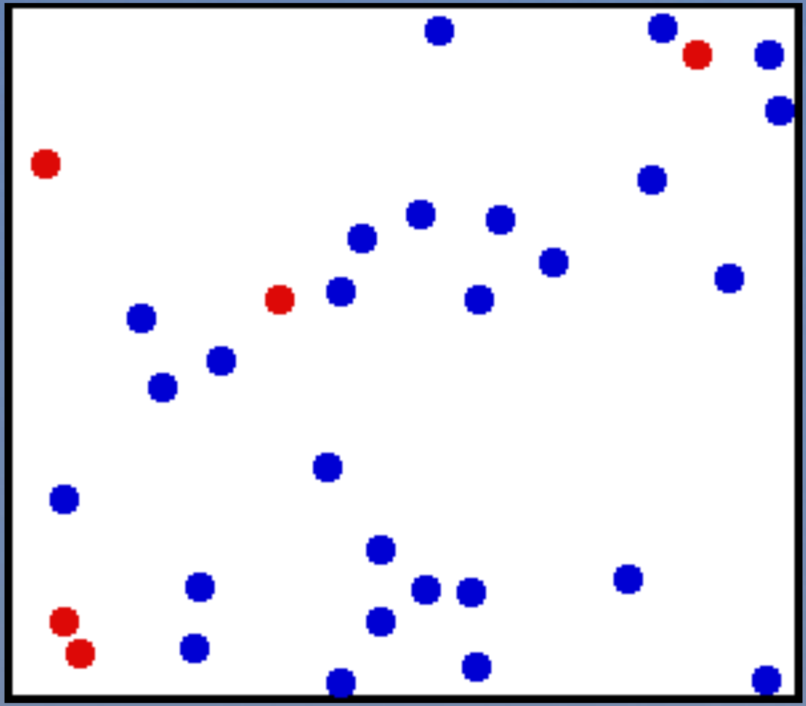
Thomson scattering

- 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**

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Incoherent scatter is neither incoherent nor incomprehensible

Radar Equations

Hard target:

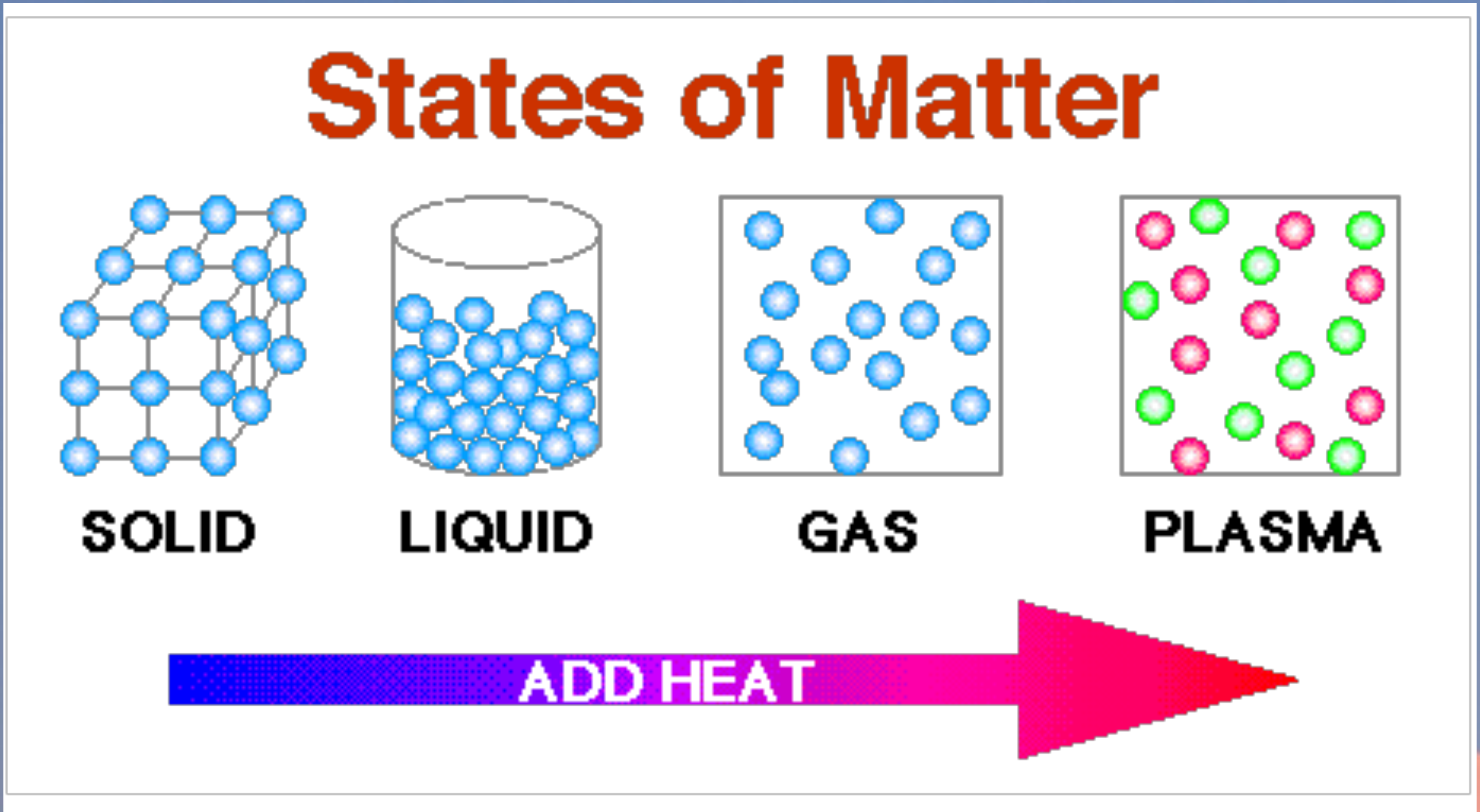
$$P_r = \frac{P_t G_t A_r \sigma}{(4\pi)^2 R^4}$$

Incoherent Scatter Radar

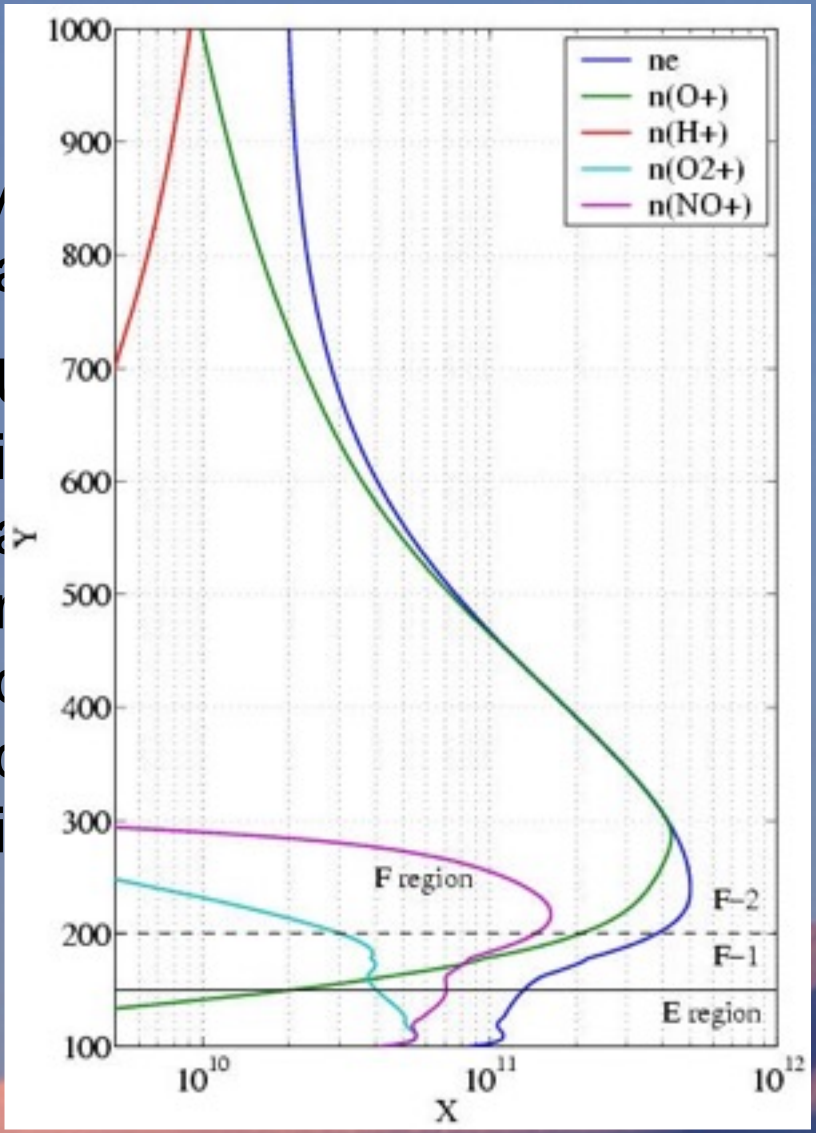
$$P_r = \frac{C c_0 G \lambda^2}{2(4\pi)^2} \frac{P_t \tau_p}{R^2} \frac{\sigma_e n_e(R)}{(1+k^2\lambda_D^2)(1+k^2\lambda_D^2+T_r)}$$

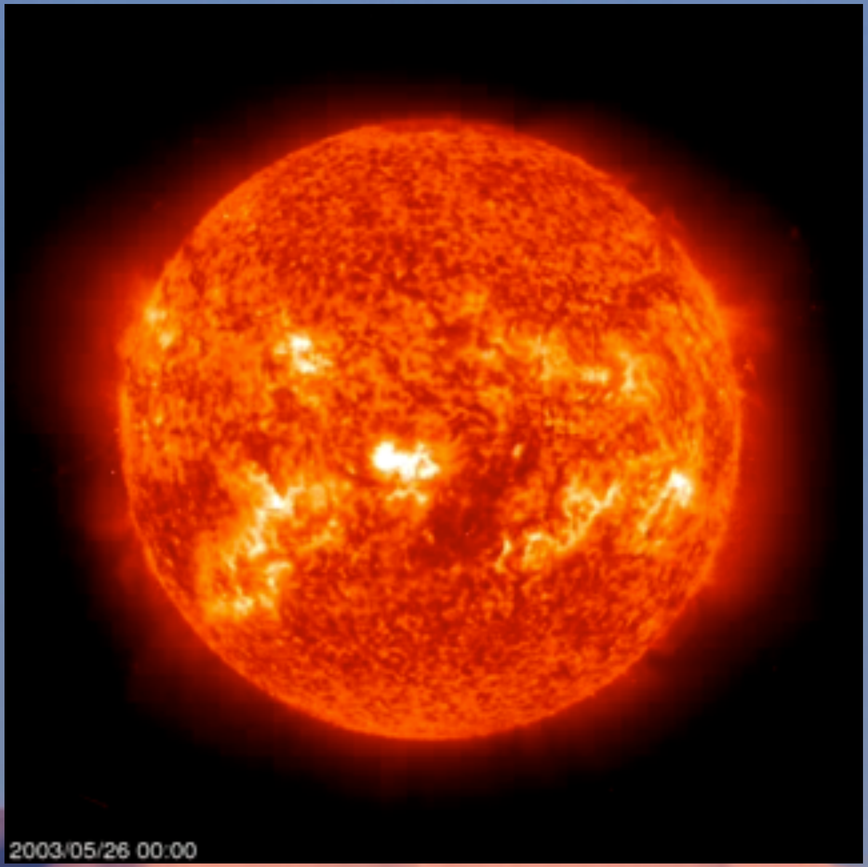
The ionospheric plasma

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

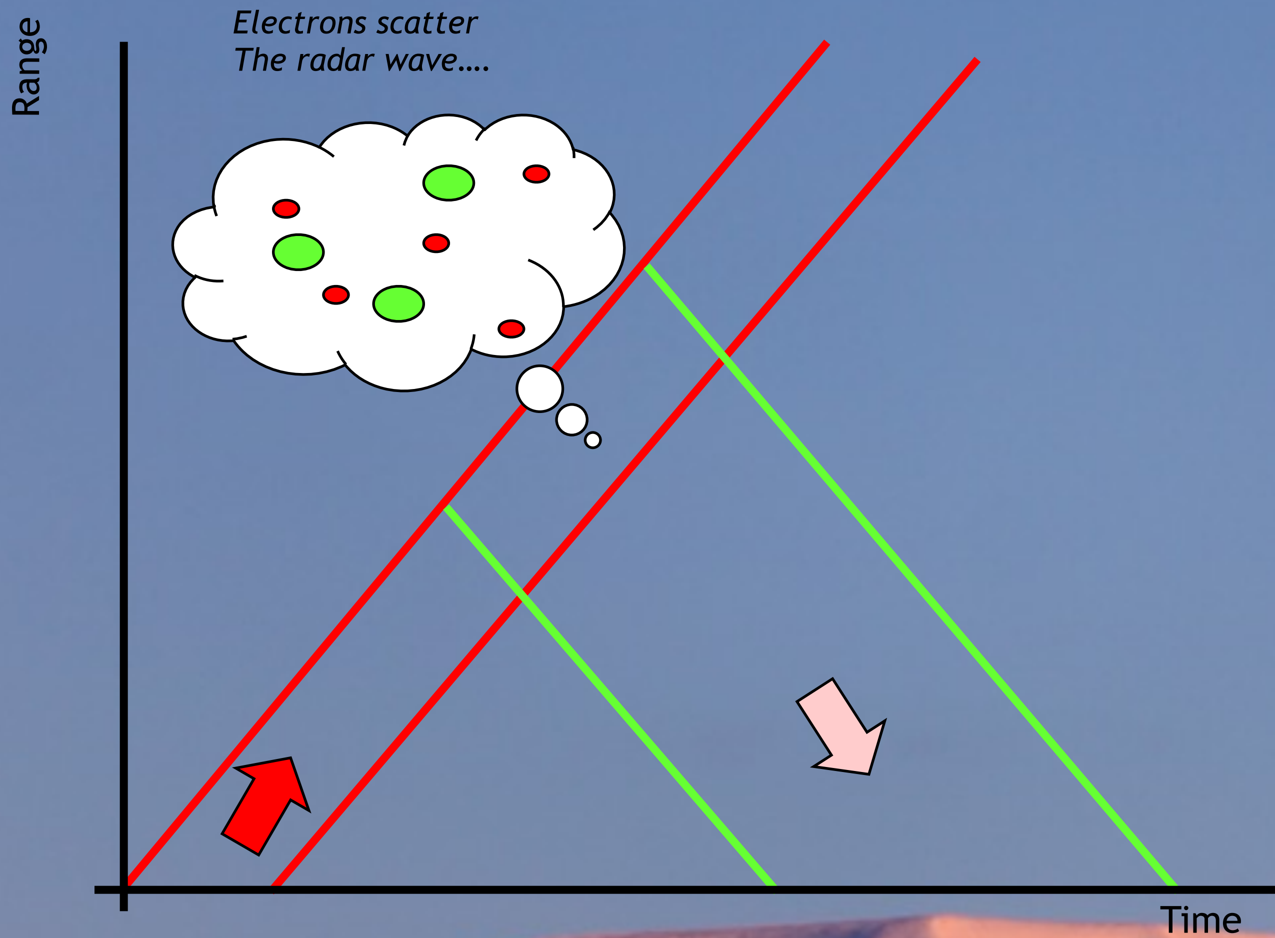

States of Matter
SOLID
LIQUID
GAS
PLASMA
ADD HEAT

The Earth's Ionosphere





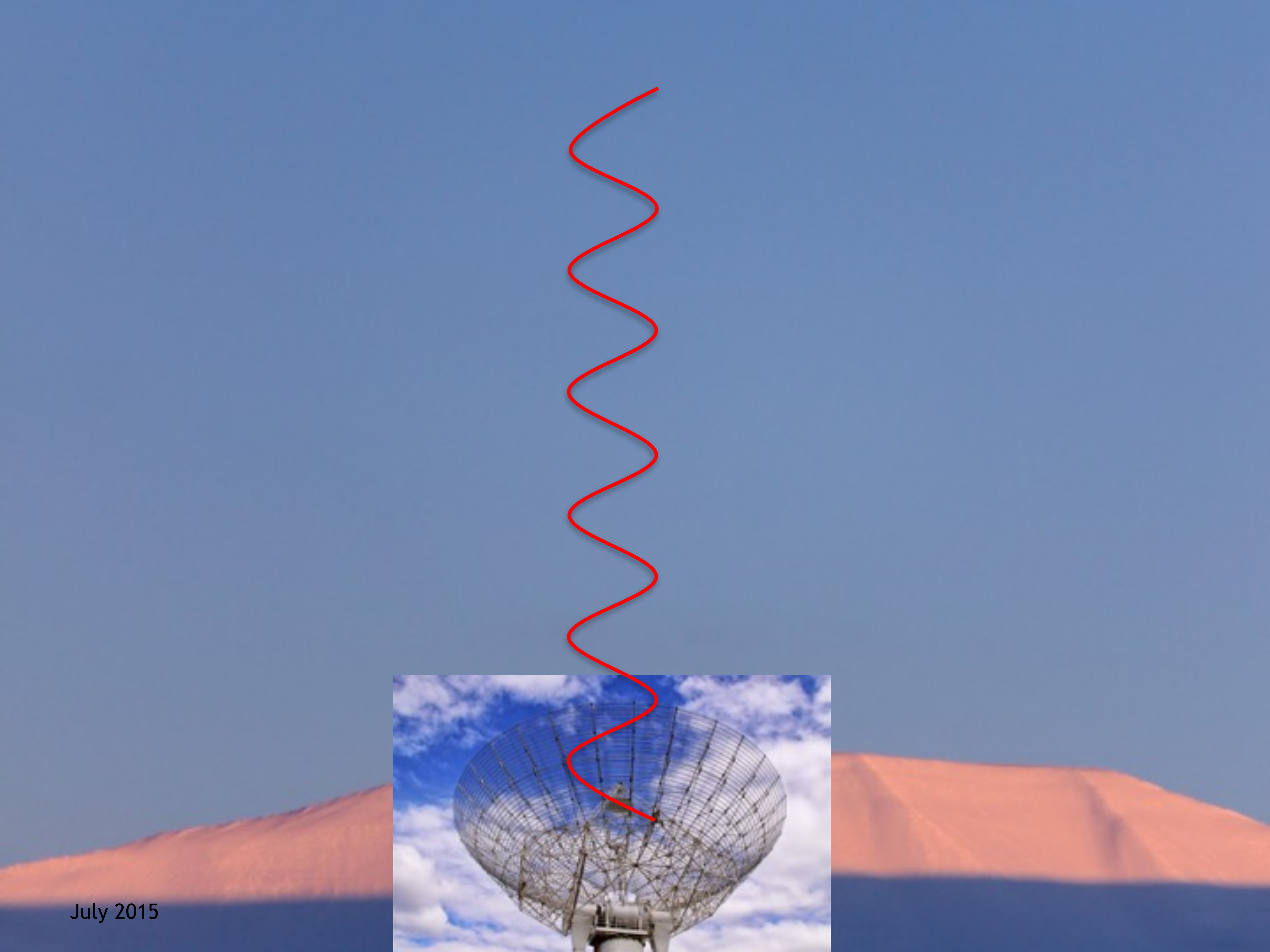
How ISRs work...

