The short introduction to Incoherent Scatter (IS) Theory

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Outline

- Some basic radar concepts
- The ionosphere
- Incoherent Scatter Radars and theory

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oversimplified   As simple as possible   mindbogglingly difficult

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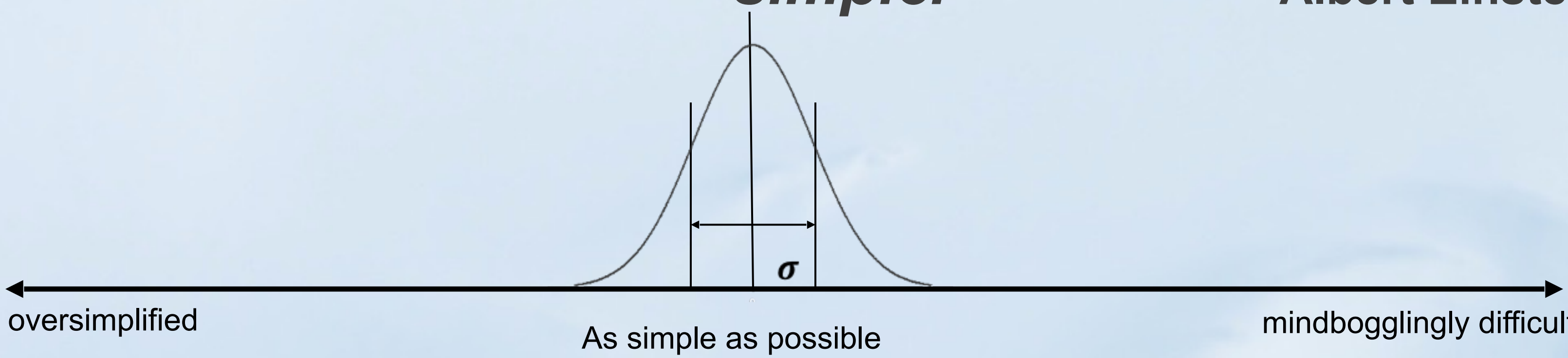

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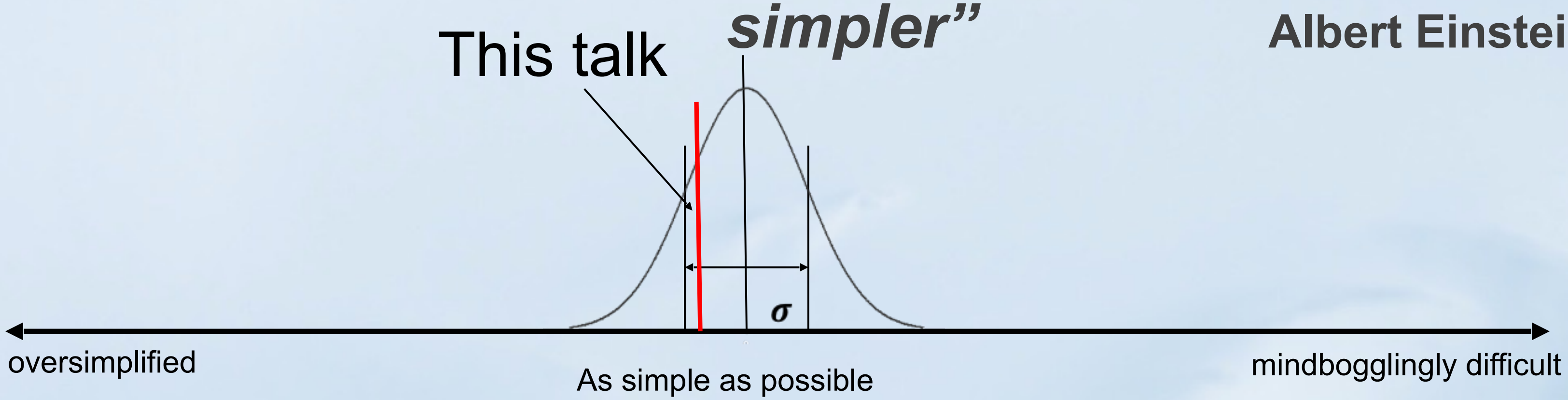