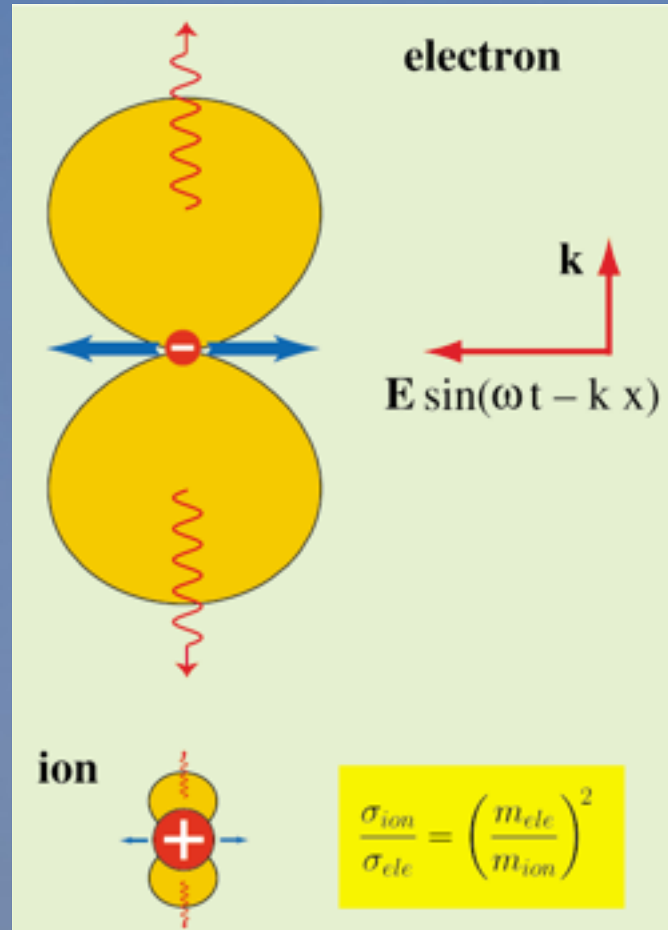


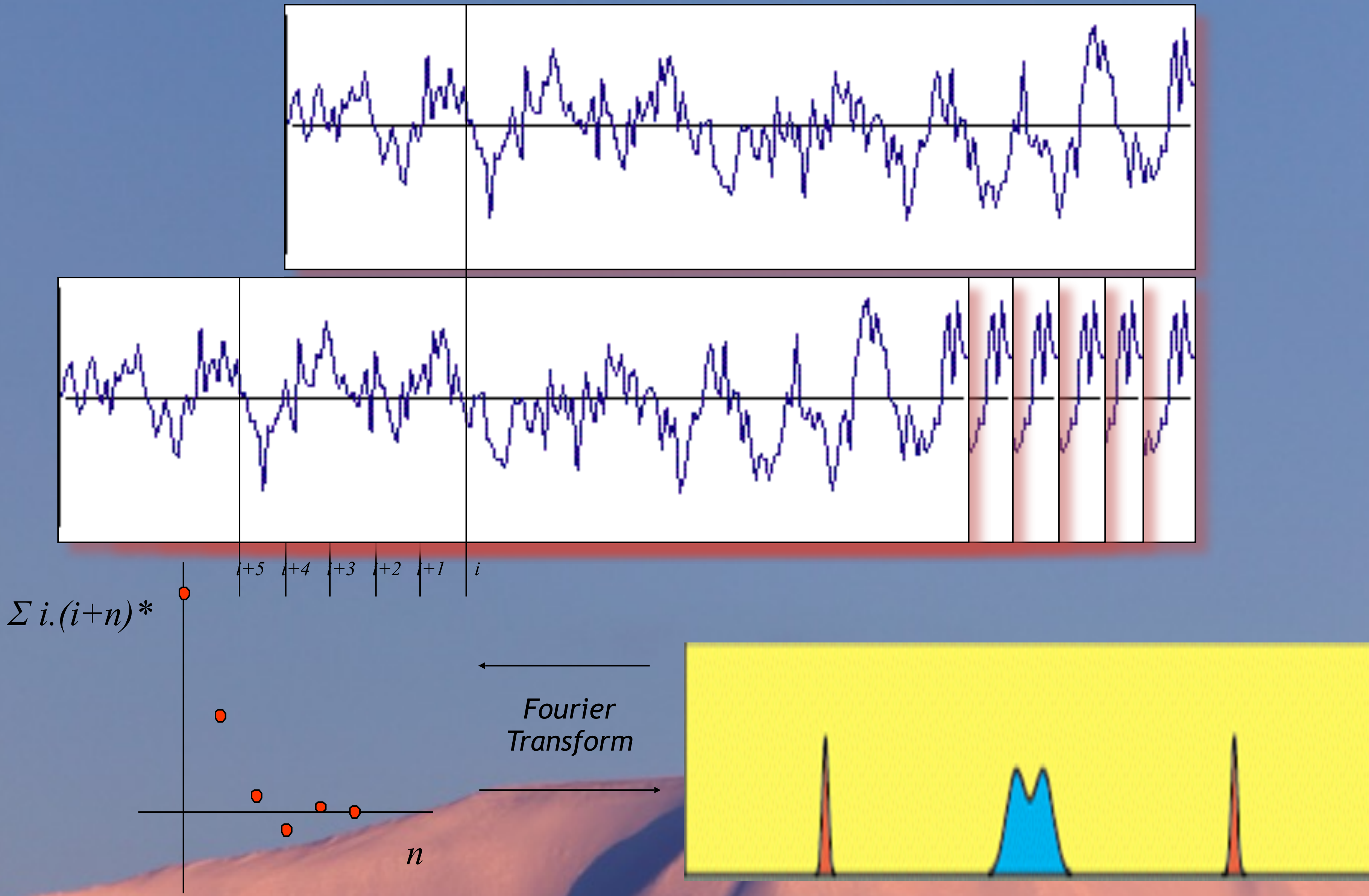
High power transmitter

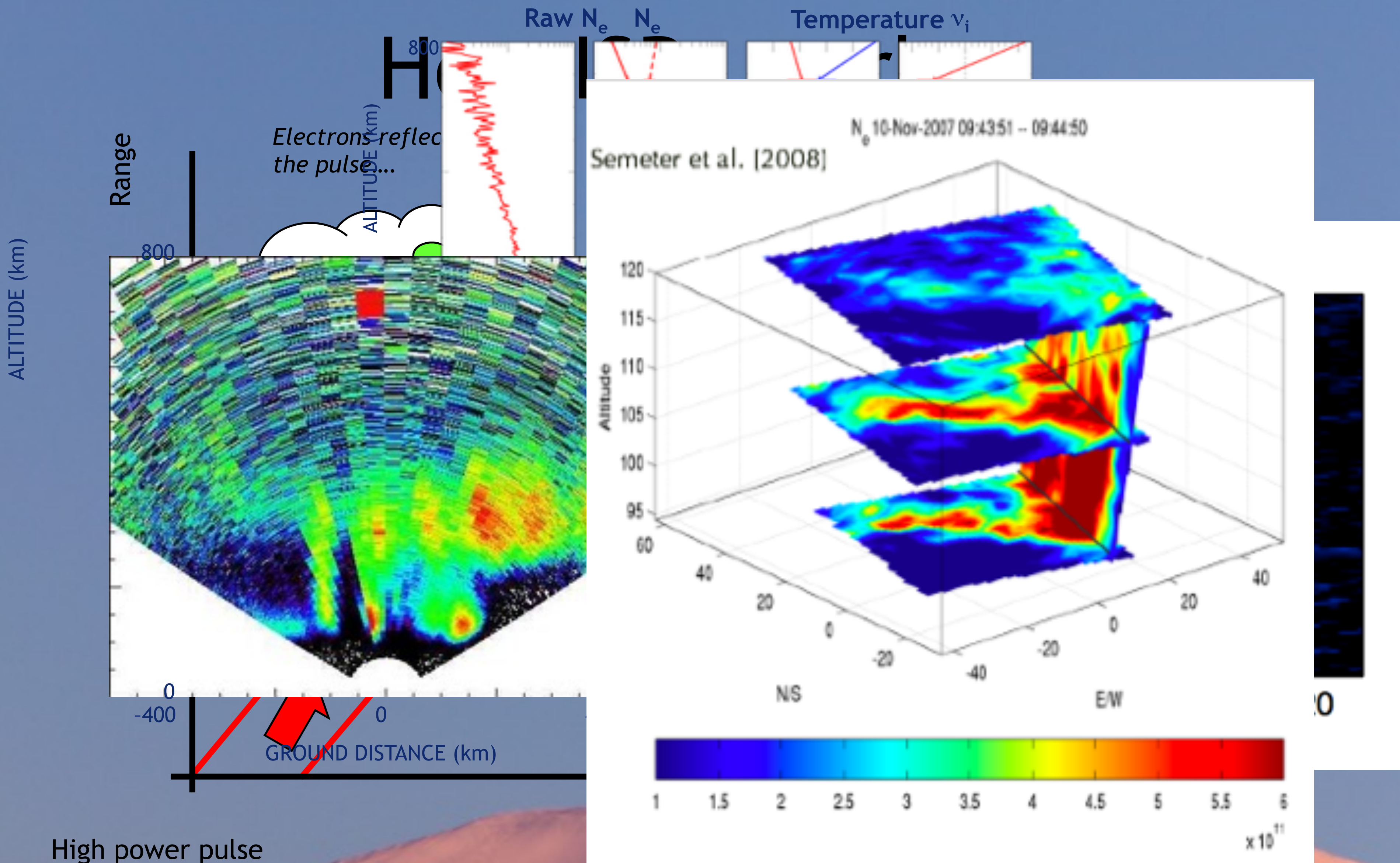
Very sensitive receiver

Only ~0.000000000000000001% of the transmitted power is returned!




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

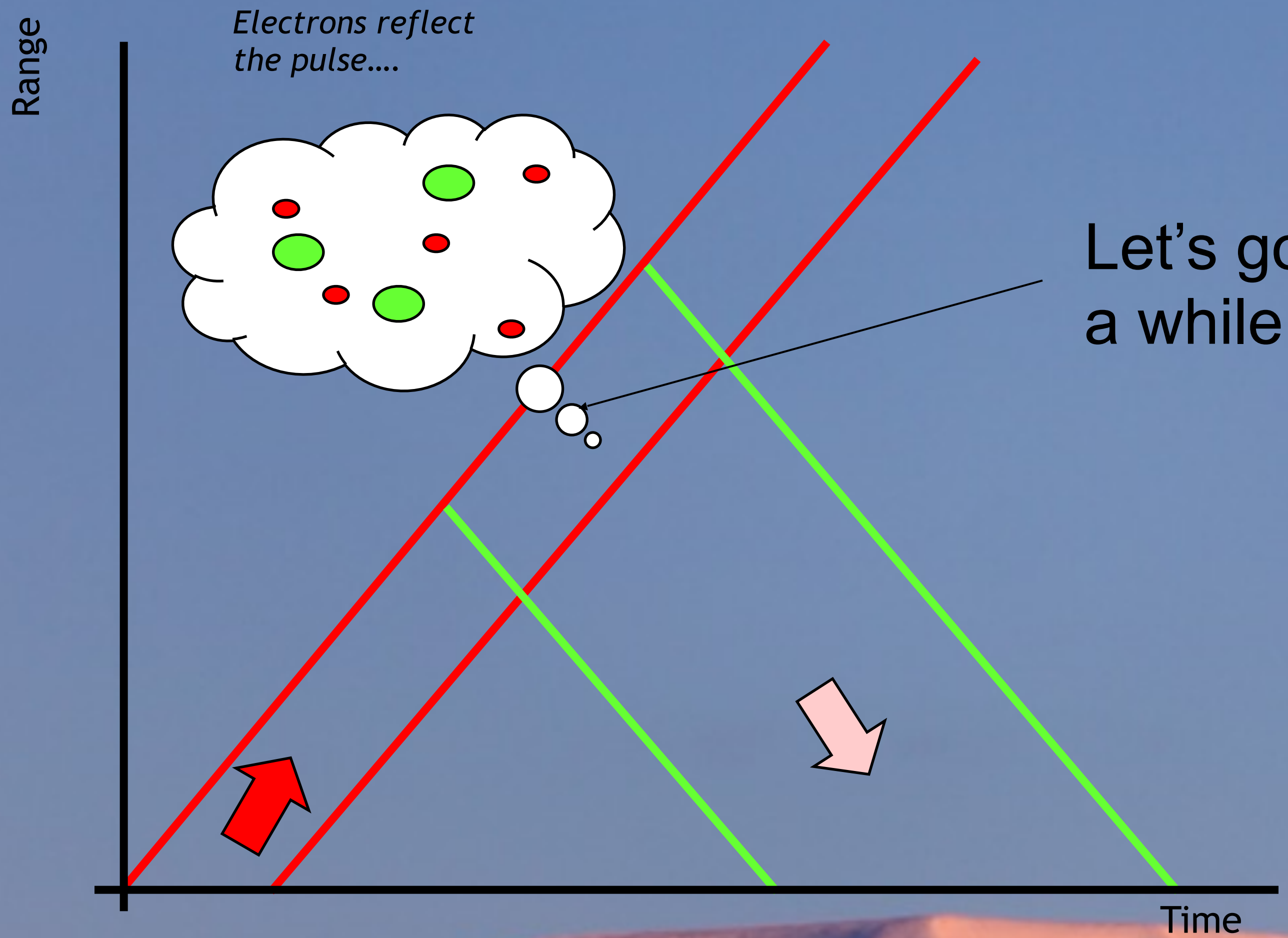

i+5
i+4
i+3
i+2
i+1
i
Σ i.(i+n)*
n
Fourier
Transform



High power pulse

Only ~0.000000000000000001% of the transmitted power is returned!

How ISRs work…



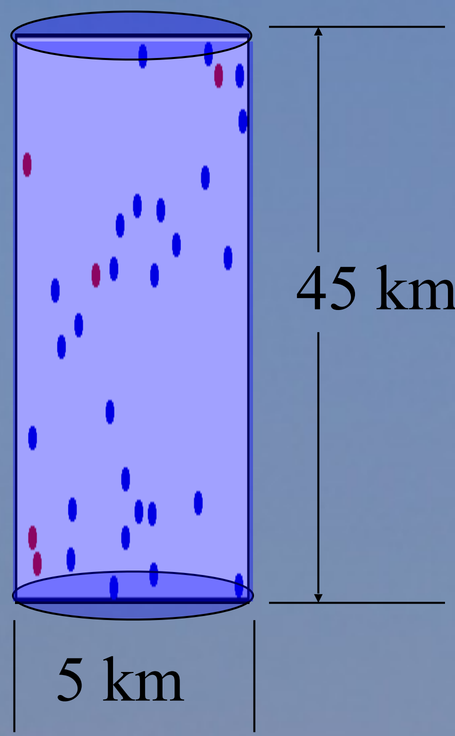
Let's go back here for a while…

High power pulse

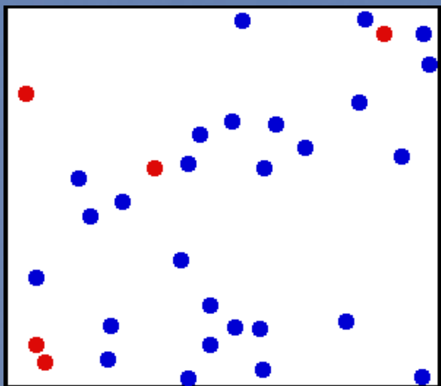
Very sensitive receiver

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!



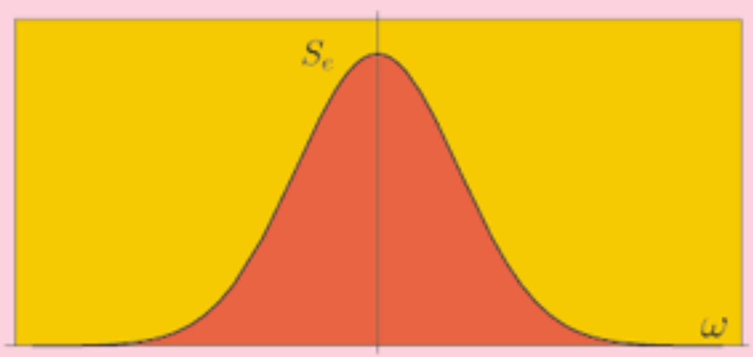
For TRUE incoherent scatter…



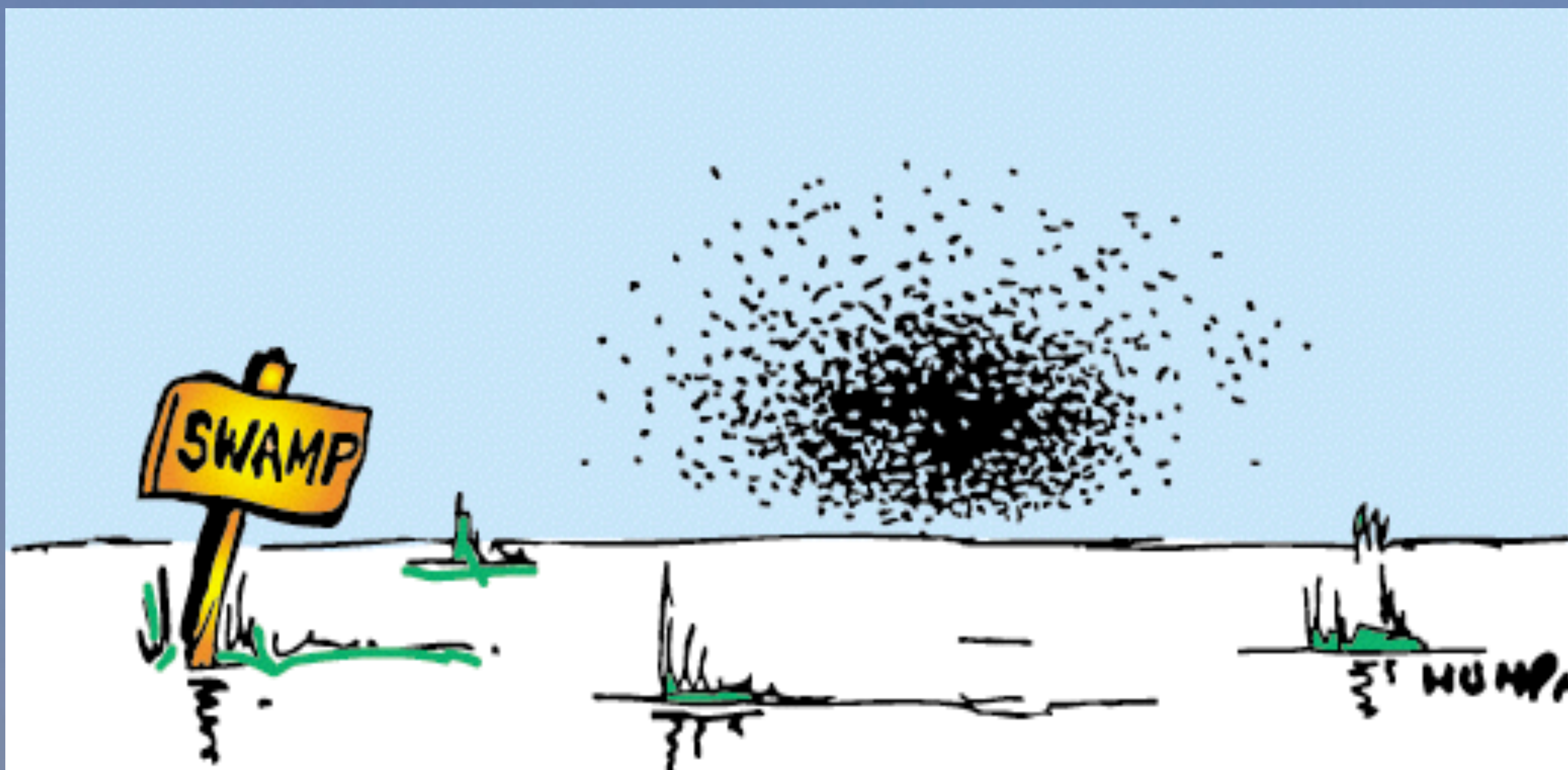
no collective interactions

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

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



Incoherent scattering - the short story



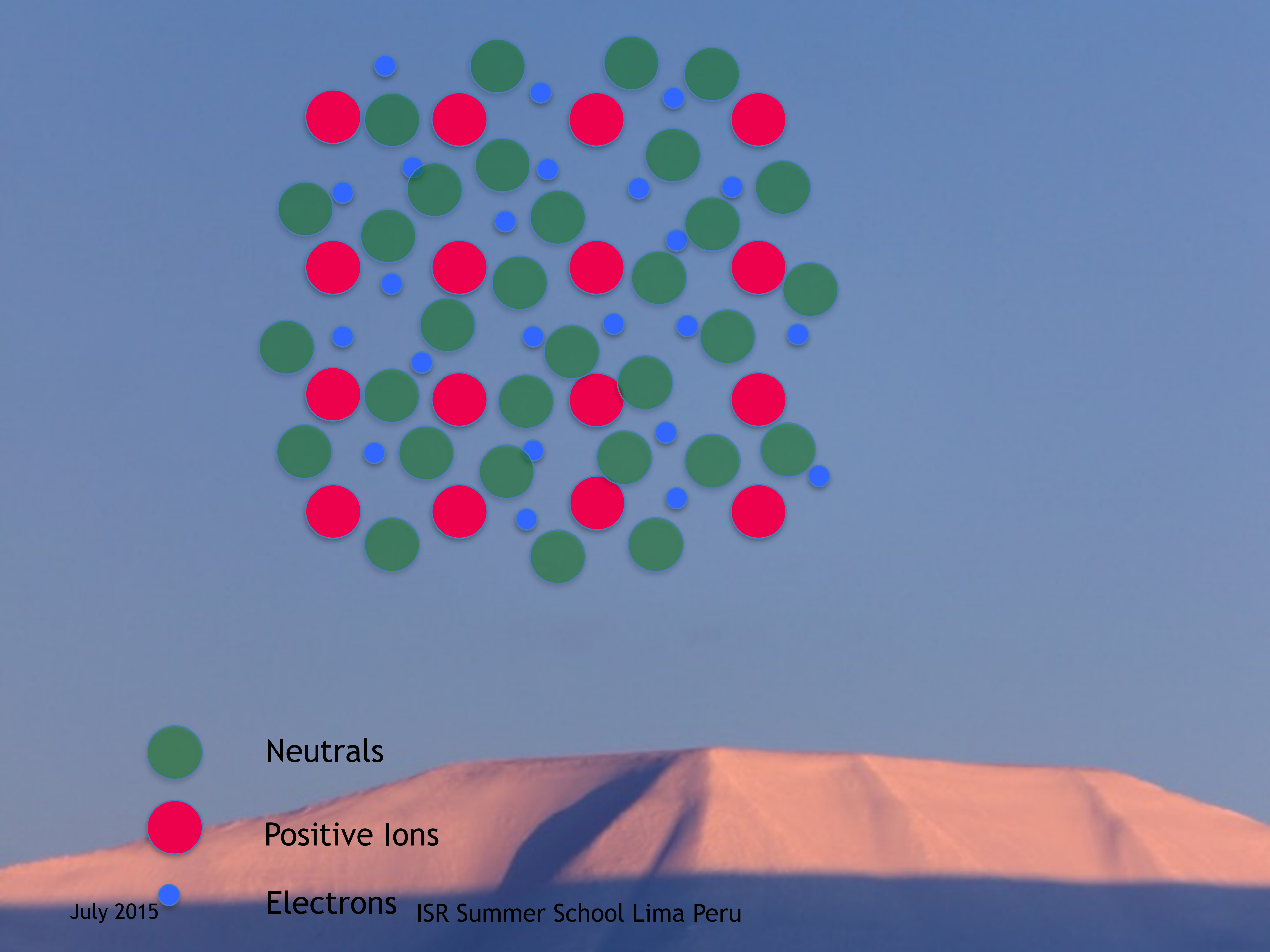
Incoherent scattering - the short story

- We only see scattering from the electrons

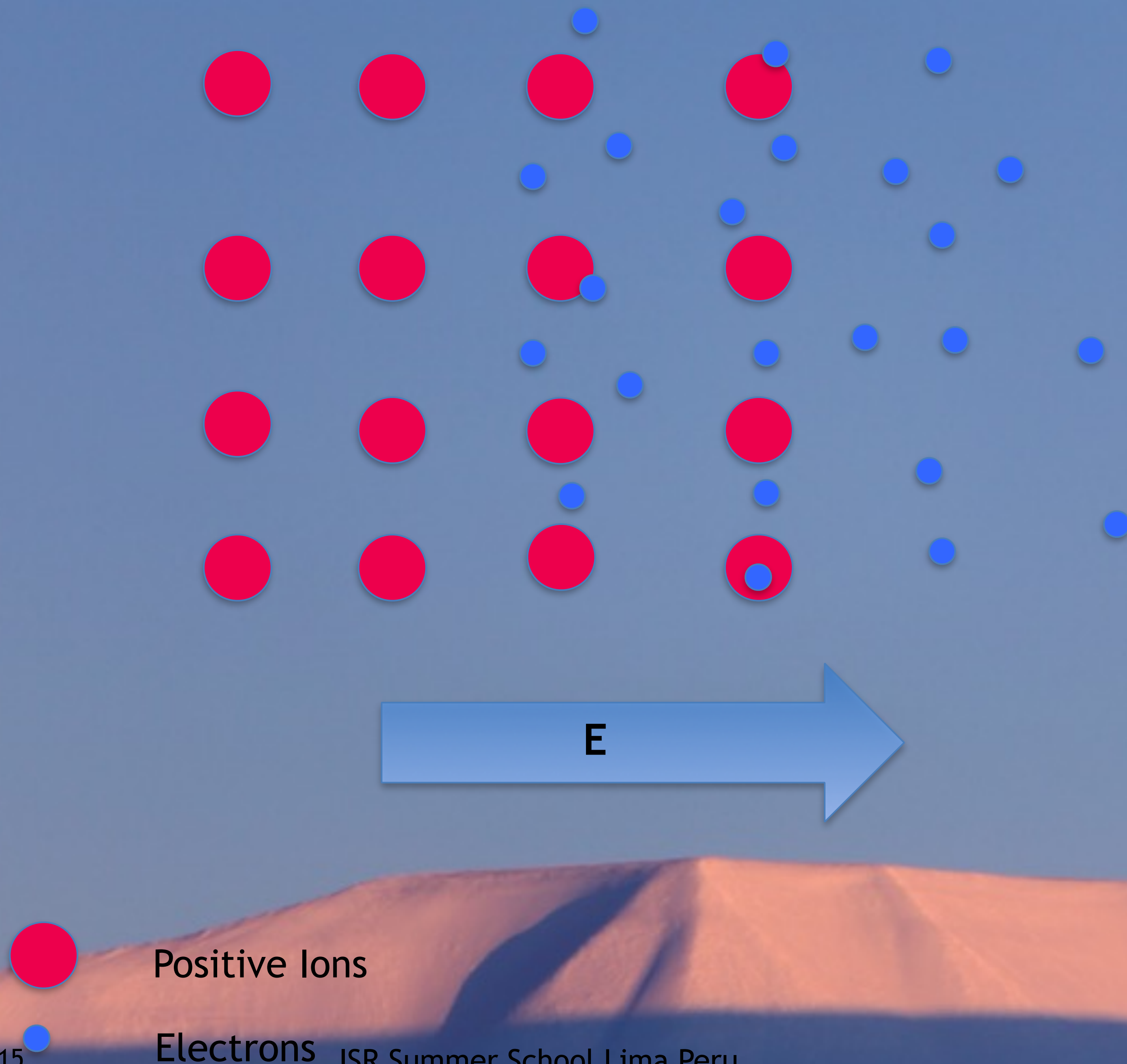
  …but they also tell the story about the ion dynamics…