Outline

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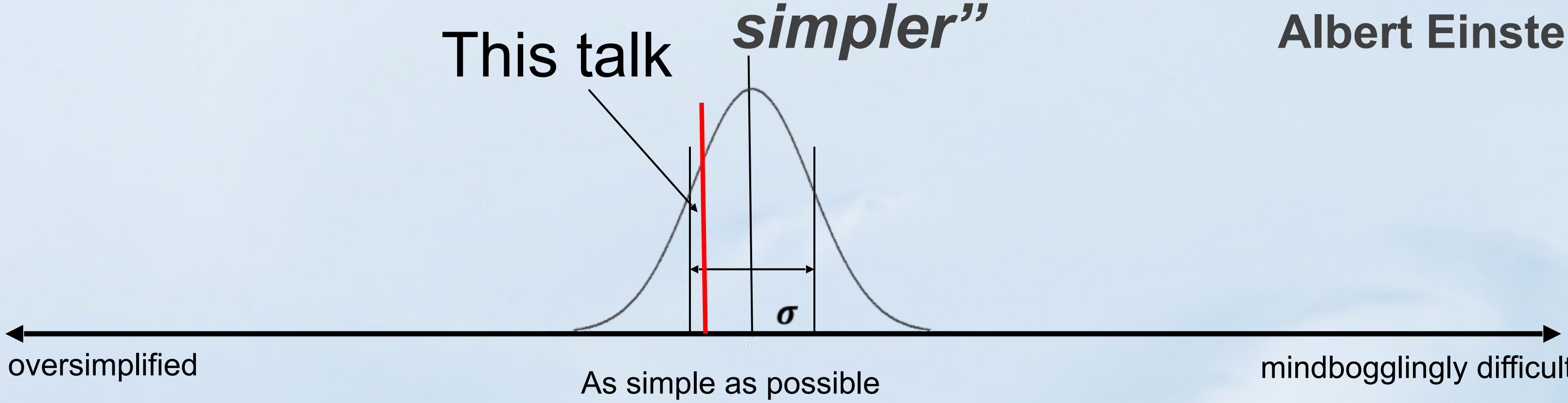
- The ionosphere
- Inco ... ory

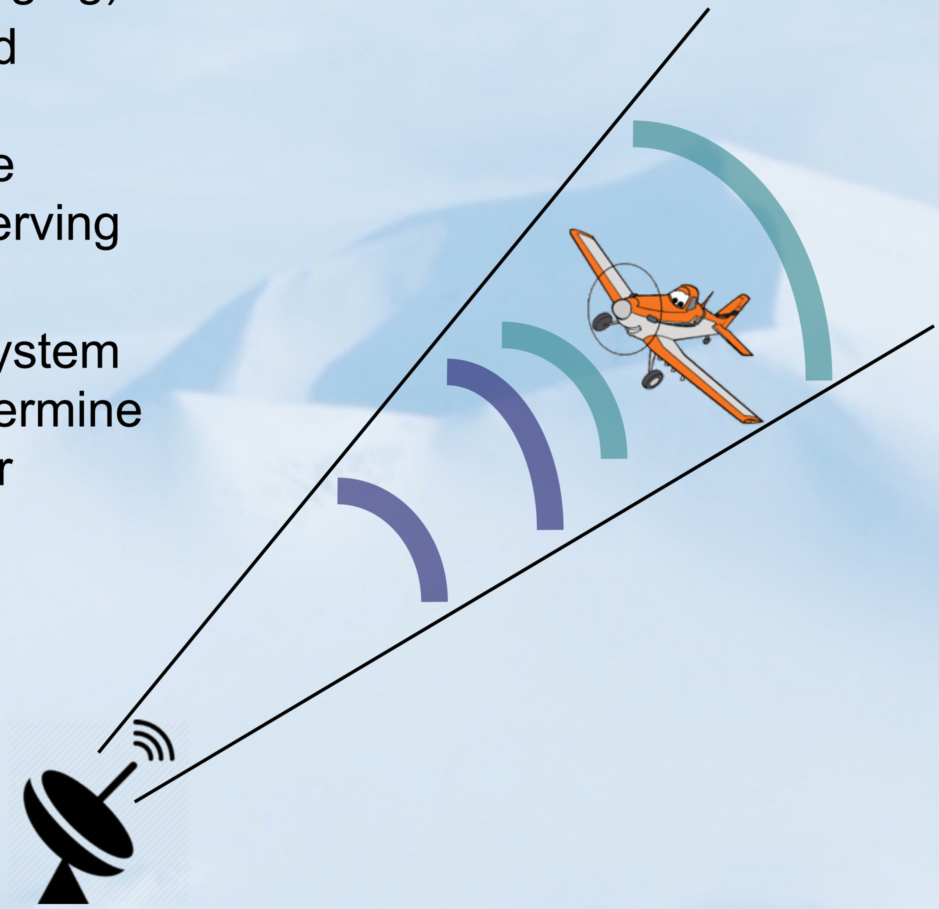
"For every complex problem there is an answer that is clear, simple, and wrong" **H. L. Mencken**