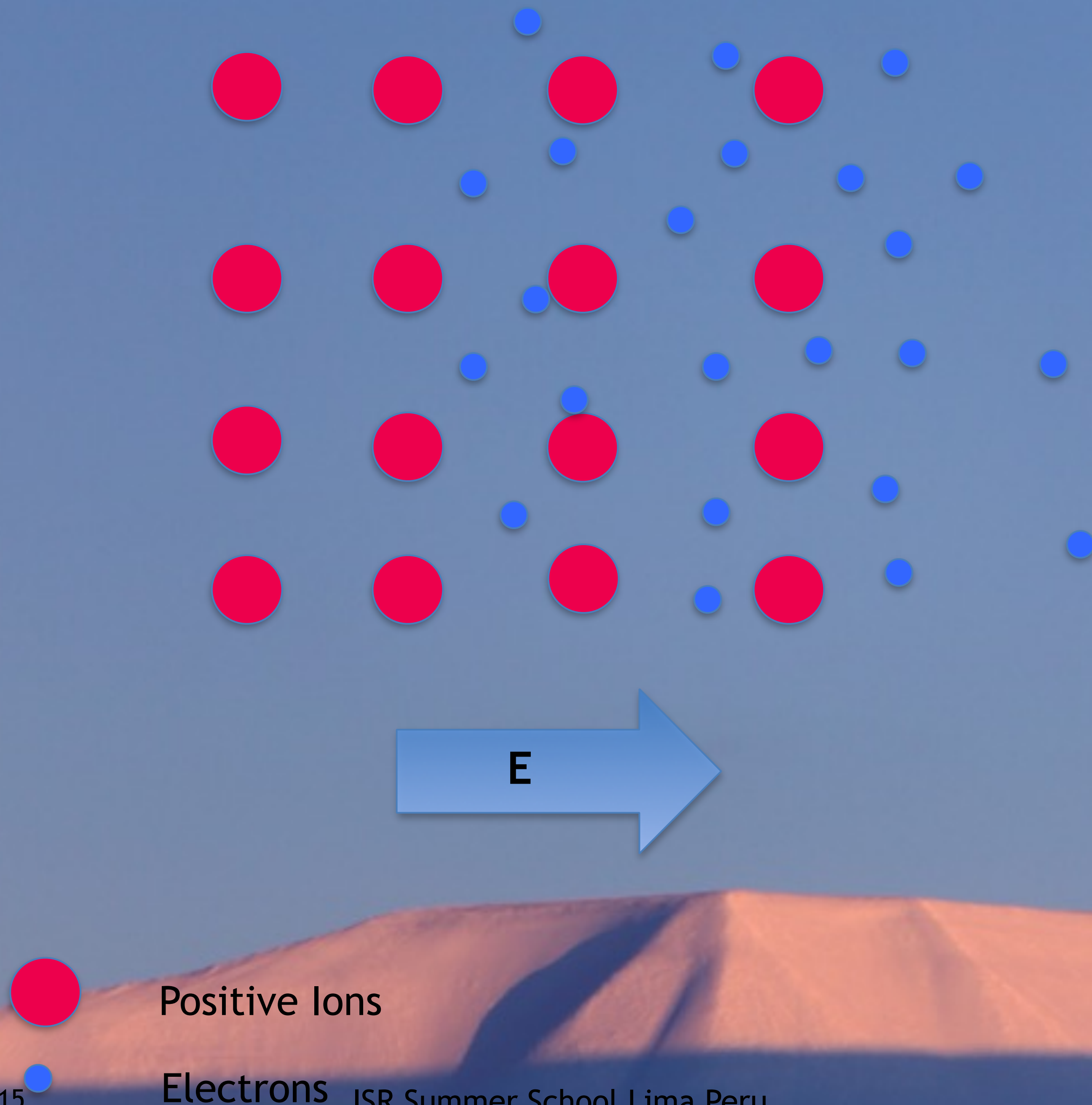
Collective behavior…

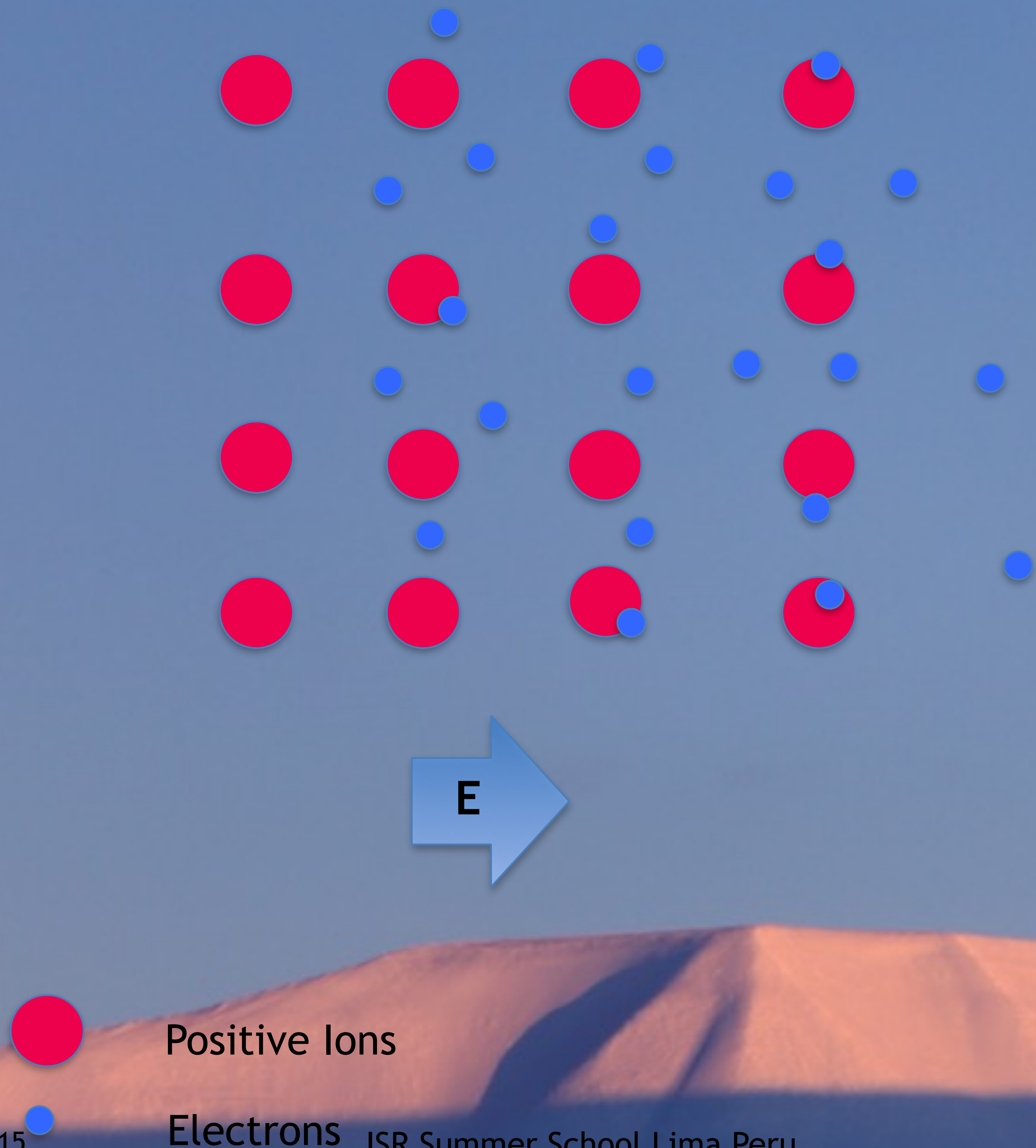
- There are a number of wave modes existing inherently in the ionospheric plasma…