... be made ... ble, but no simpler" **Albert Einstein**



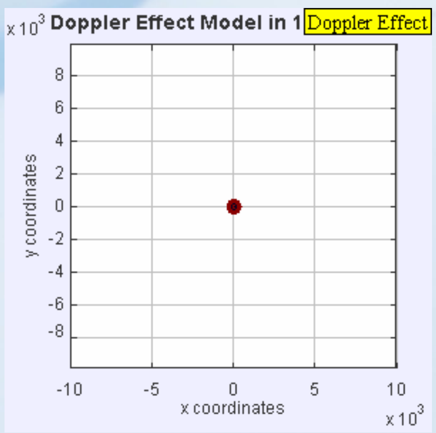
Radar

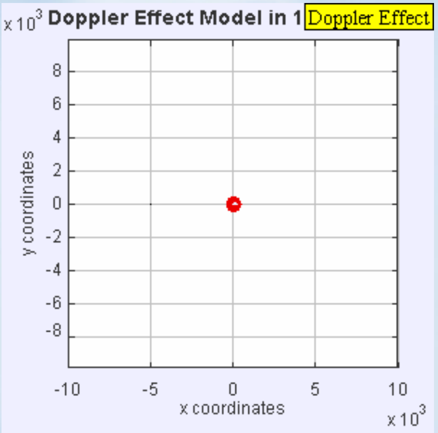
- RADAR (RAdio Detection And Ranging)
  - is a technique for detecting and studying remote targets by transmitting a radio wave in the direction of the target and observing the reflection of the wave.
  - **Radar** is an object detection system which uses radio waves to determine the range, altitude,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



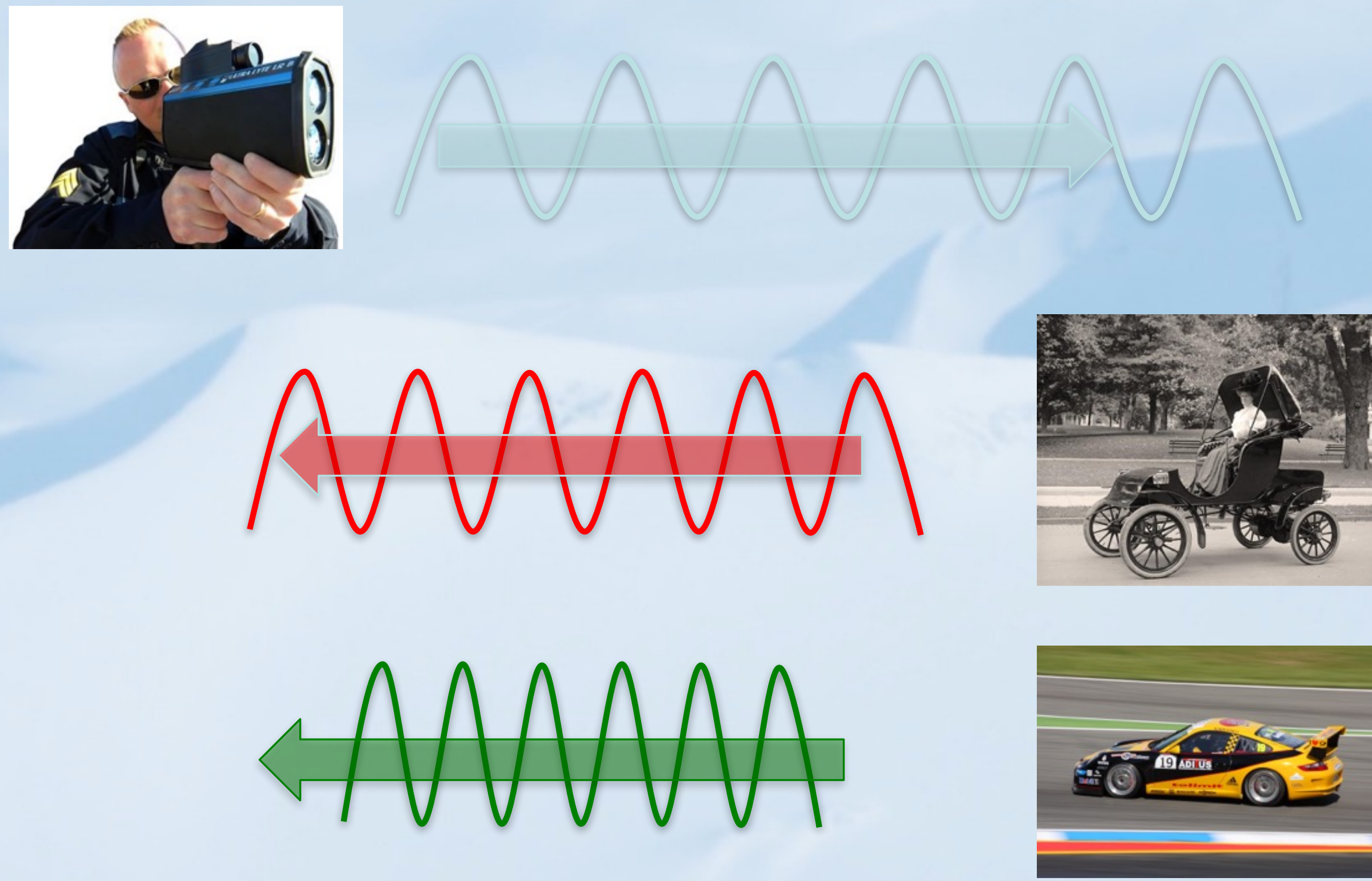
Doppler Radar

- In order to detect the velocity of the target we are taking advantage of a concept called Doppler Shifts
- We are rather familiar with it when if comes to sound waves

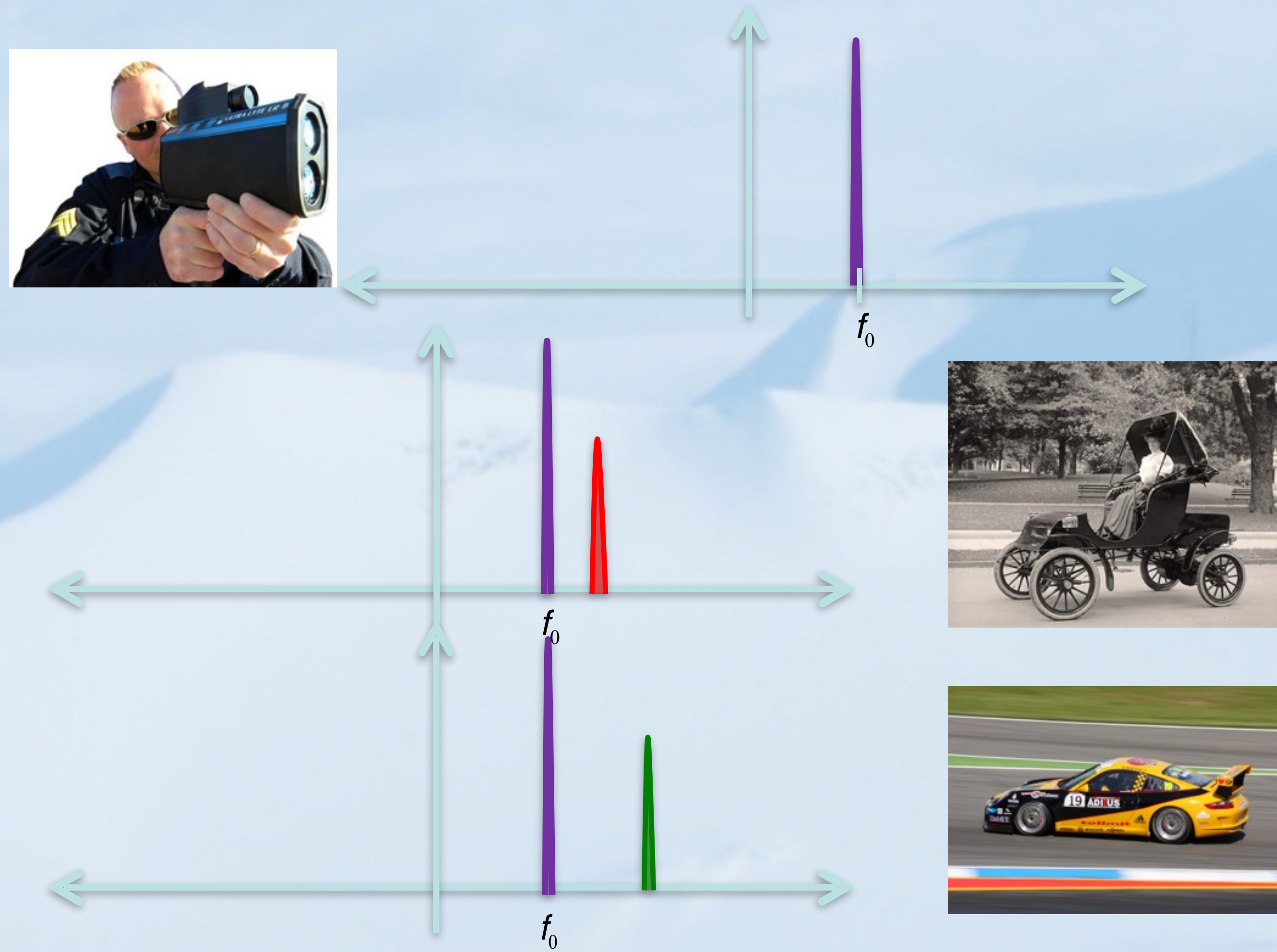




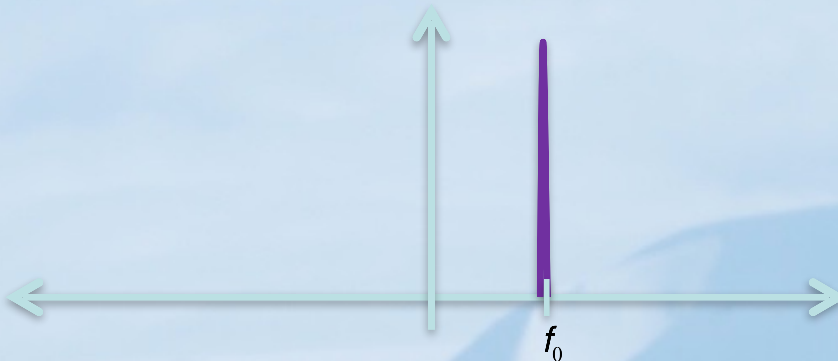
Doppler Radar – time domain

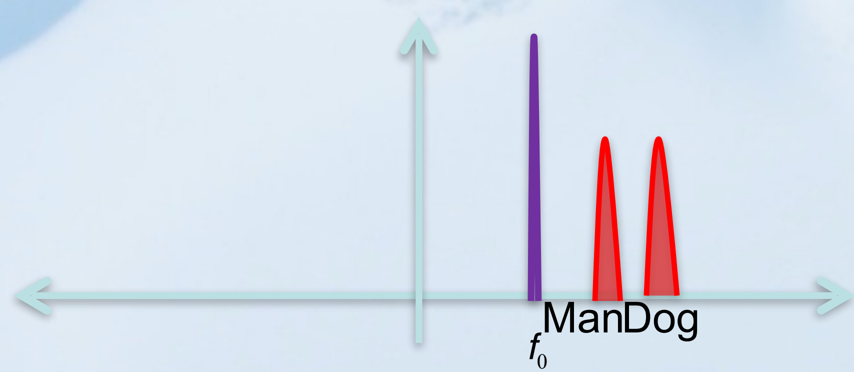


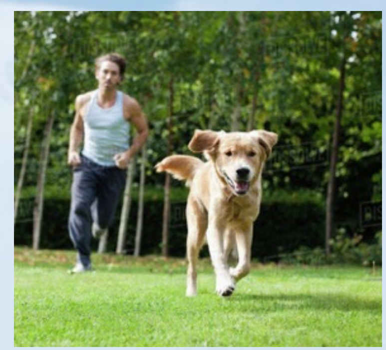
Doppler Radar – frequency domain

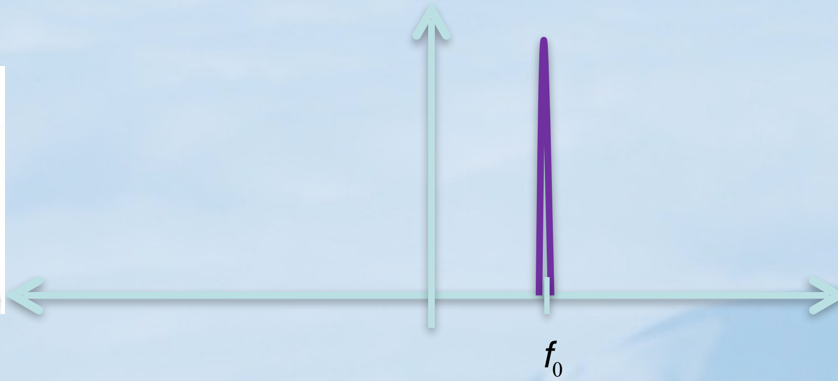