Neutrals
Positive Ions
Electrons

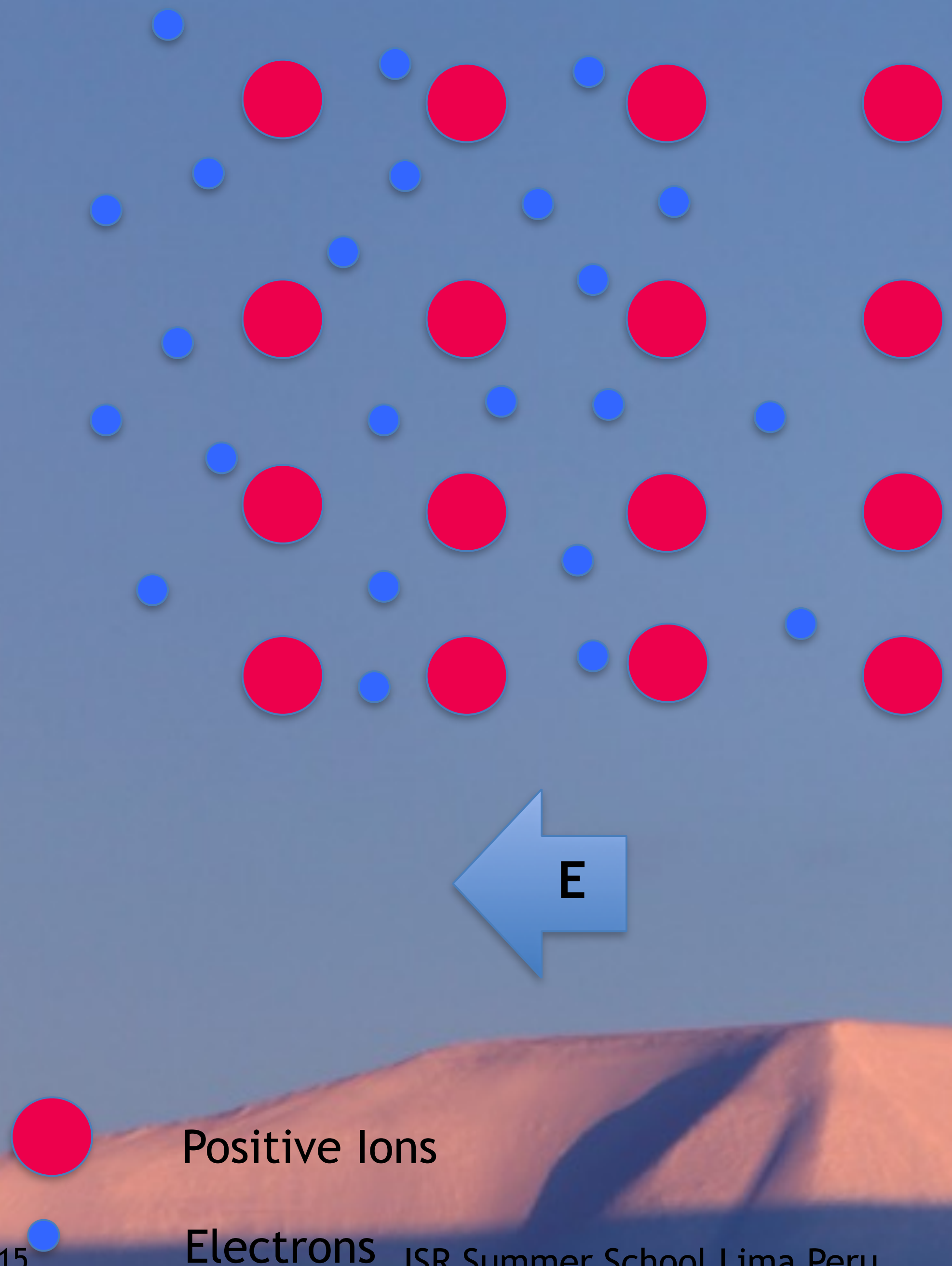

Positive Ions
Electrons

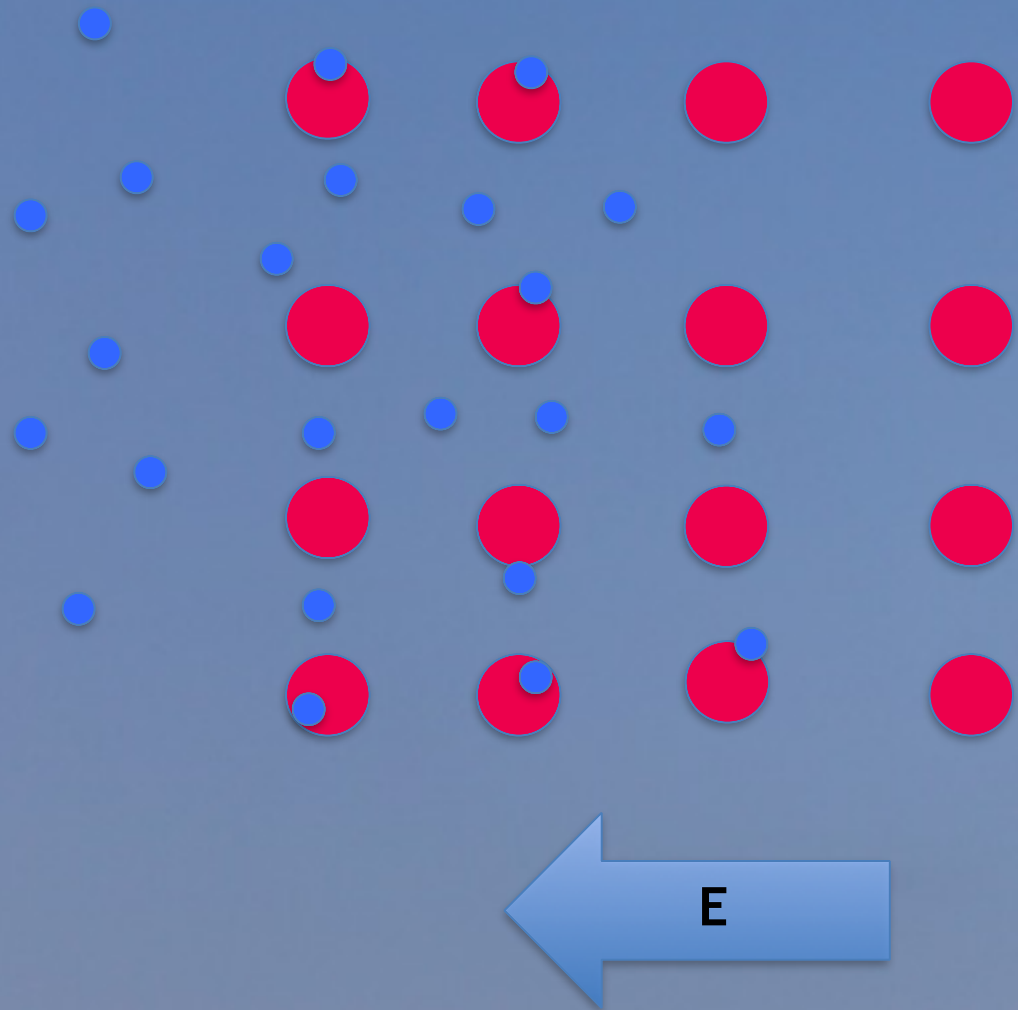

E
Positive Ions
Electrons


E
Positive Ions
Electrons


E
Positive Ions
Electrons

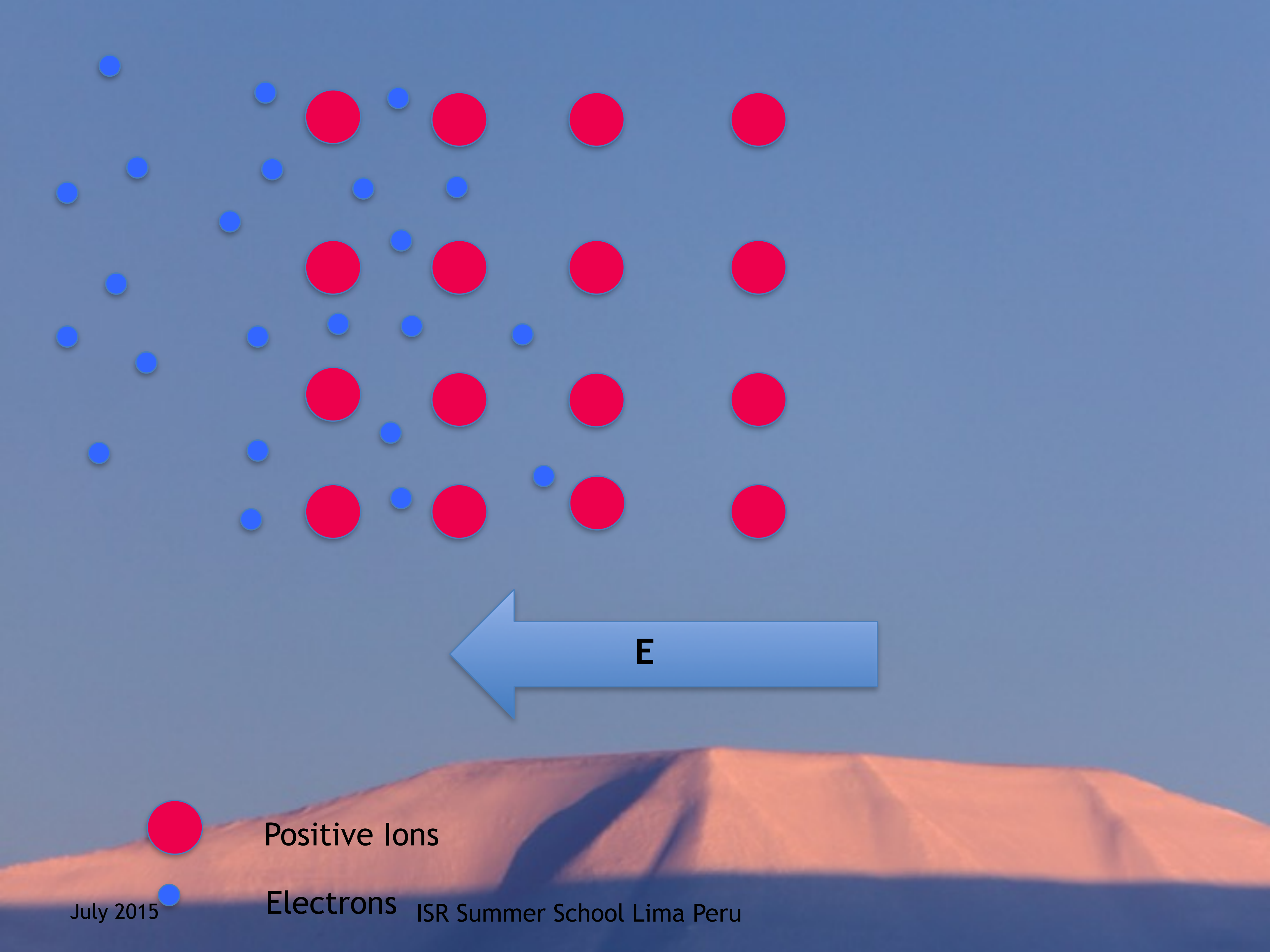

Positive Ions
Electrons

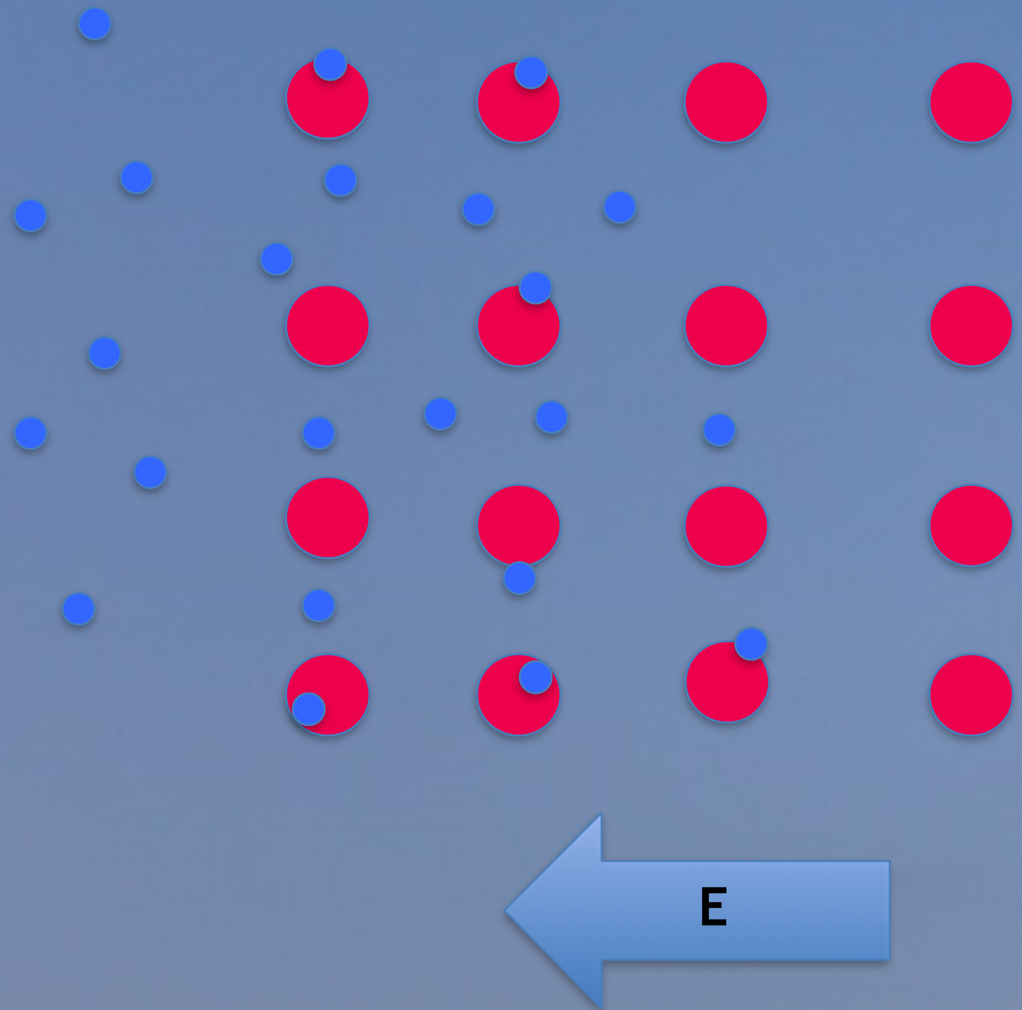

E
Positive Ions
Electrons



Positive Ions

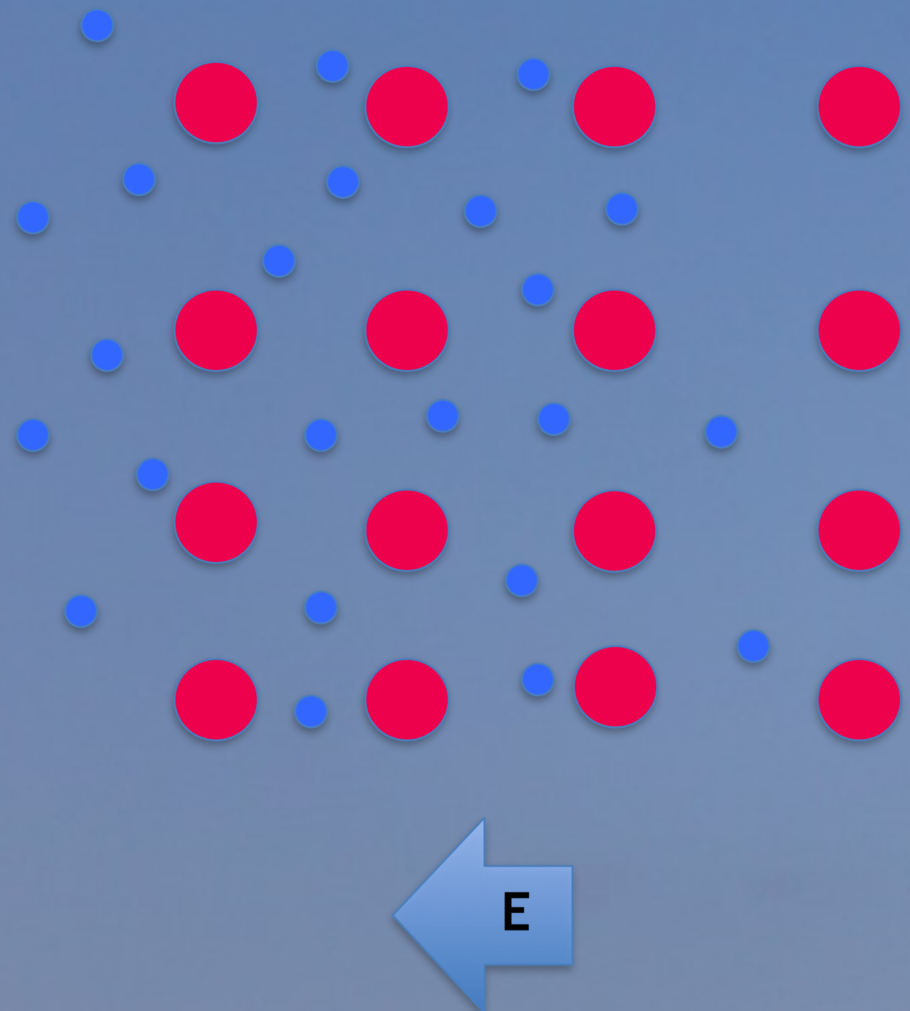
Electrons


E
Positive Ions
Electrons



Positive Ions

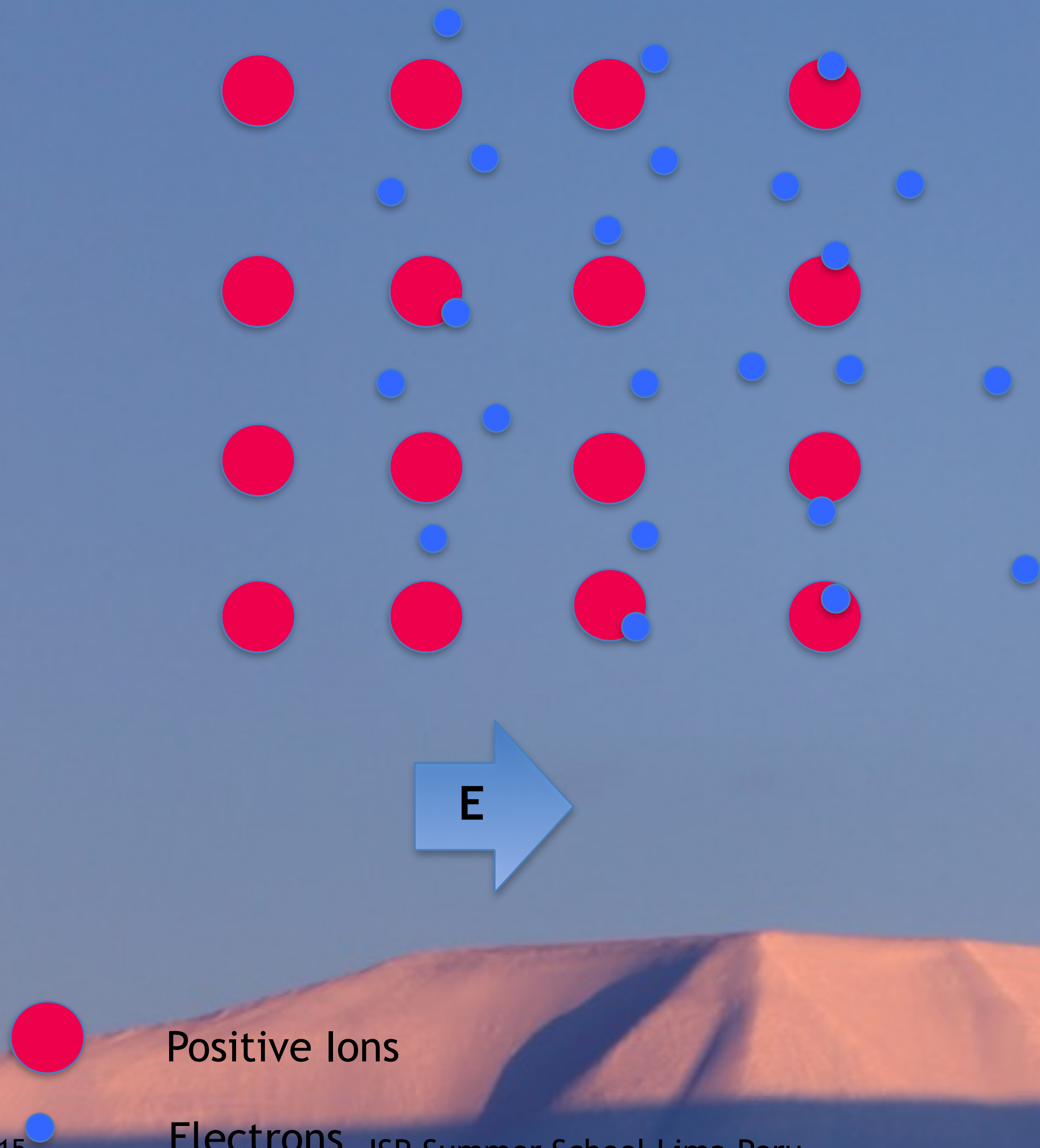
Electrons

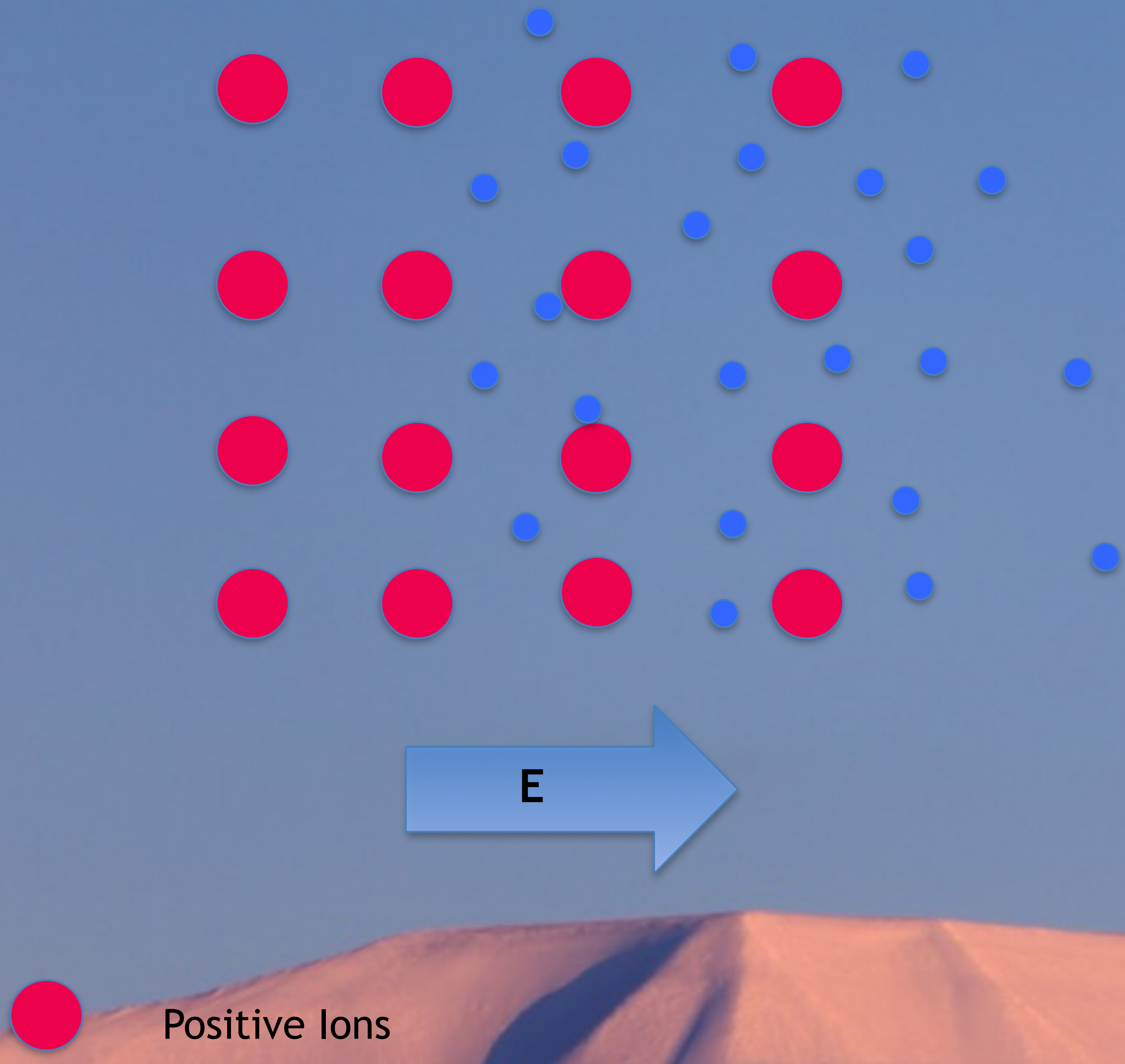


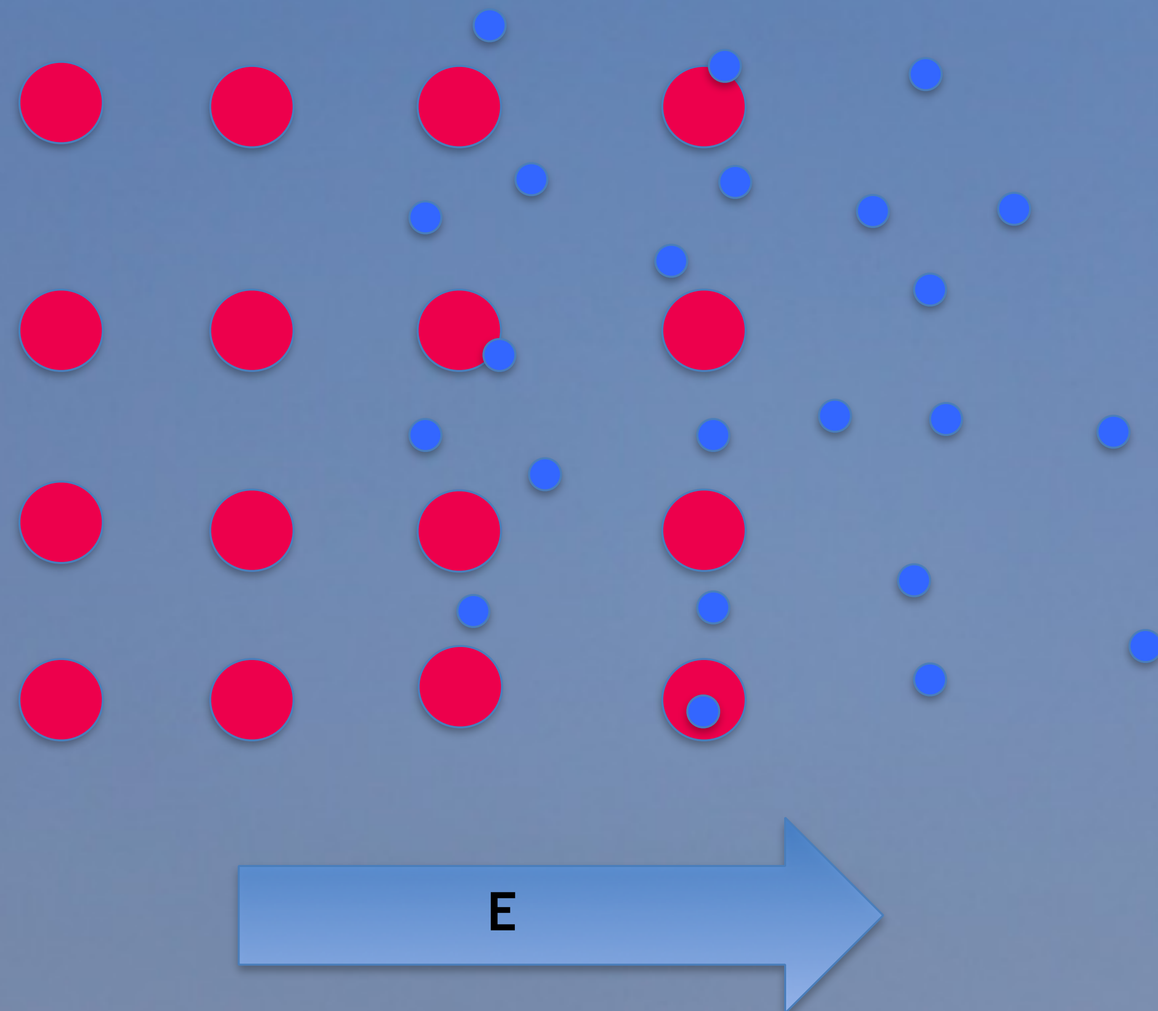
Positive Ions

Electrons


Positive Ions
Electrons


E
Positive Ions
Electrons


E
Positive Ions
Electrons



Positive Ions

Electrons

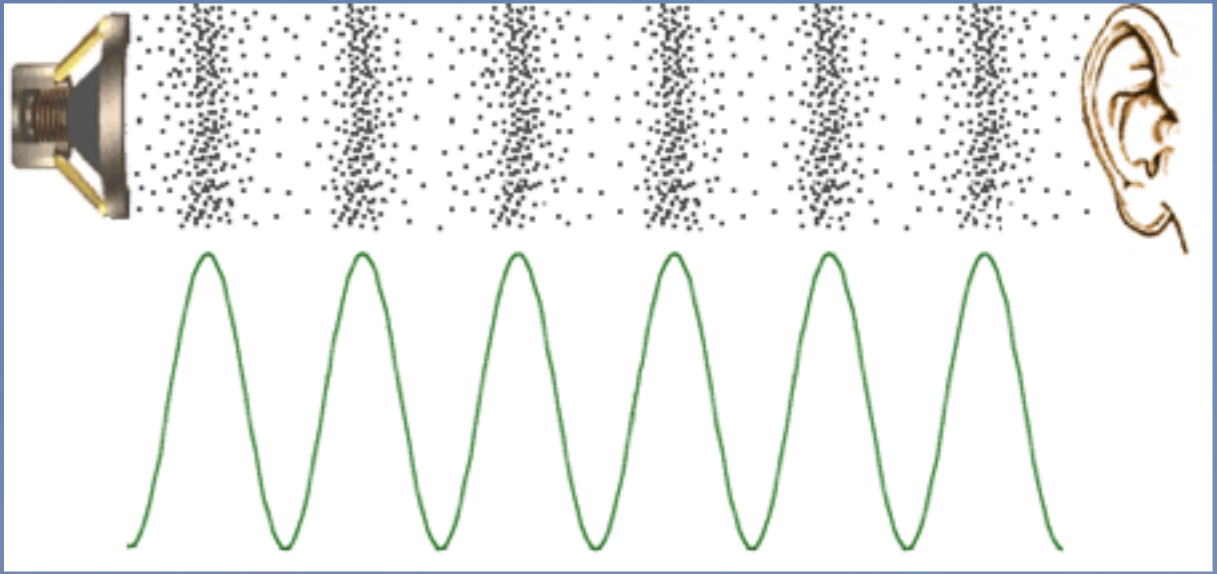
Langmuir waves

- 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…



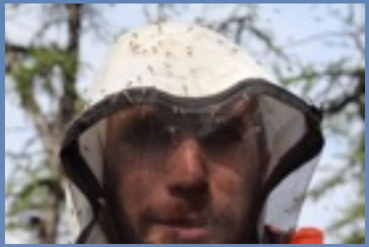
"Pressure" waves in the ion density.

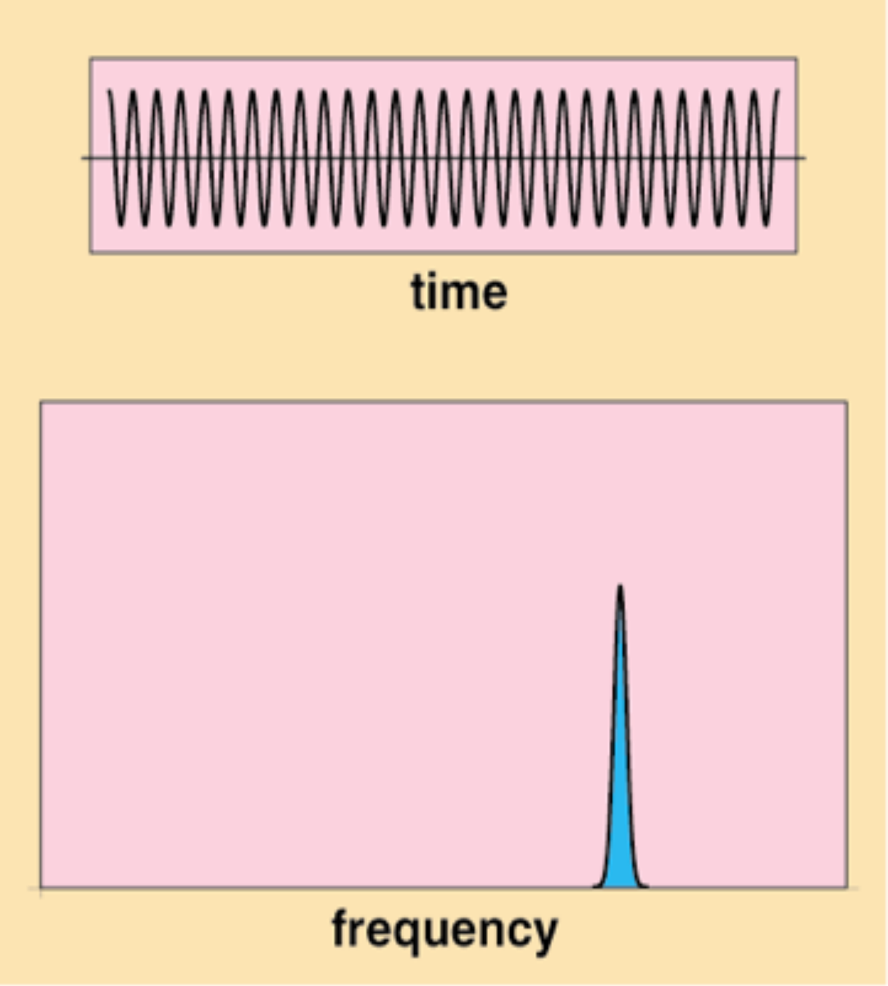
Ion acoustic waves

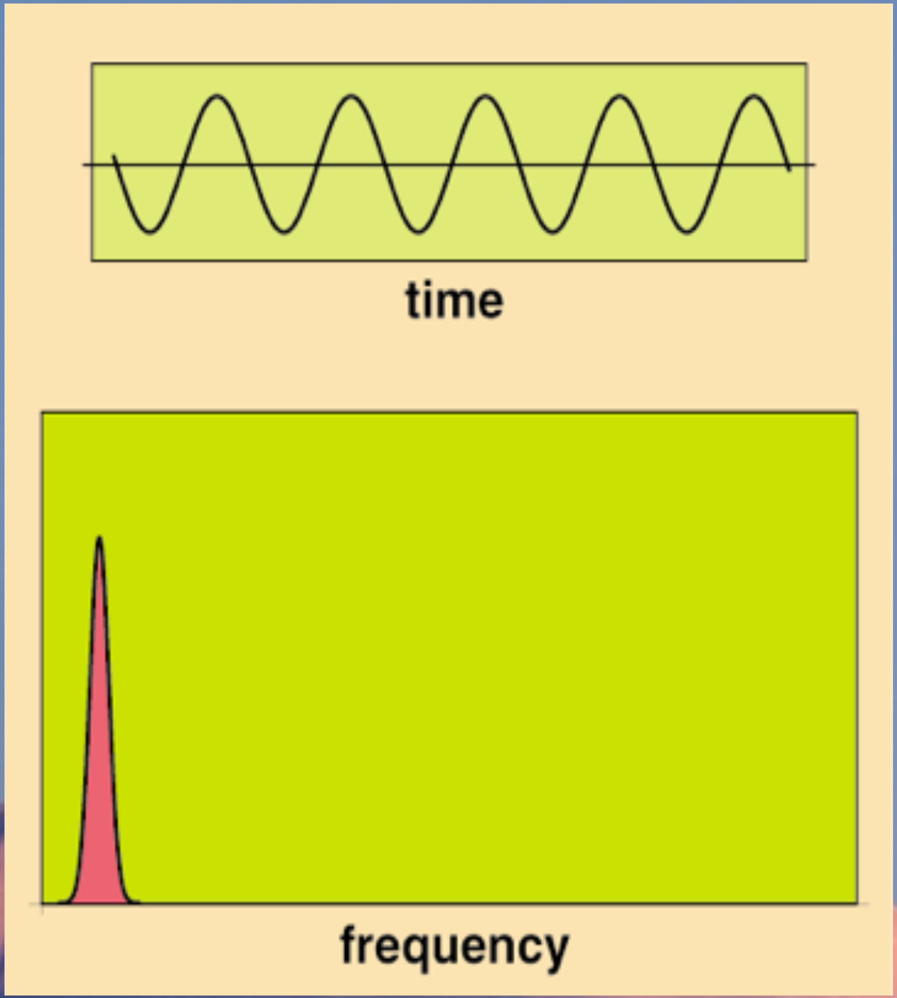
* Ion acoustic waves:

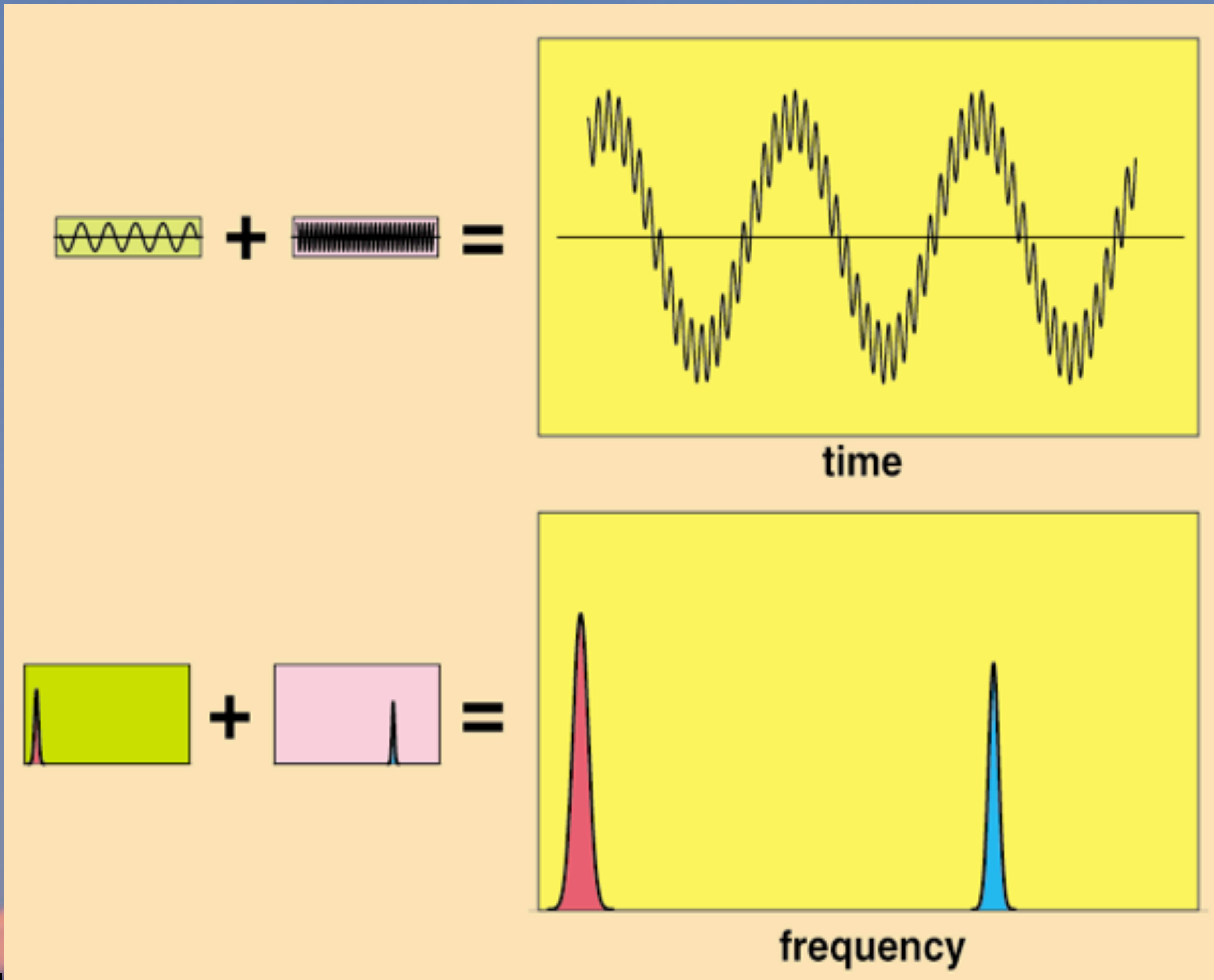
(63) $$\omega_r = \frac{k c_s}{1 + k^2 \lambda_{De}^2}, \qquad c_s = \left(\frac{k_B T_e + 3 k_B T_i}{m_i} \right)^{1/2}$$

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

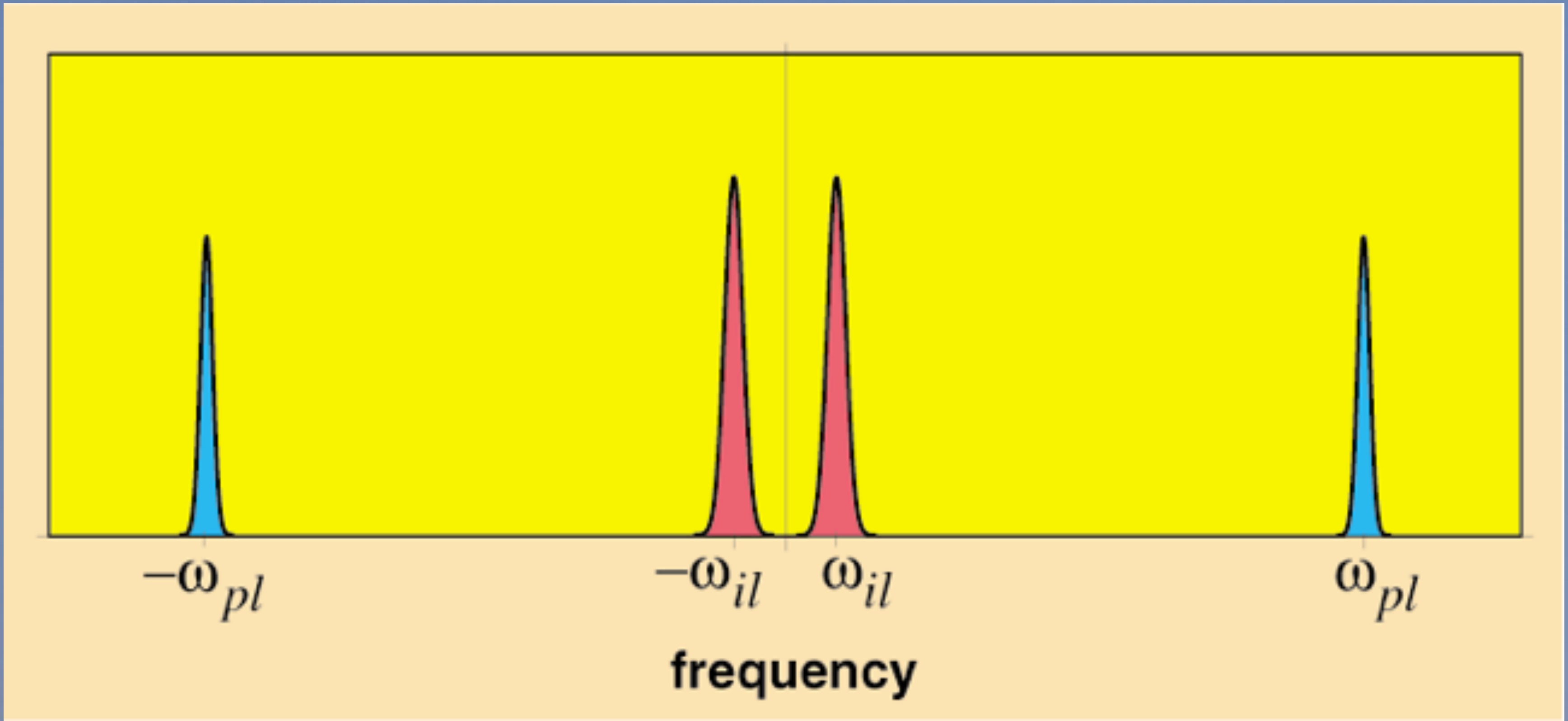


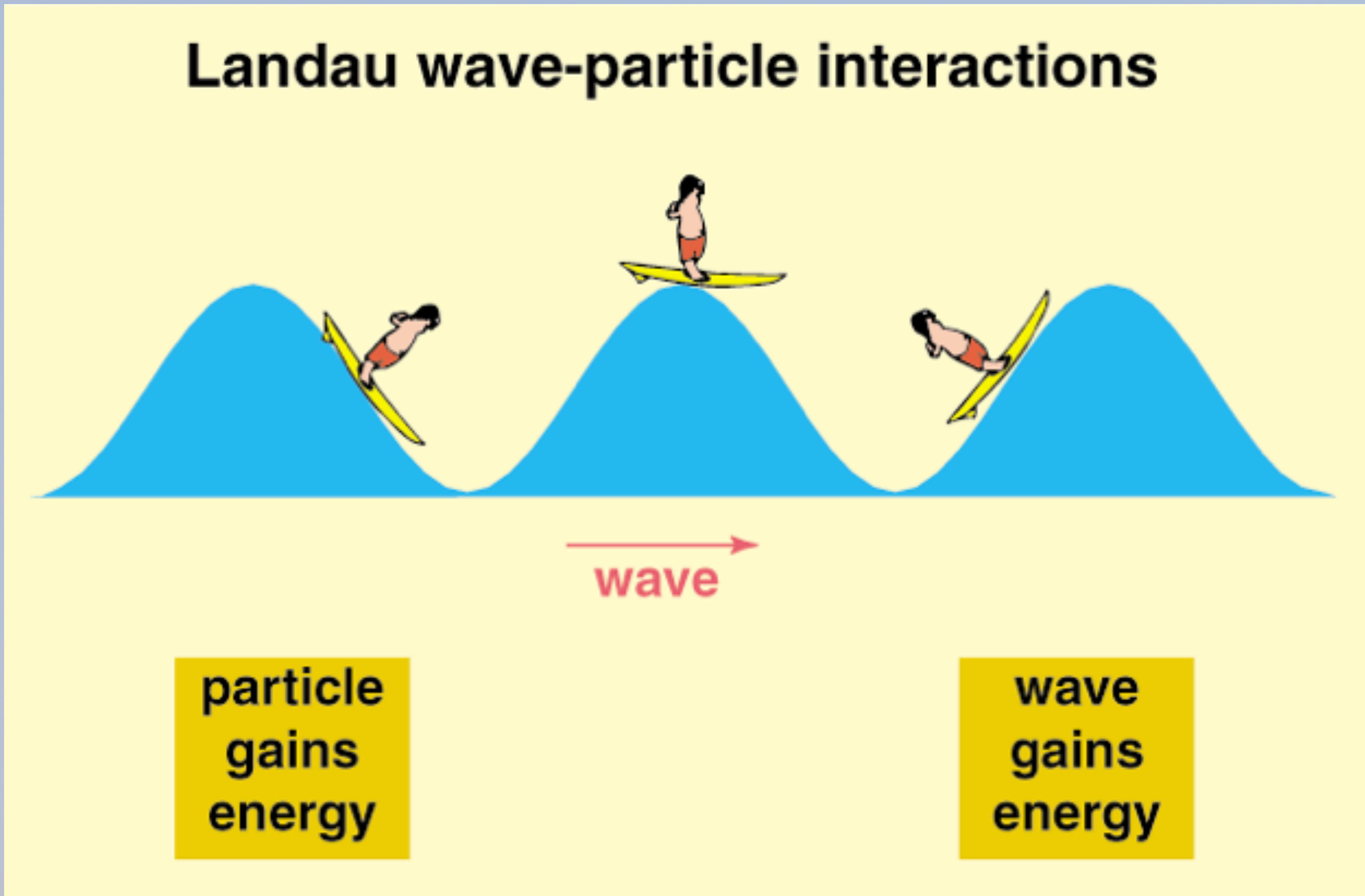

time
frequency

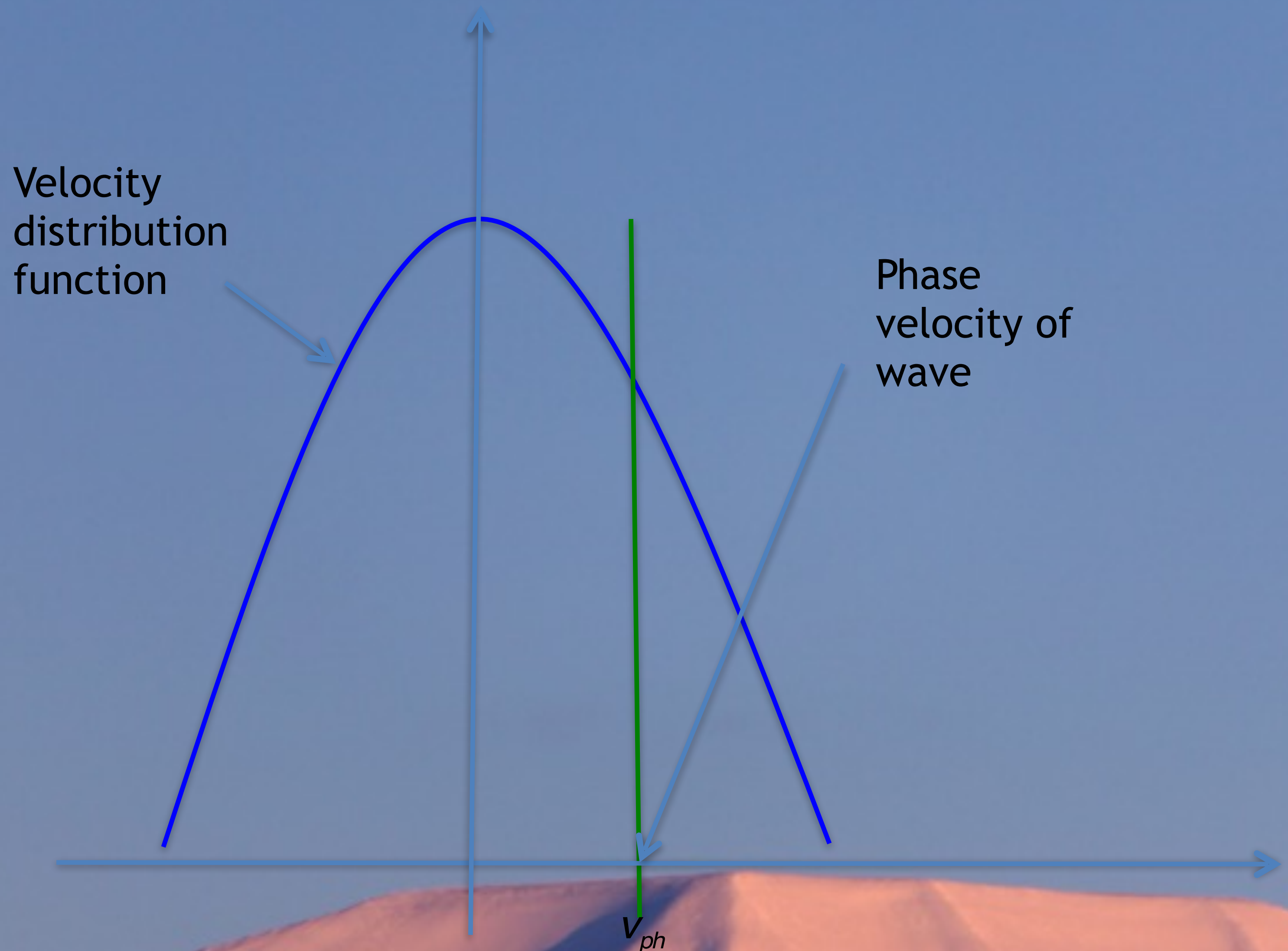

time
frequency

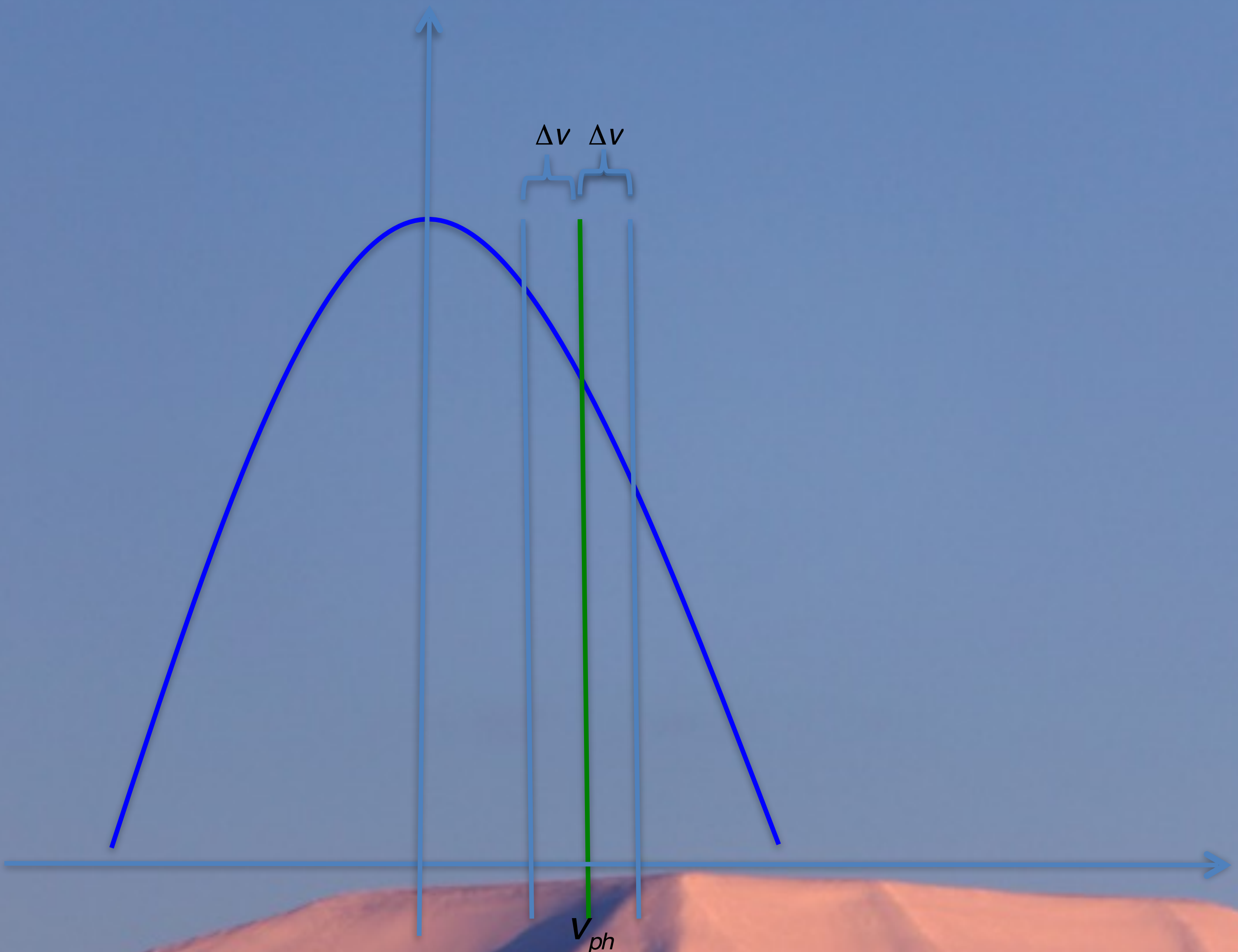

time
frequency

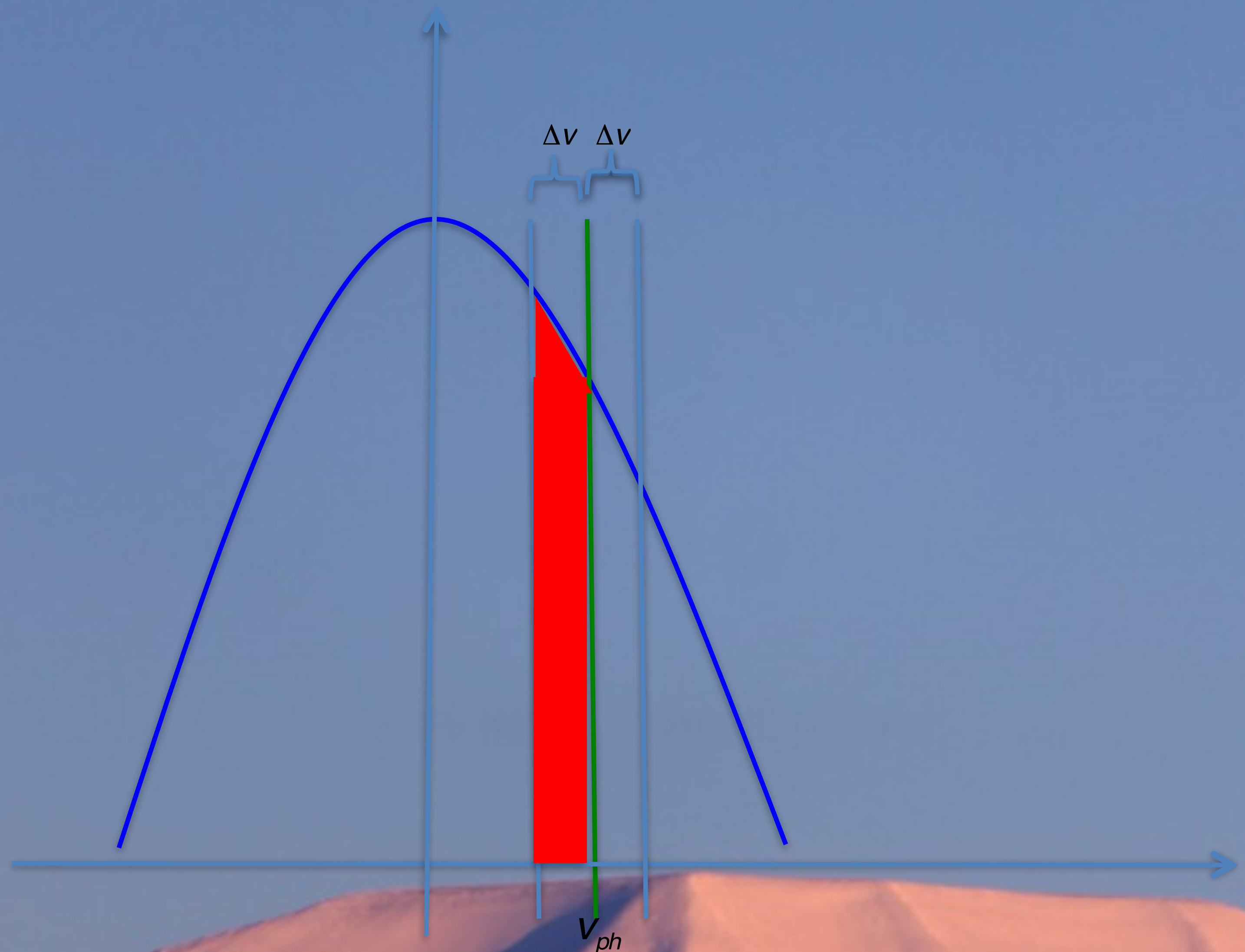
Plasma Wave Approach (cont'd)