Doppler Radar – frequency domain





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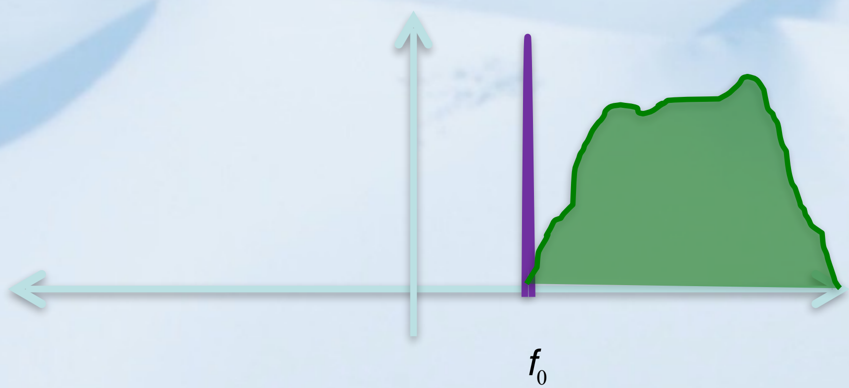
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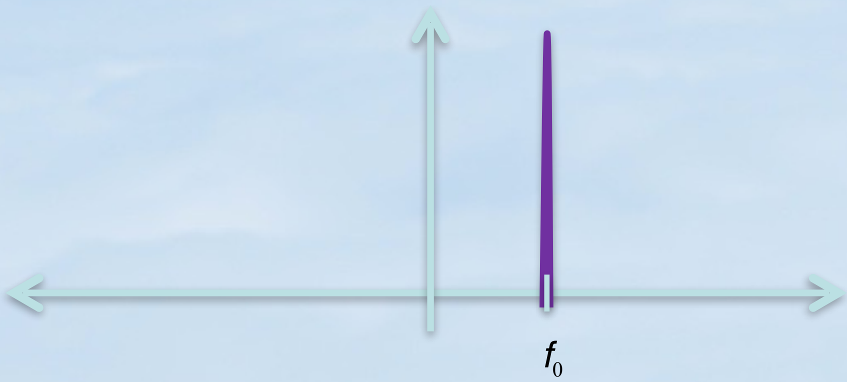
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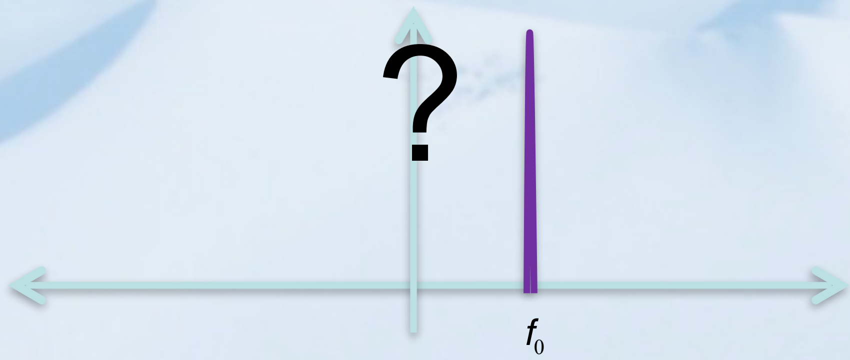