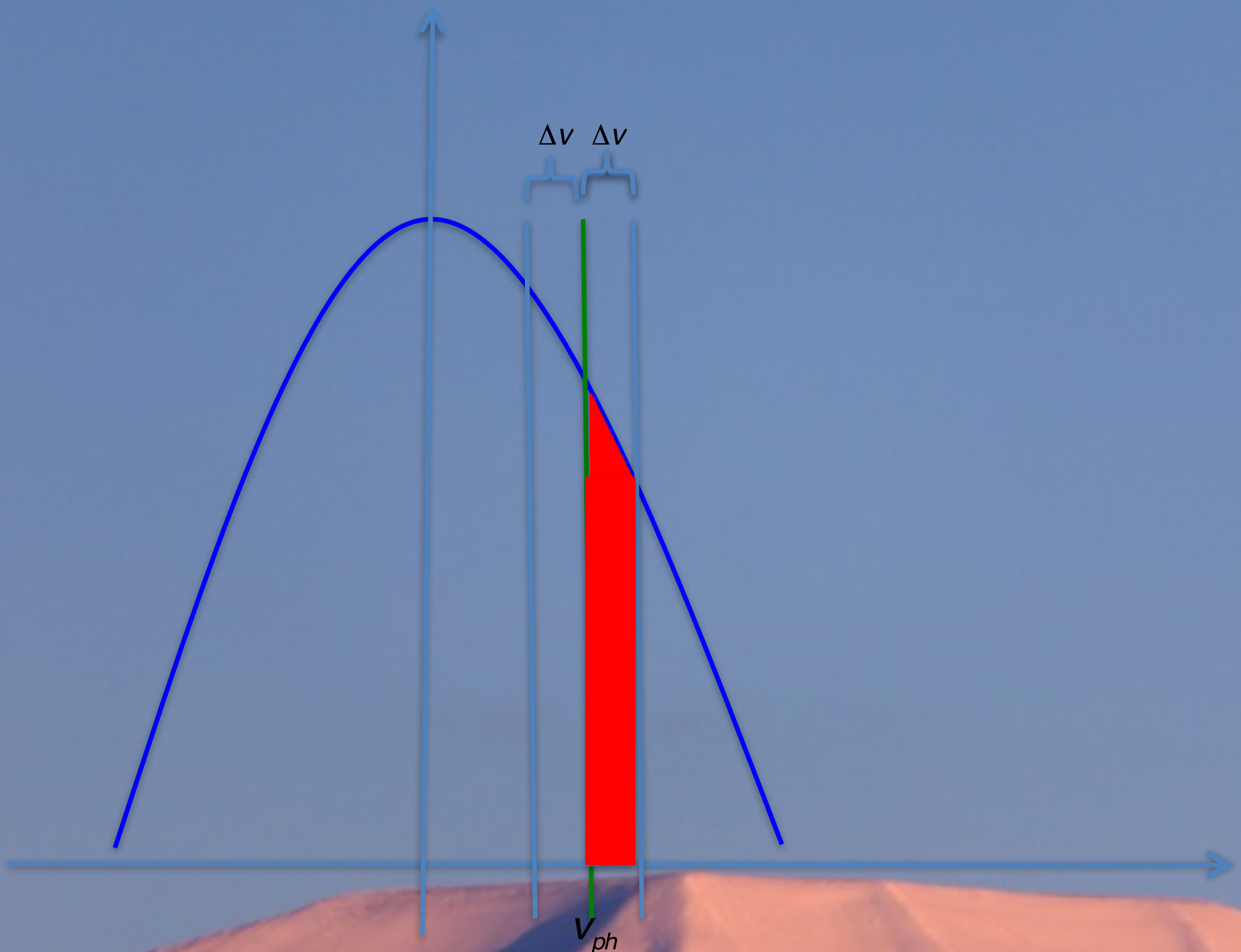



Landau wave-particle interactions
wave
particle gains energy
wave gains energy

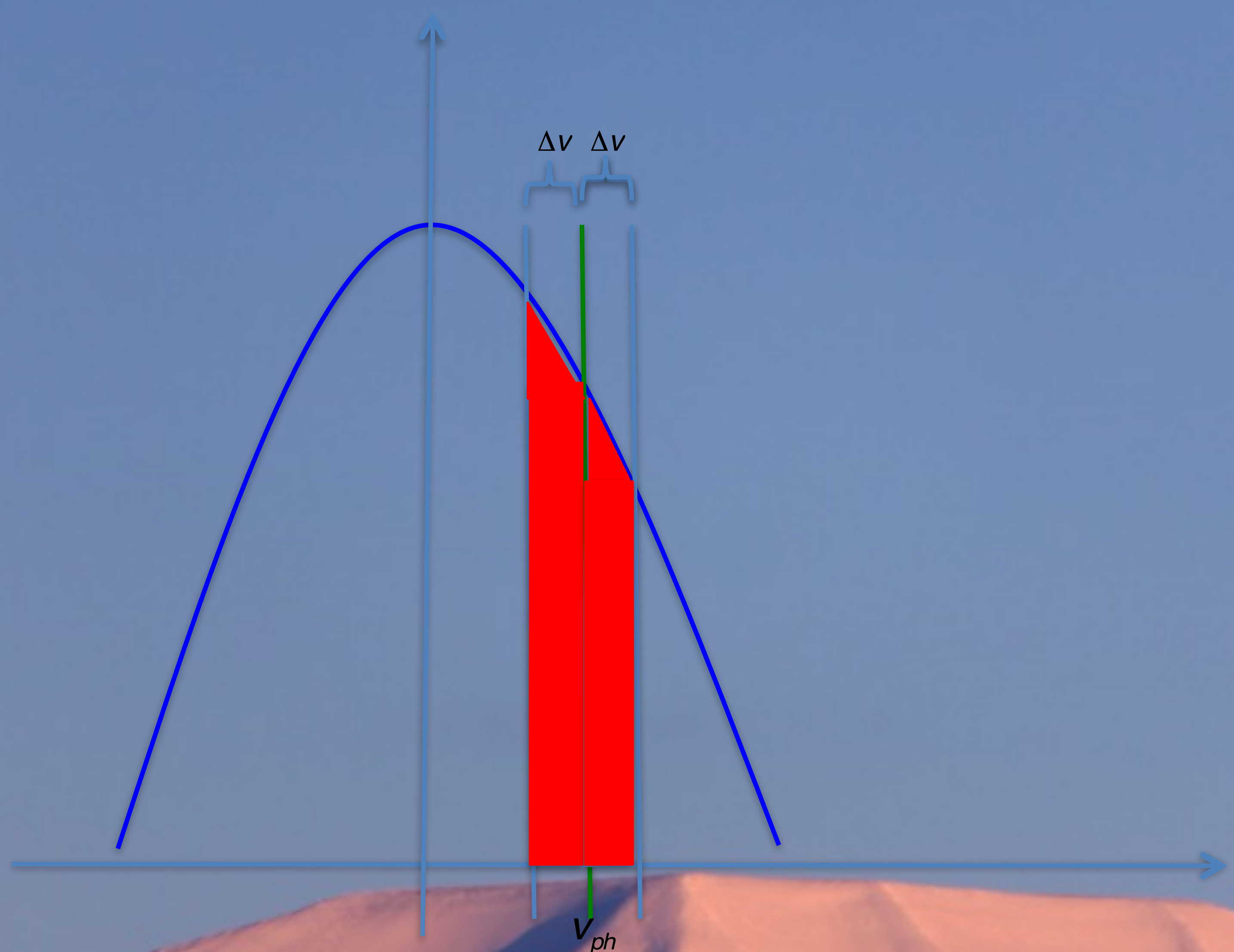

Velocity distribution function
Phase velocity of wave
v_{ph}


Δv Δv
v_{ph}

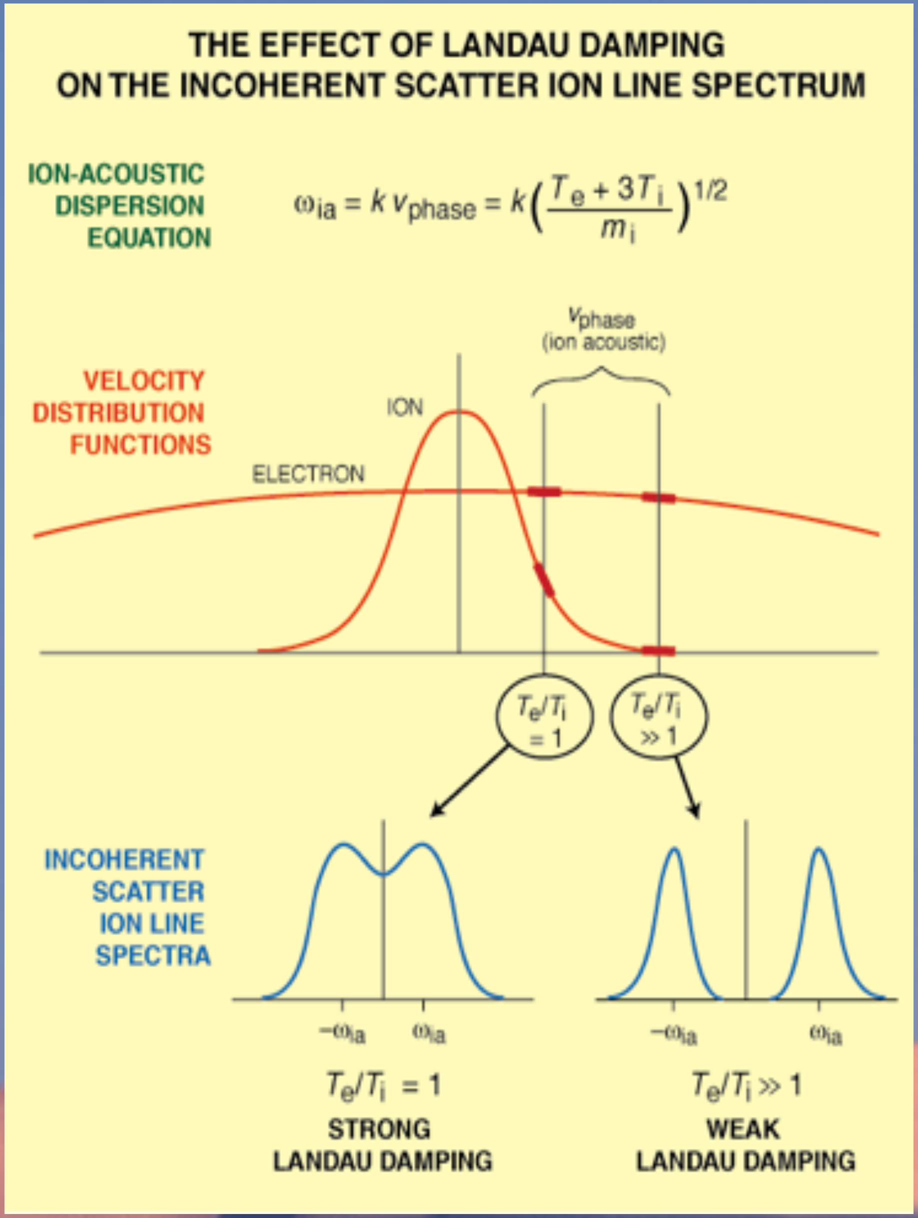

Δv Δv
v_{ph}



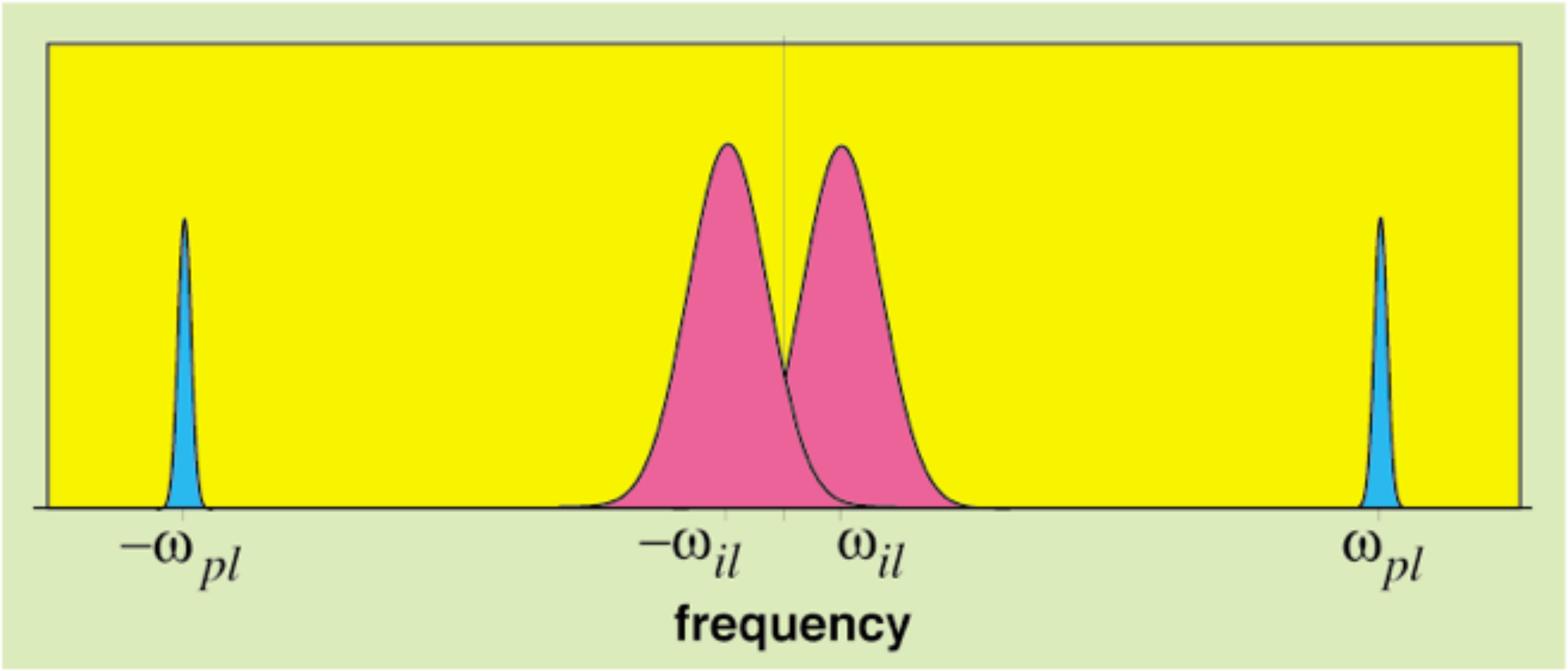
Δv Δv
v_{ph}

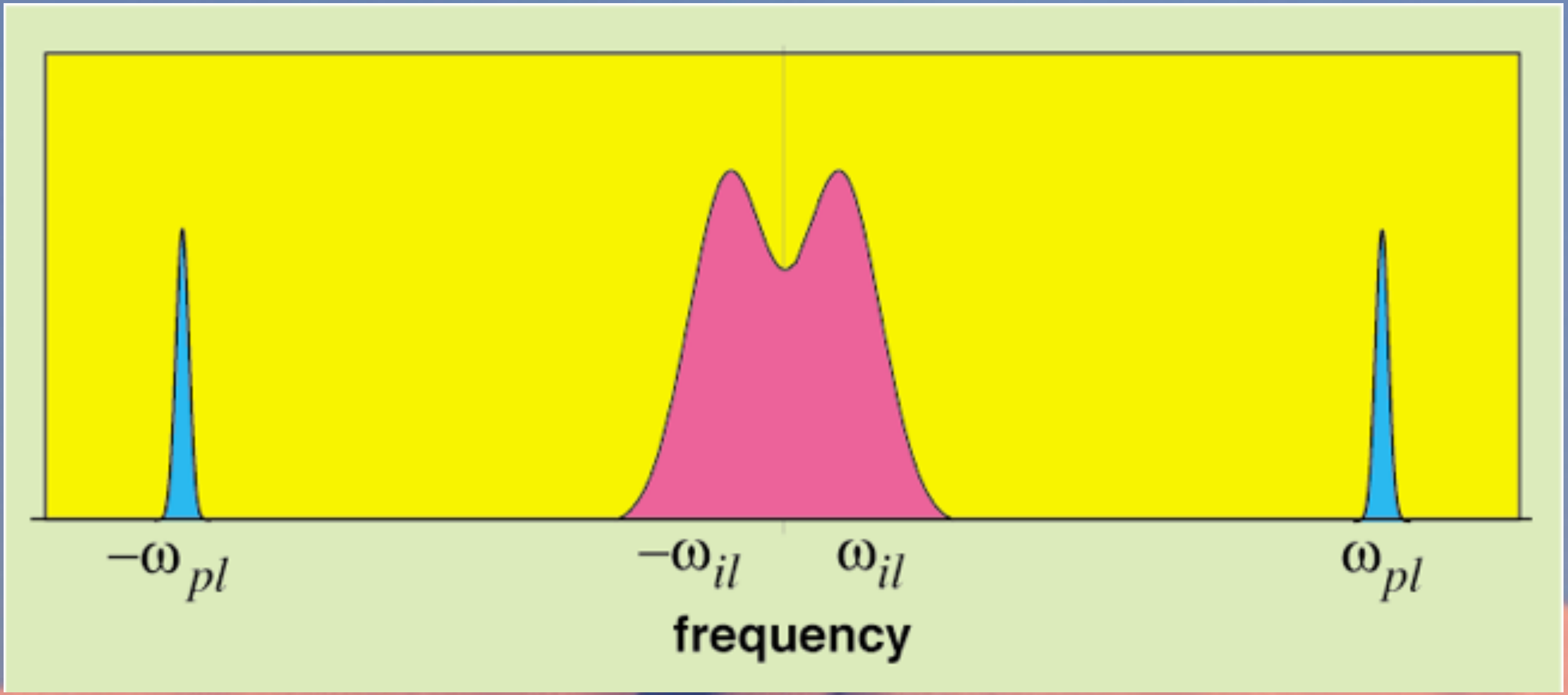


Δv Δv
v_{ph}



THE EFFECT OF LANDAU DAMPING
ON THE INCOHERENT SCATTER ION LINE SPECTRUM
ION-ACOUSTIC DISPERSION EQUATION
$\omega_{ia} = k\,v_{phase} = k\left(\frac{T_e + 3T_i}{m_i}\right)^{1/2}$
v_{phase} (ion acoustic)
VELOCITY DISTRIBUTION FUNCTIONS
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

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

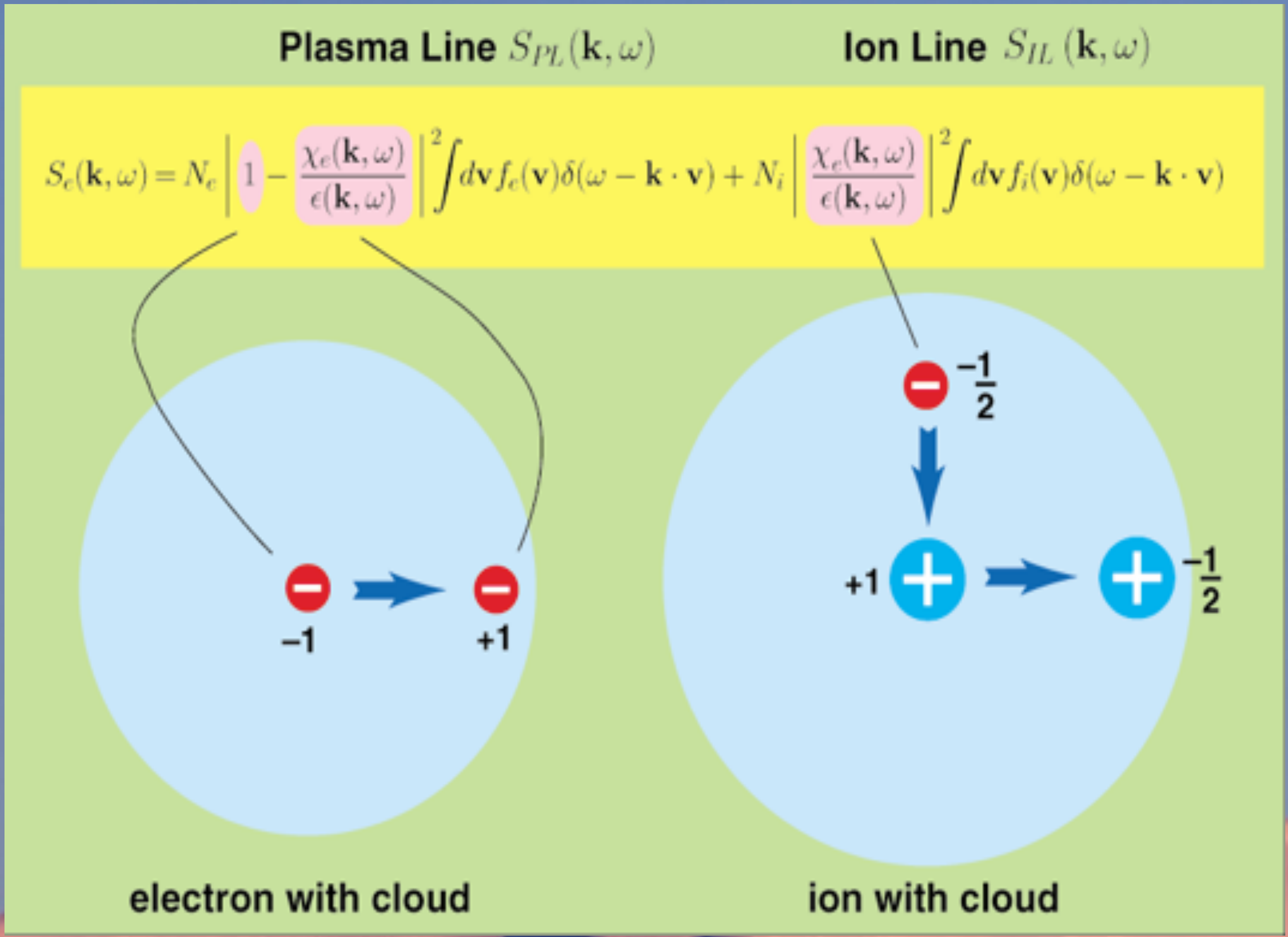
Plasma line

Ion line

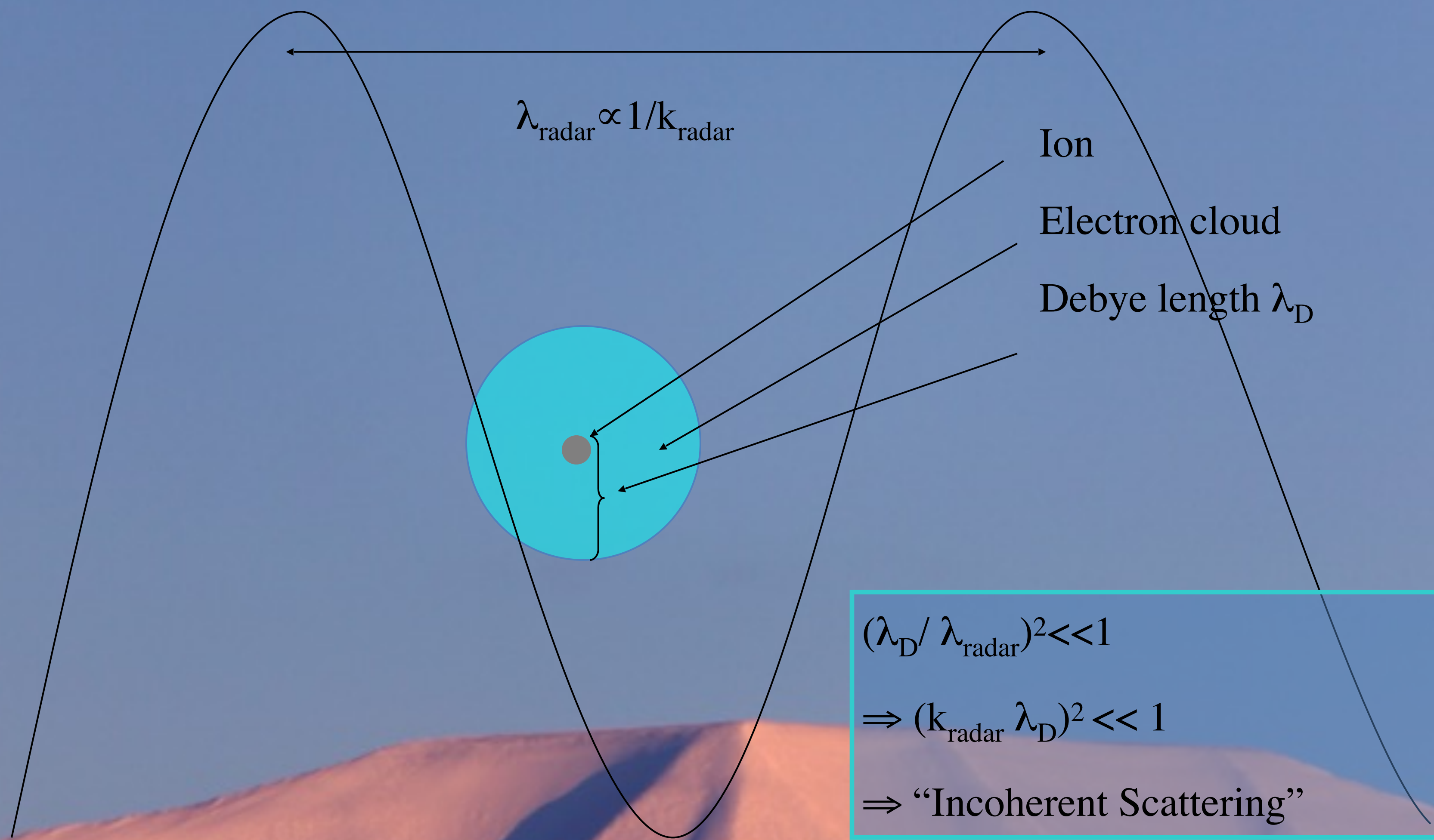
electric susceptibility $\chi_{e,i}(\mathbf{k},\omega)$

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



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

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

$\Rightarrow$ "Incoherent Scattering"

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** $S_{IL}(\mathbf{k},\omega)$

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

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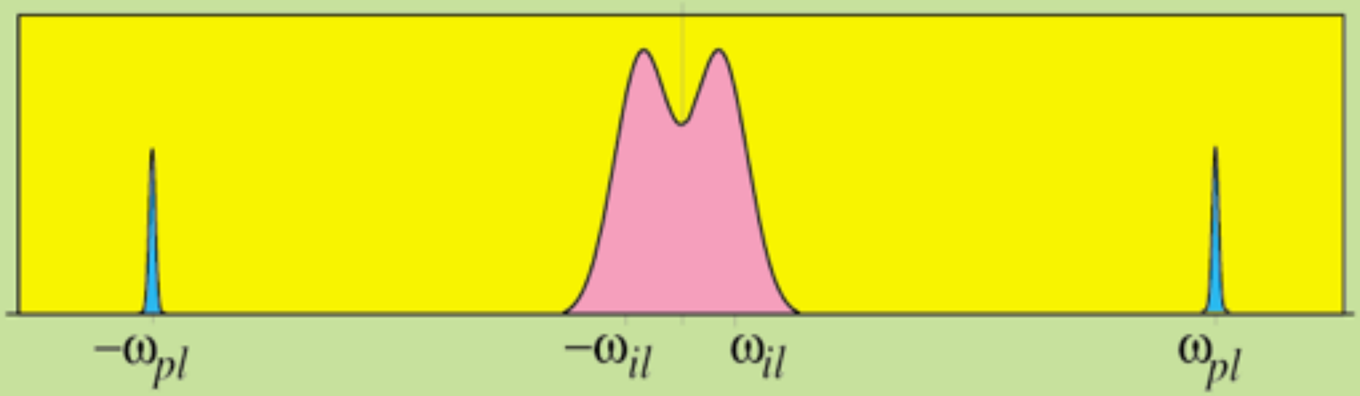
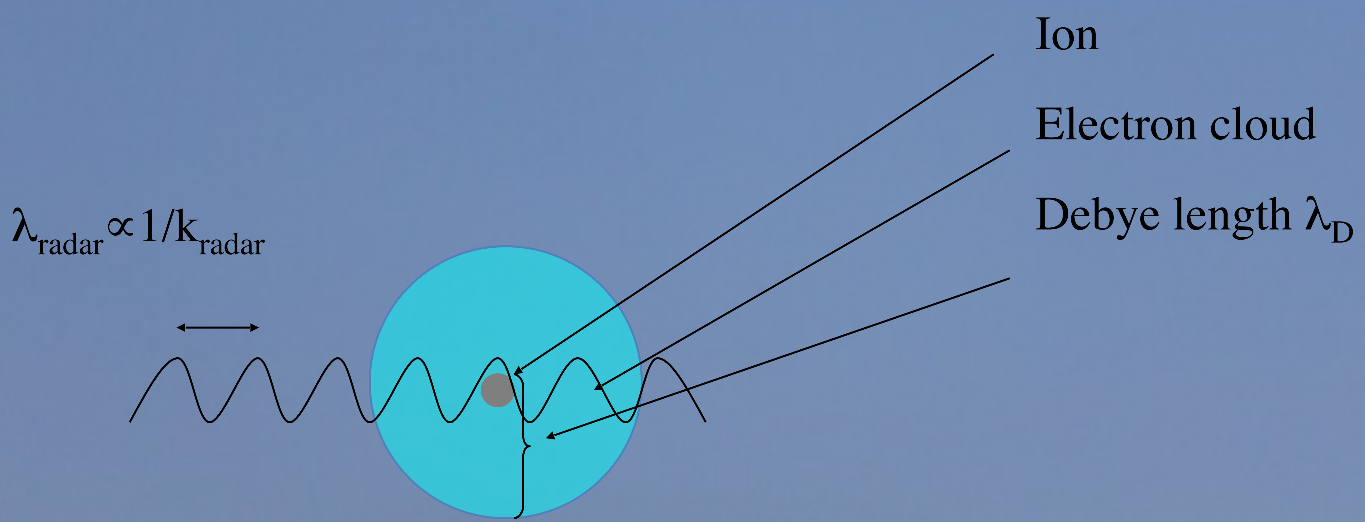


Debye length dependence



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

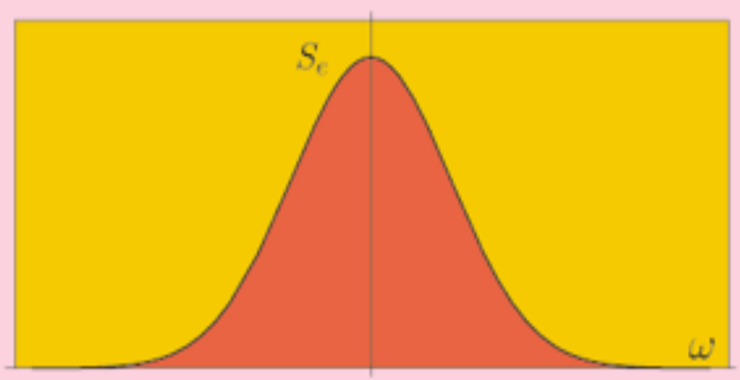
$\Rightarrow (k_{radar}\ \lambda_D)^2 > 1$