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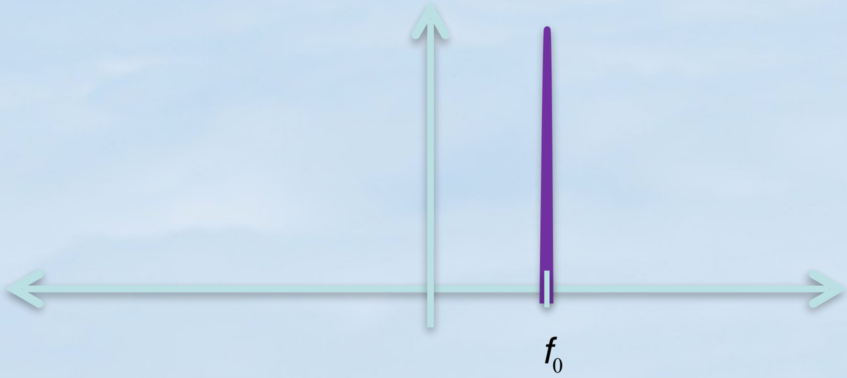
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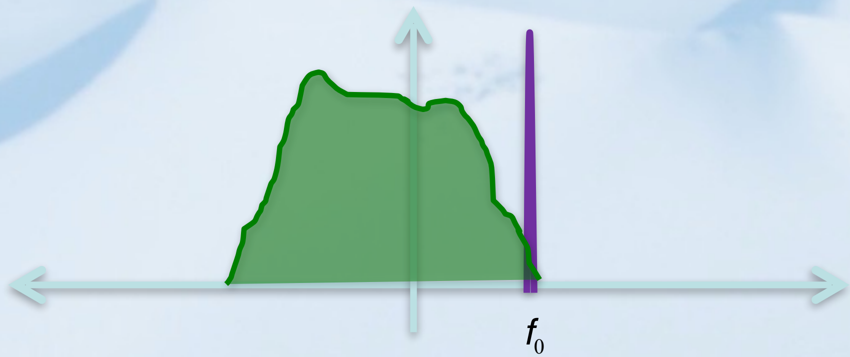
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How can we use this method here?