$\Rightarrow$ No collective interactions

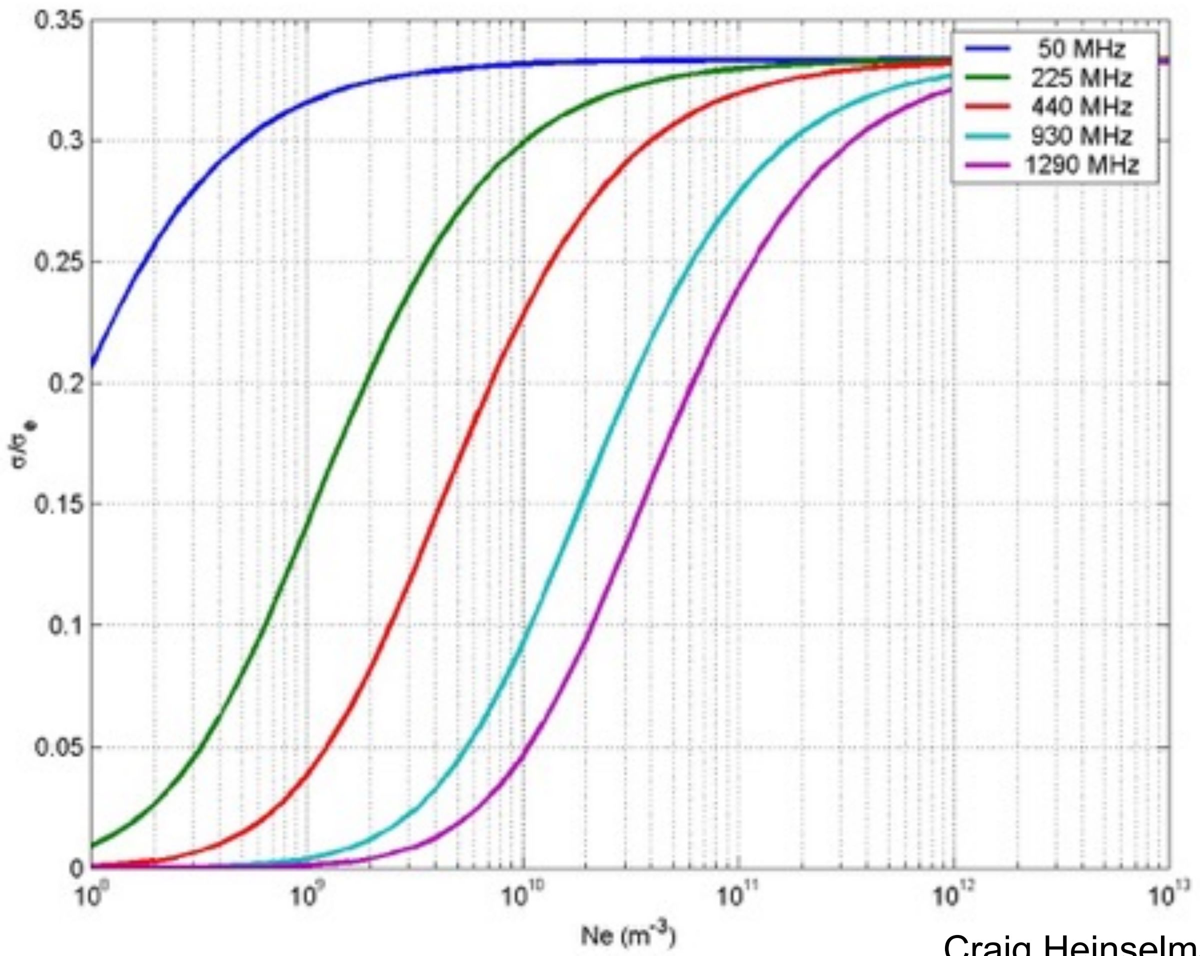
no collective interactions

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

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



Debye Length Dependencies



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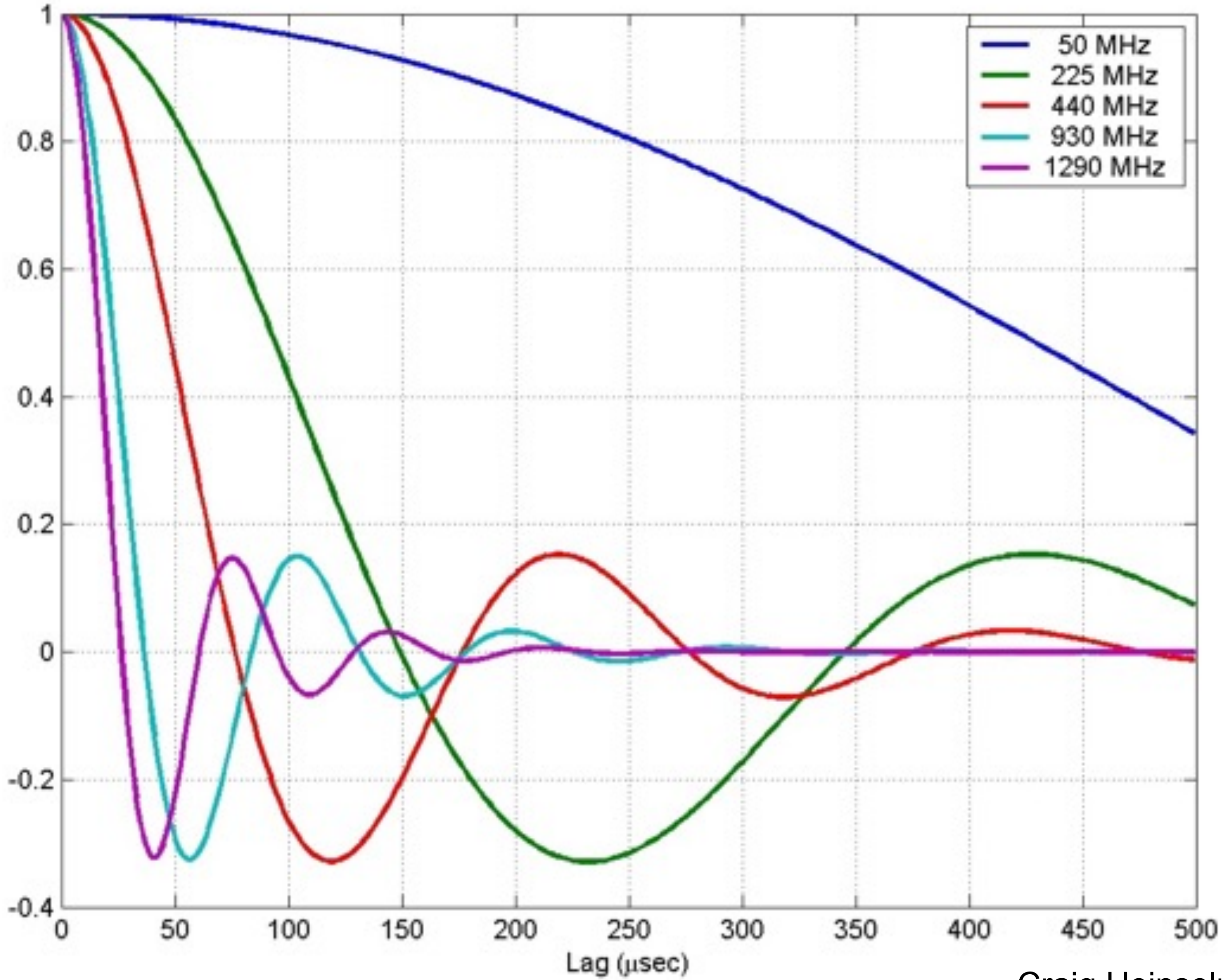
Parameters
Ti: 1000 K
Te: 2000 K

Radar Frequency Dependencies



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

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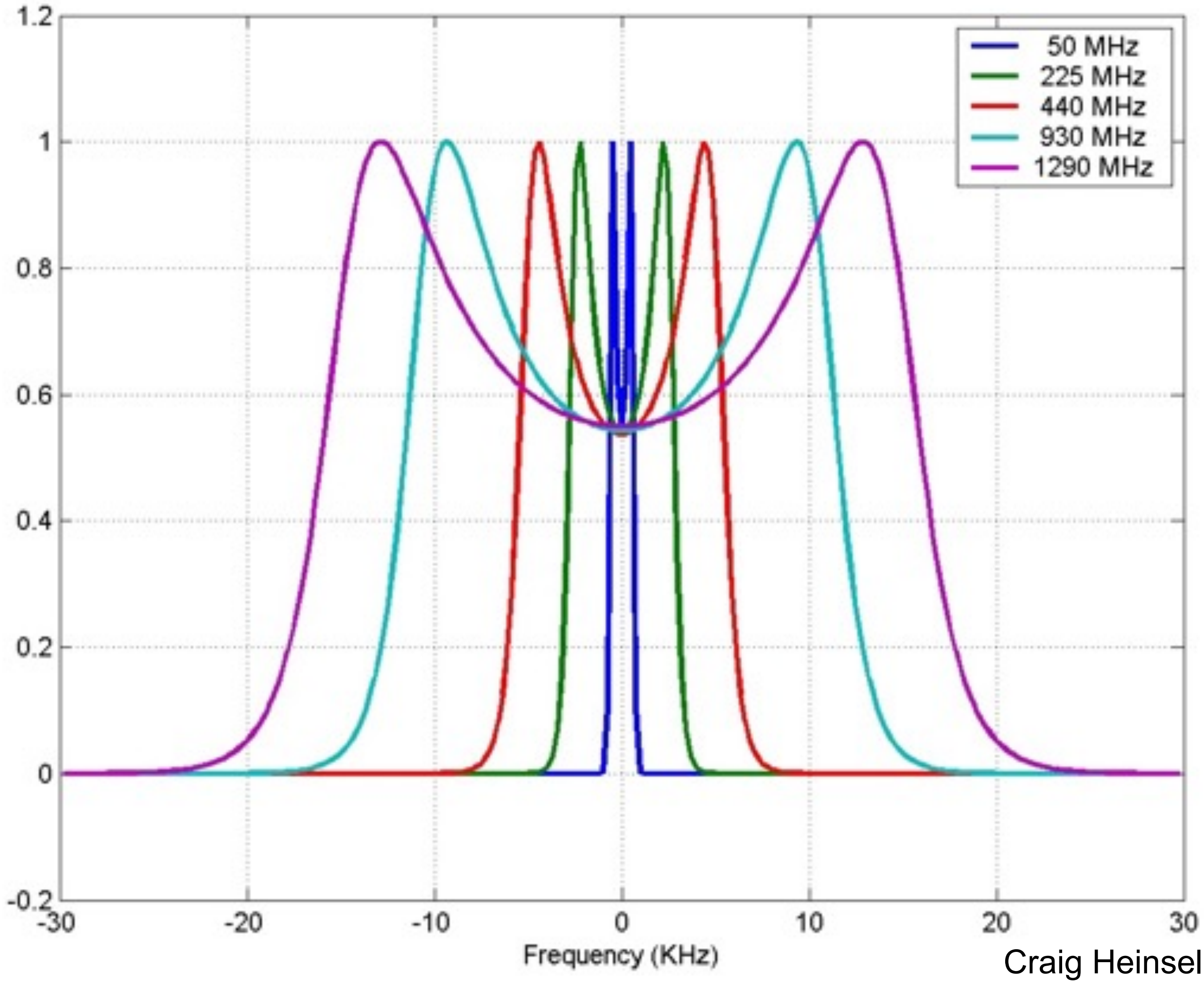
Radar Frequency Dependencies



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

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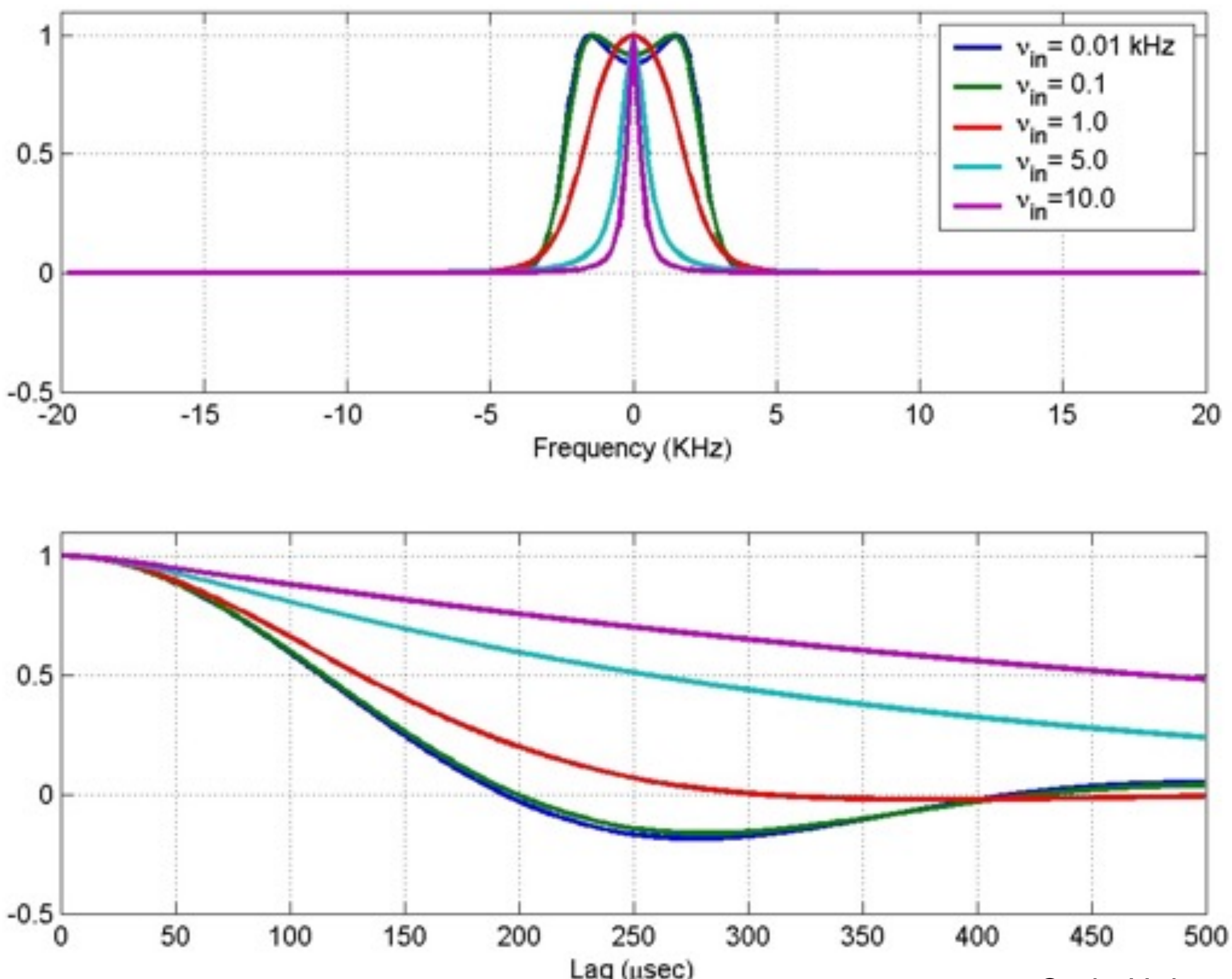
With the frequency of the radar chosen (which is a one time thing!), how does the spectra depend on geophysical parameters?

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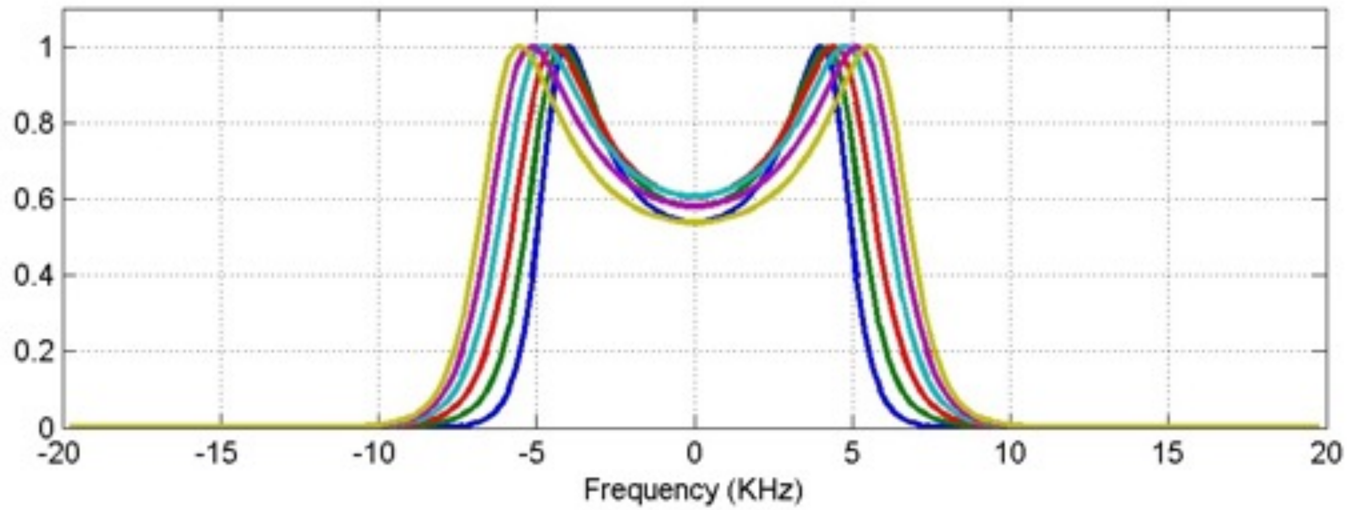
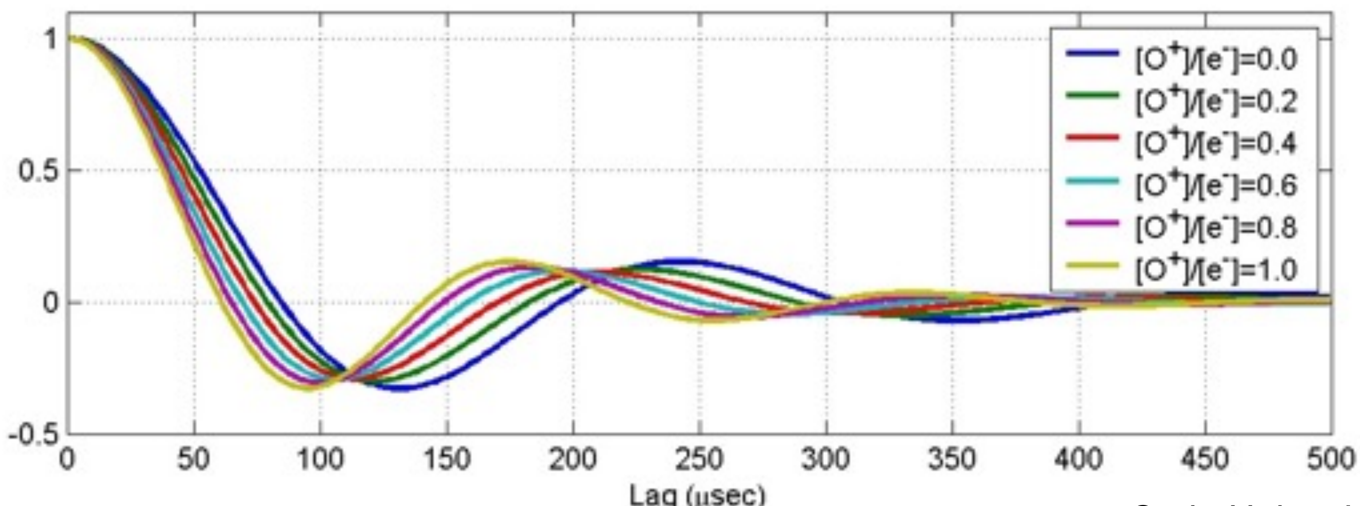
Ion Composition (O^+ vs. NO^+)



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



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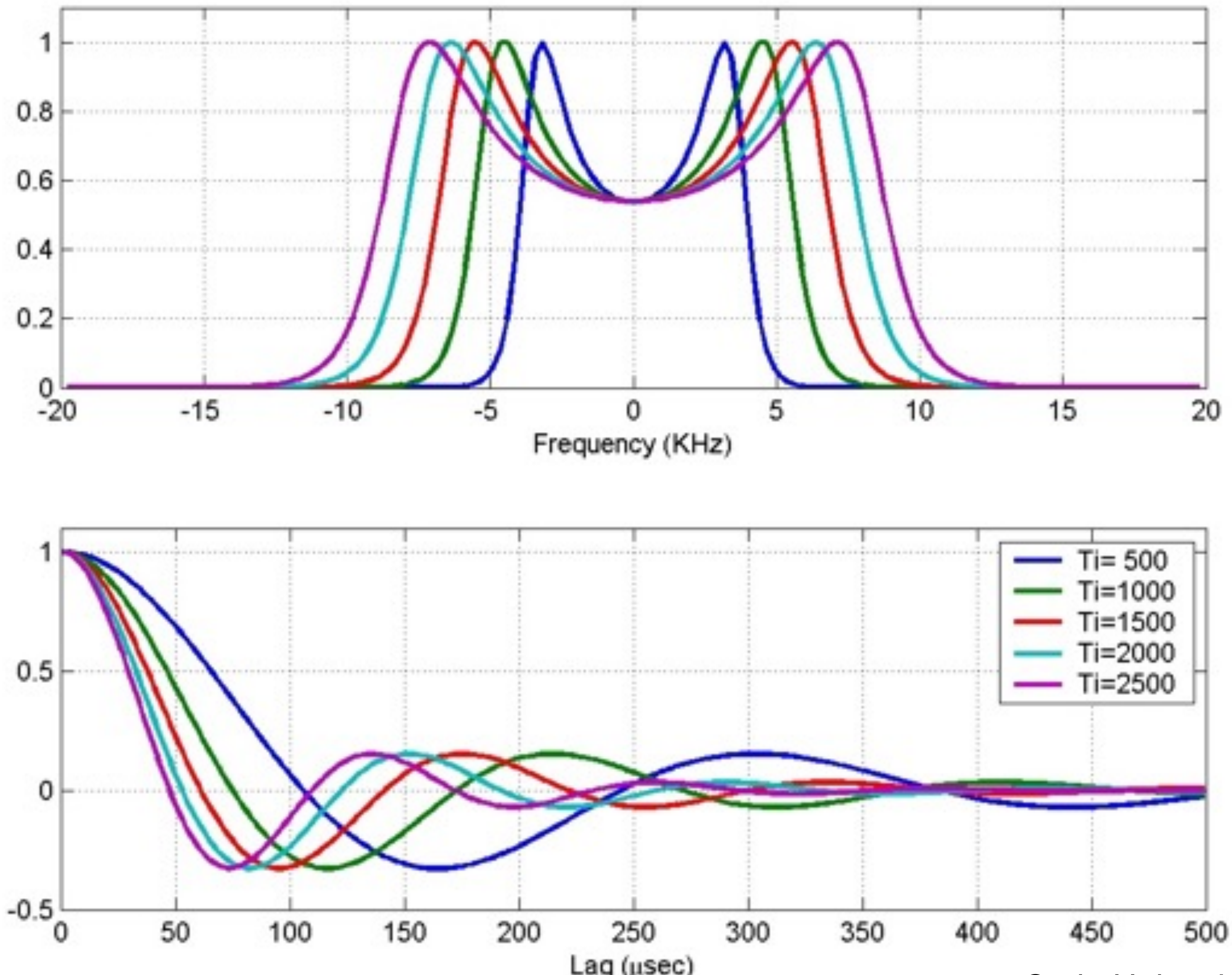
Ion Temperature



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

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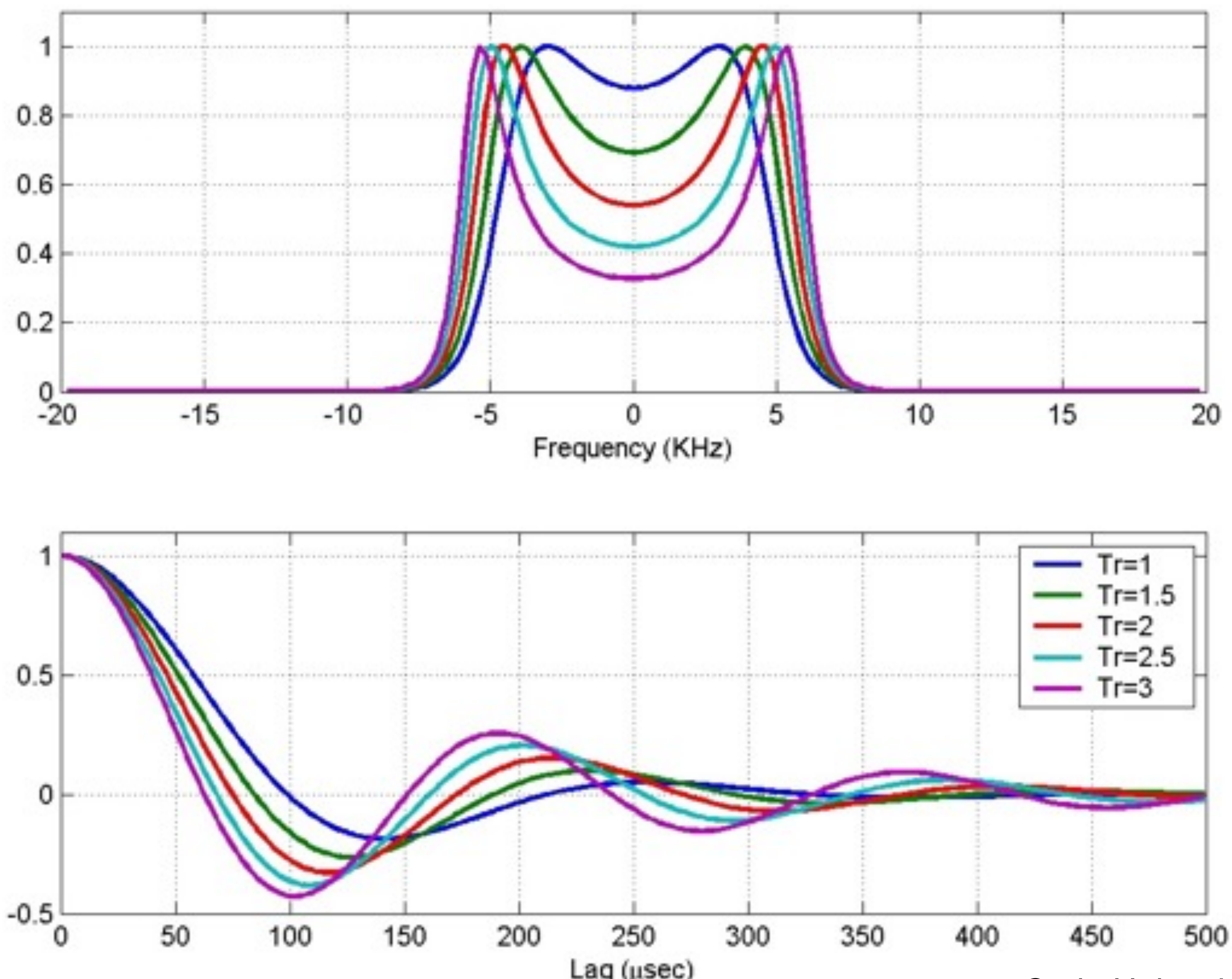
Electron/Ion Temperature Ratio



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

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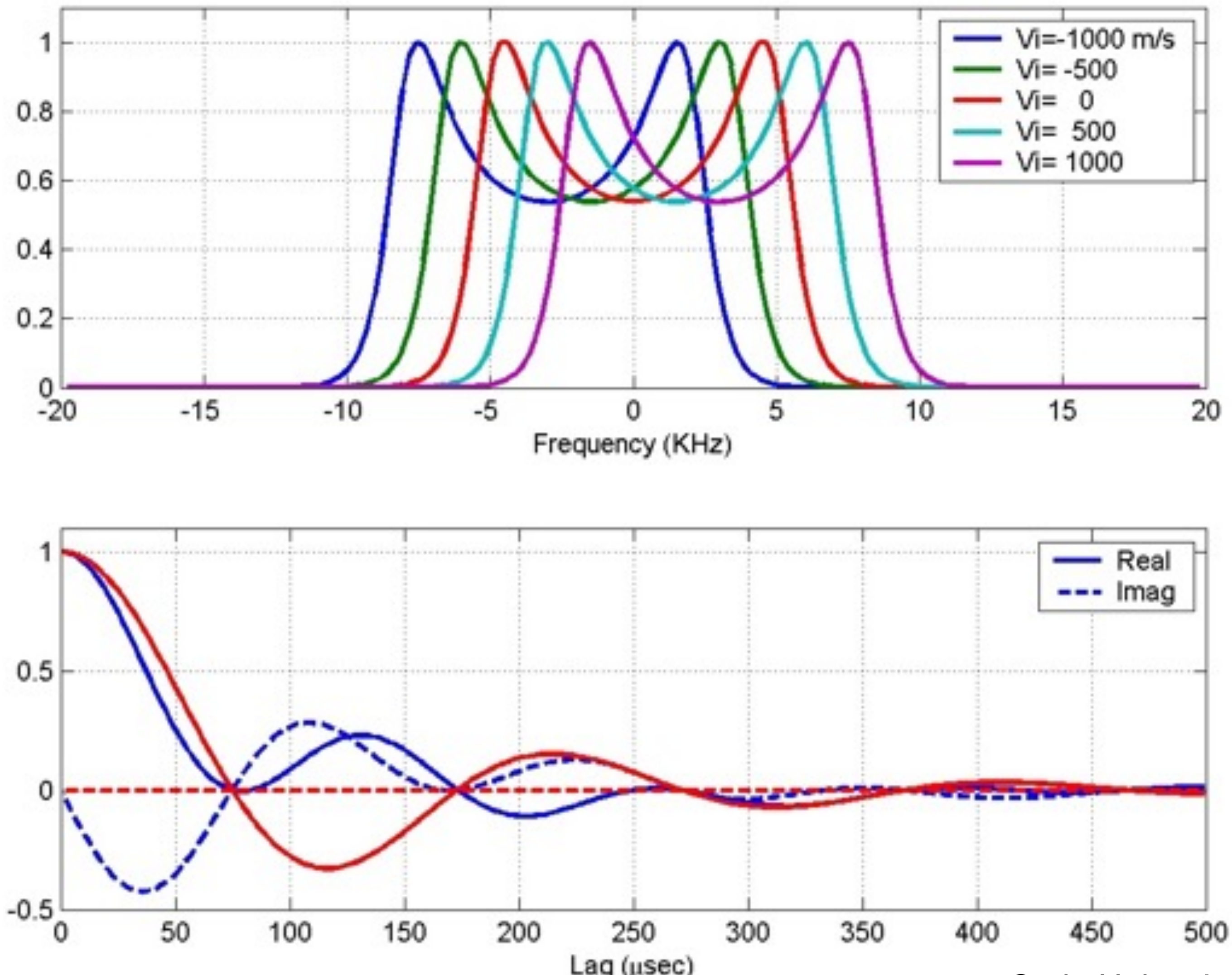
Ion Velocity



<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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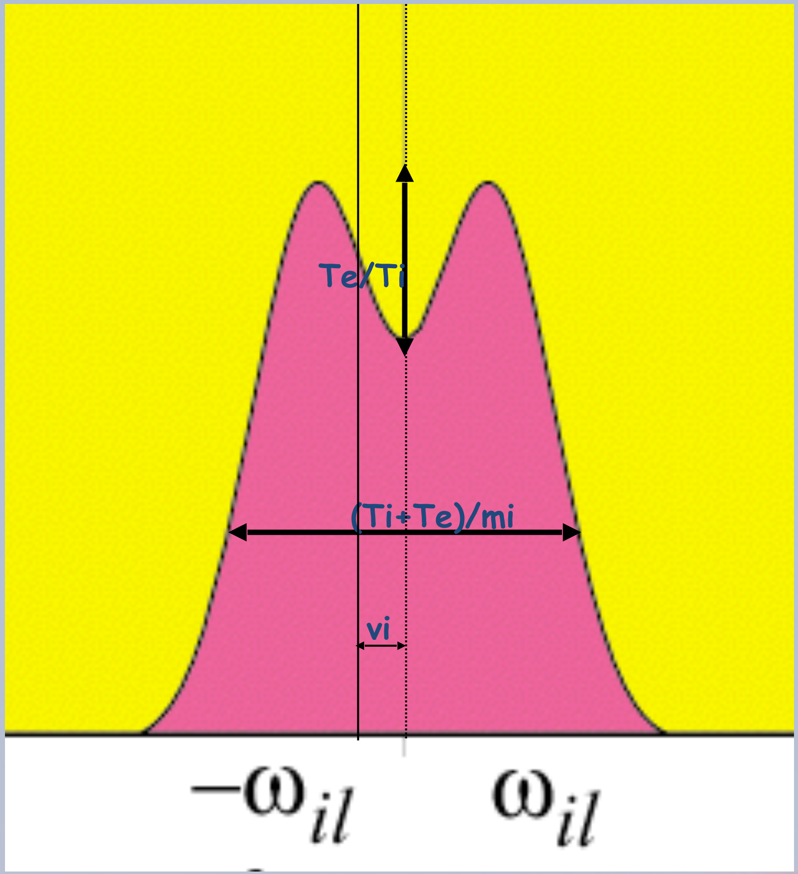
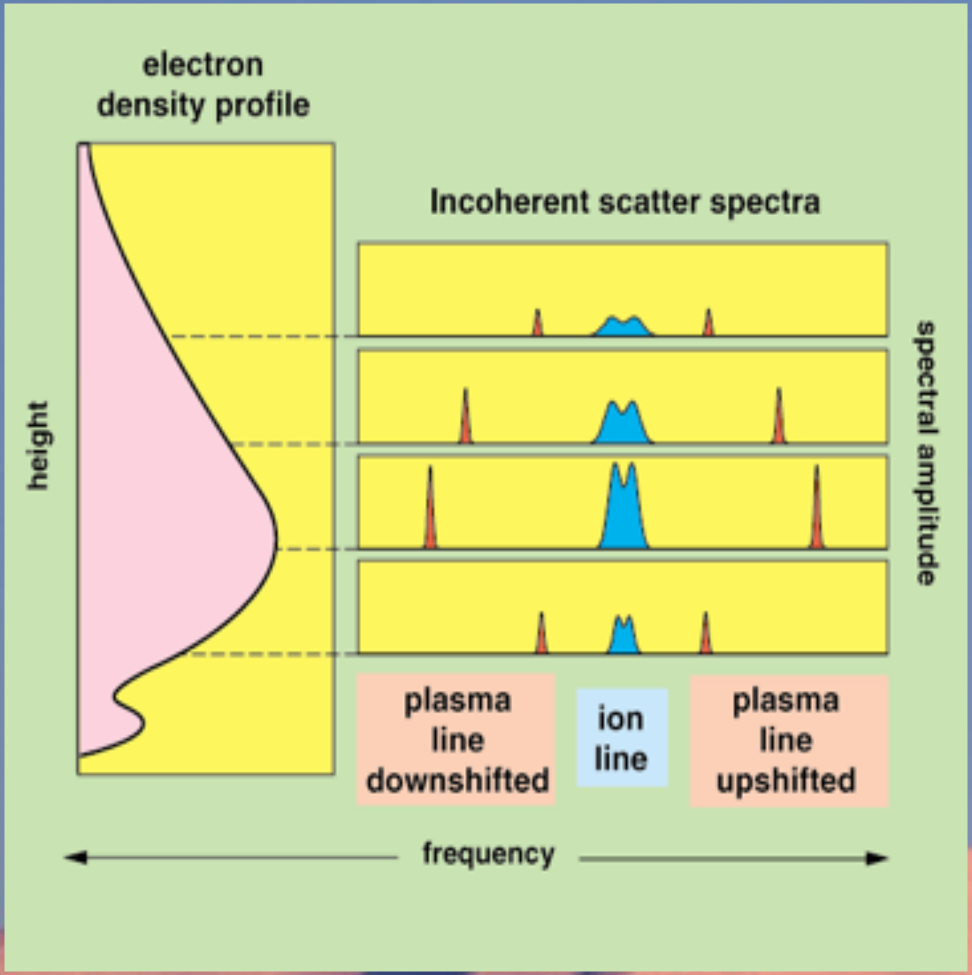
…or to sum up…

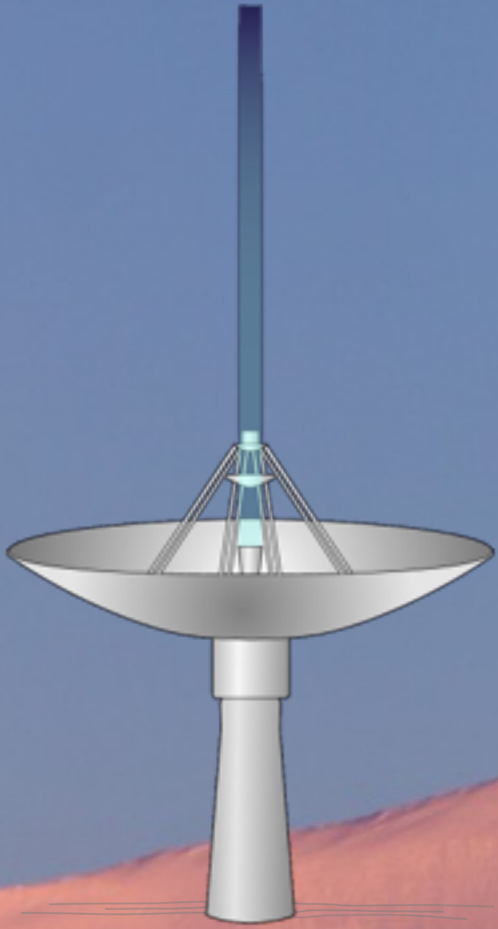


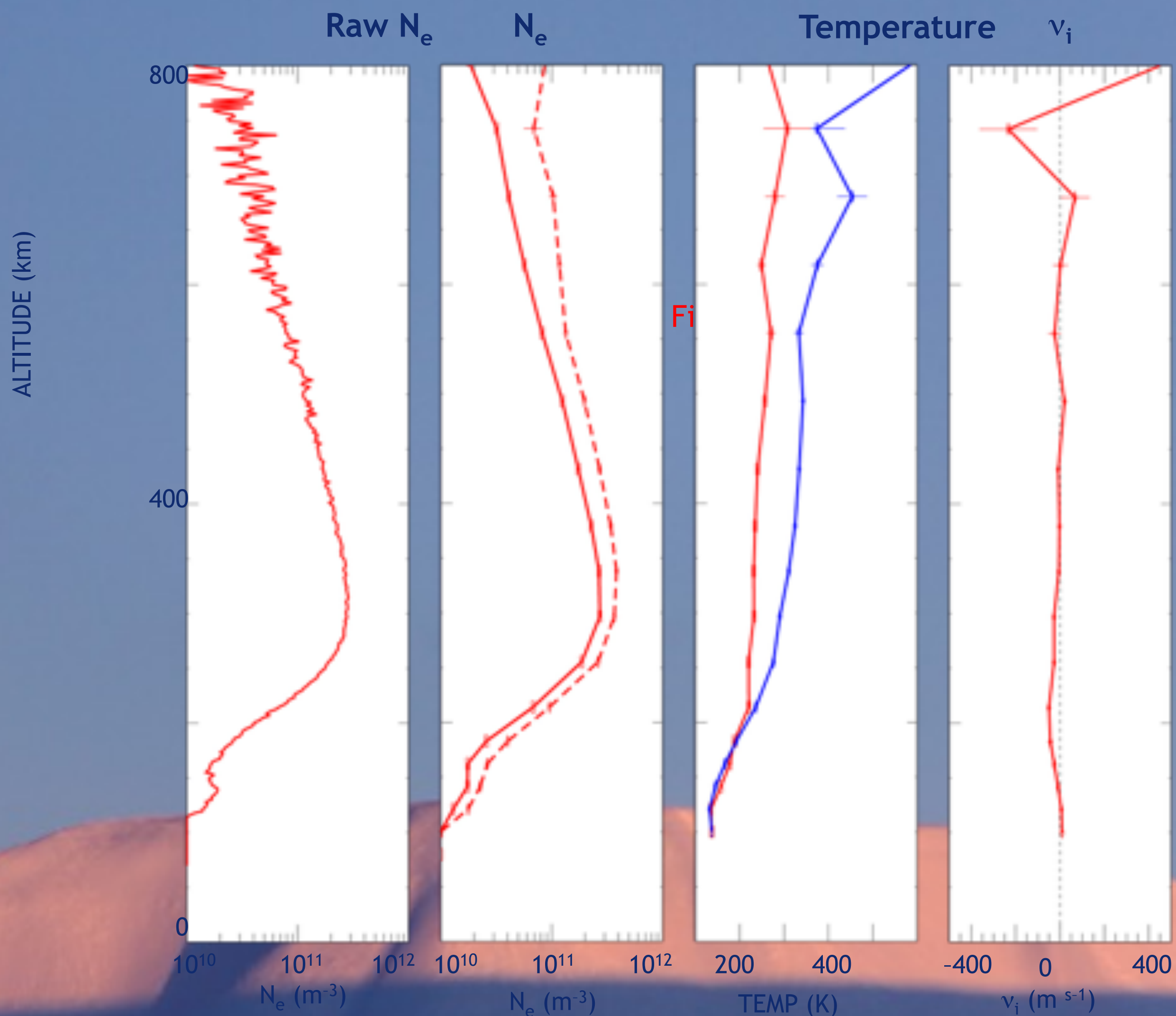
- Ion (and electron) temperature (Ti and Te) to ion mass (mi) ratio from the width of the spectra
- Electron to ion temperature ratio (Te/Ti) from "peak_to_valley" ratio
- Electron (= ion) density from total area (corrected for temperatures)
- Ion velocity (vi) from the Doppler shift

Spectral space as a function of altitude

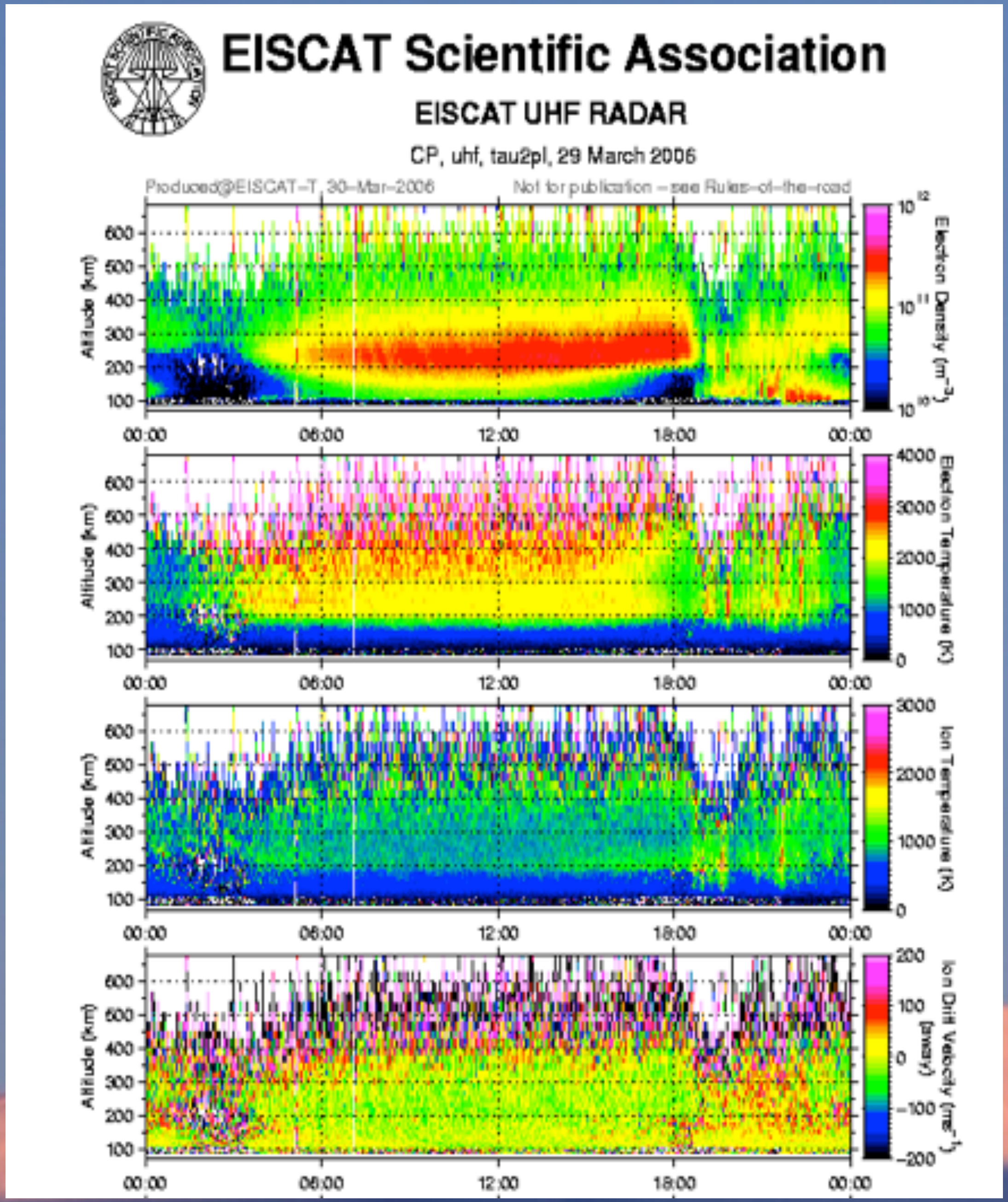


Plasma Parameter Profile

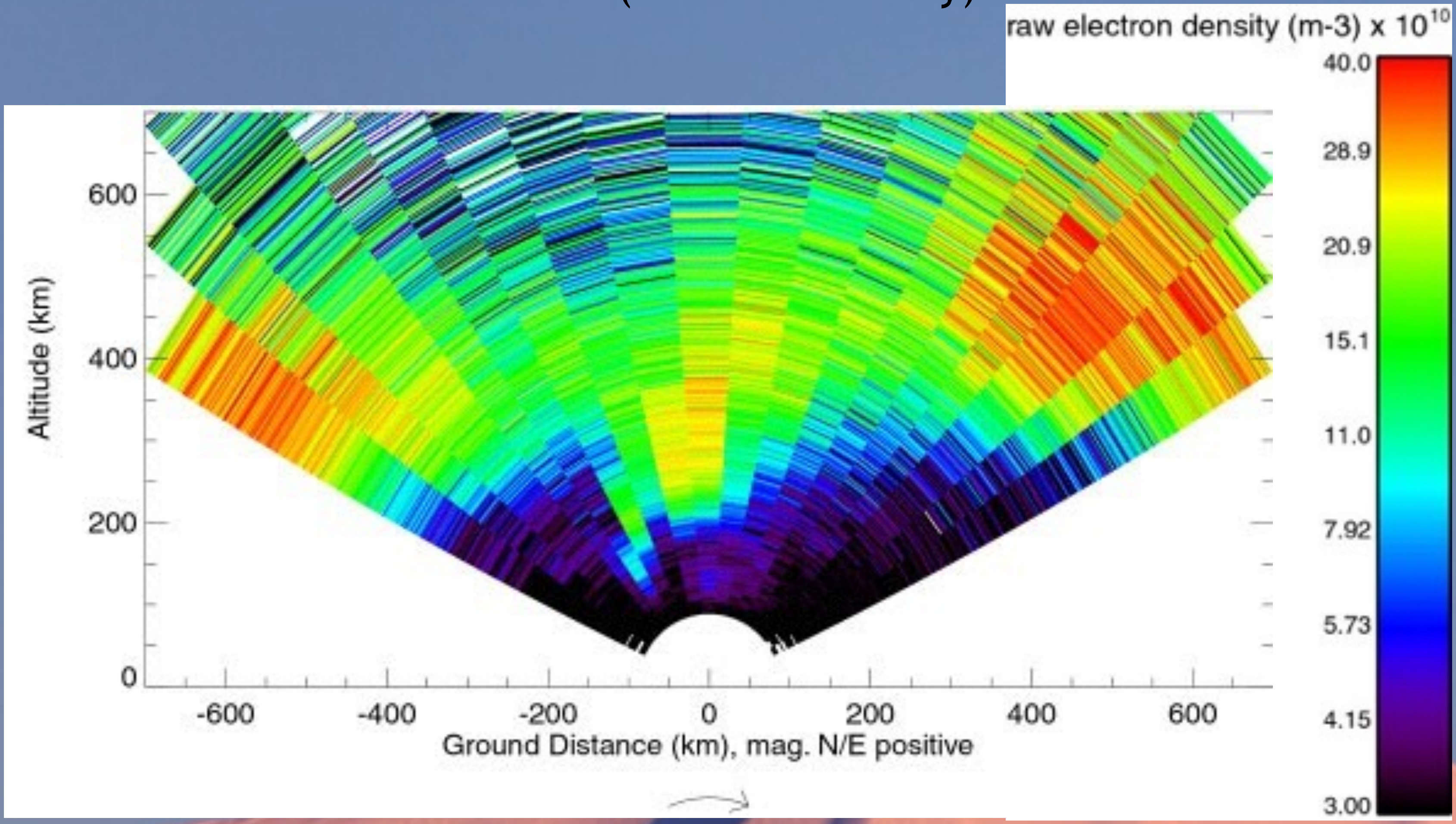




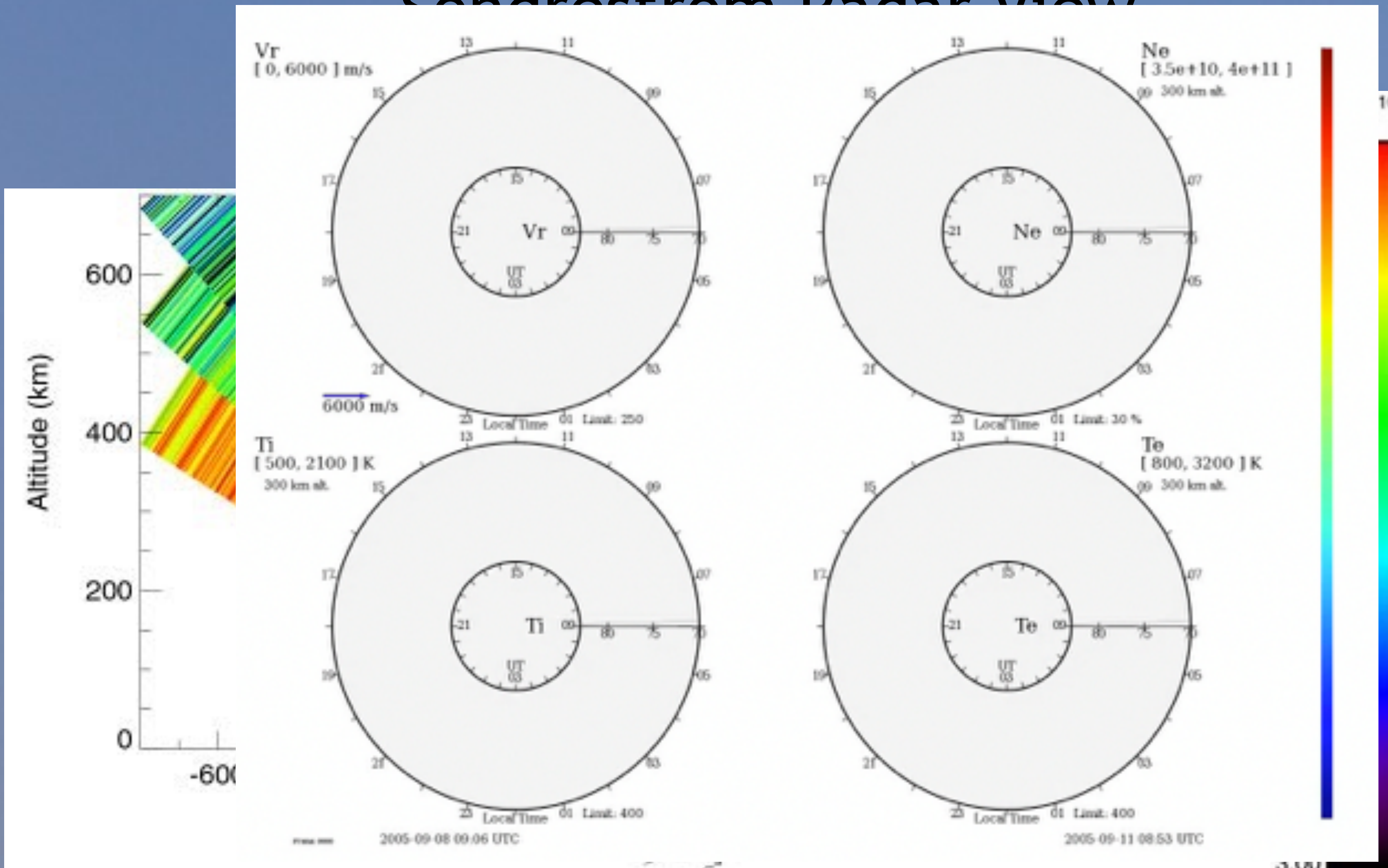
v6


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
00:00

Sondrestrom Radar View
(Electron Density)



Sondrestrom Radar View



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