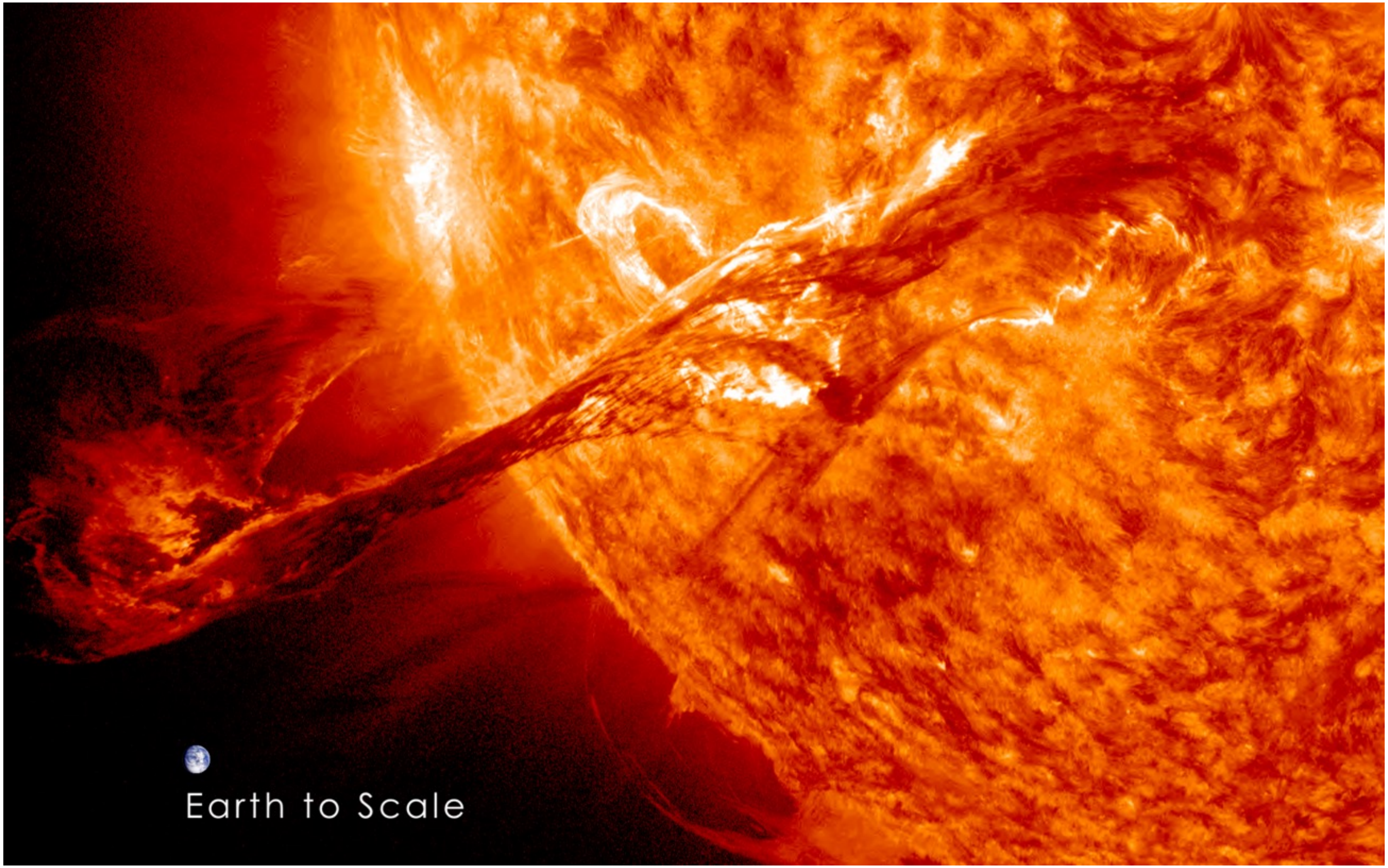
...and at slightly higher latitudes here?

The answer is....

The answer is....

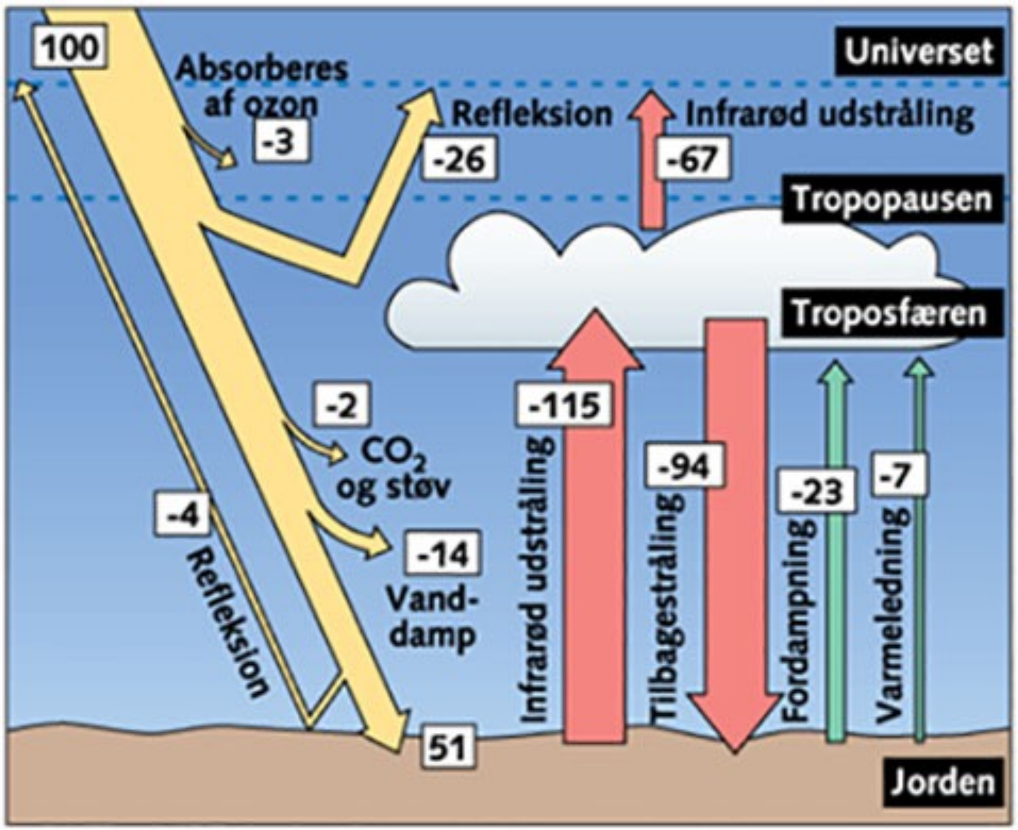
Electrons!

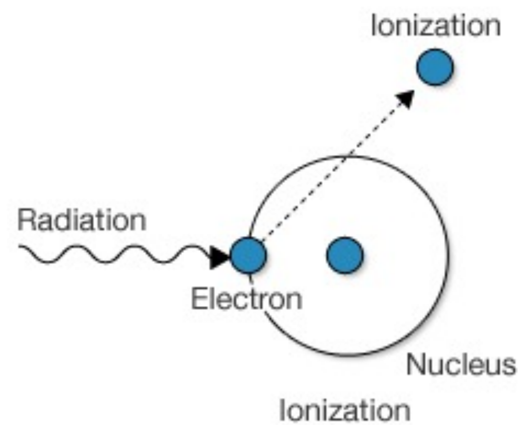
Like most things on Earth – it all starts on the Sun...



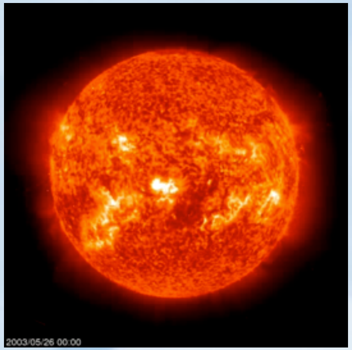
UV radiation

UV and EUV radiation is driving Earths energy balance, and are responsible for an ionosphere with charged particles in the upper part of our atmosphere.

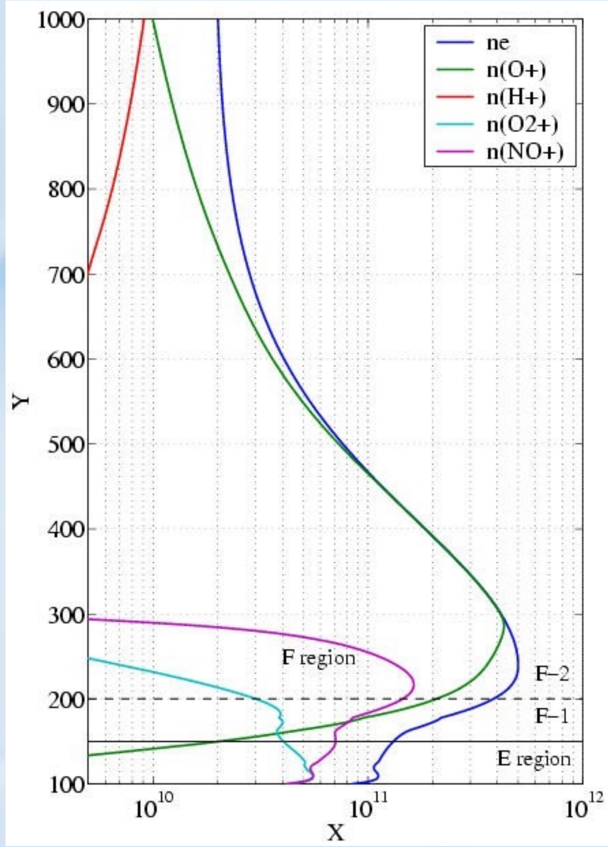




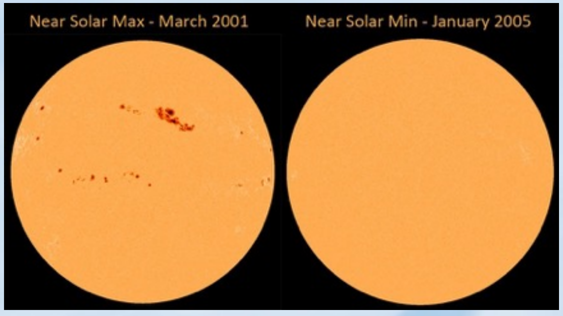
Electron Density profile

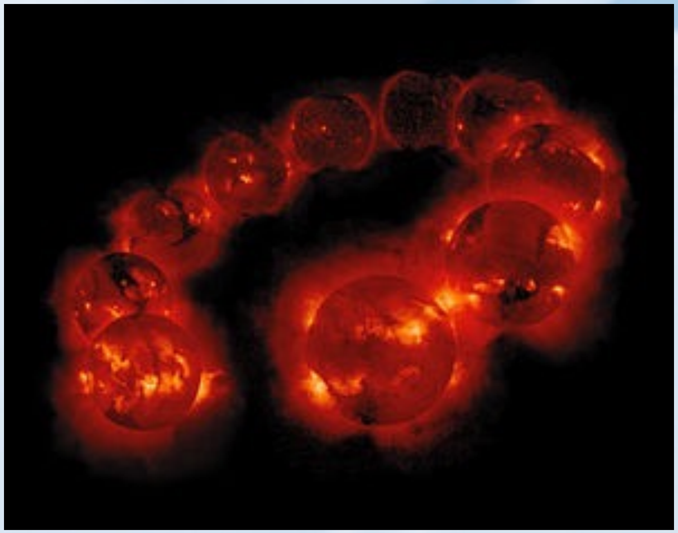


A complex balance between the ionization and recombination and diffusion results in an altitude dependent electron (and ion) density profile.

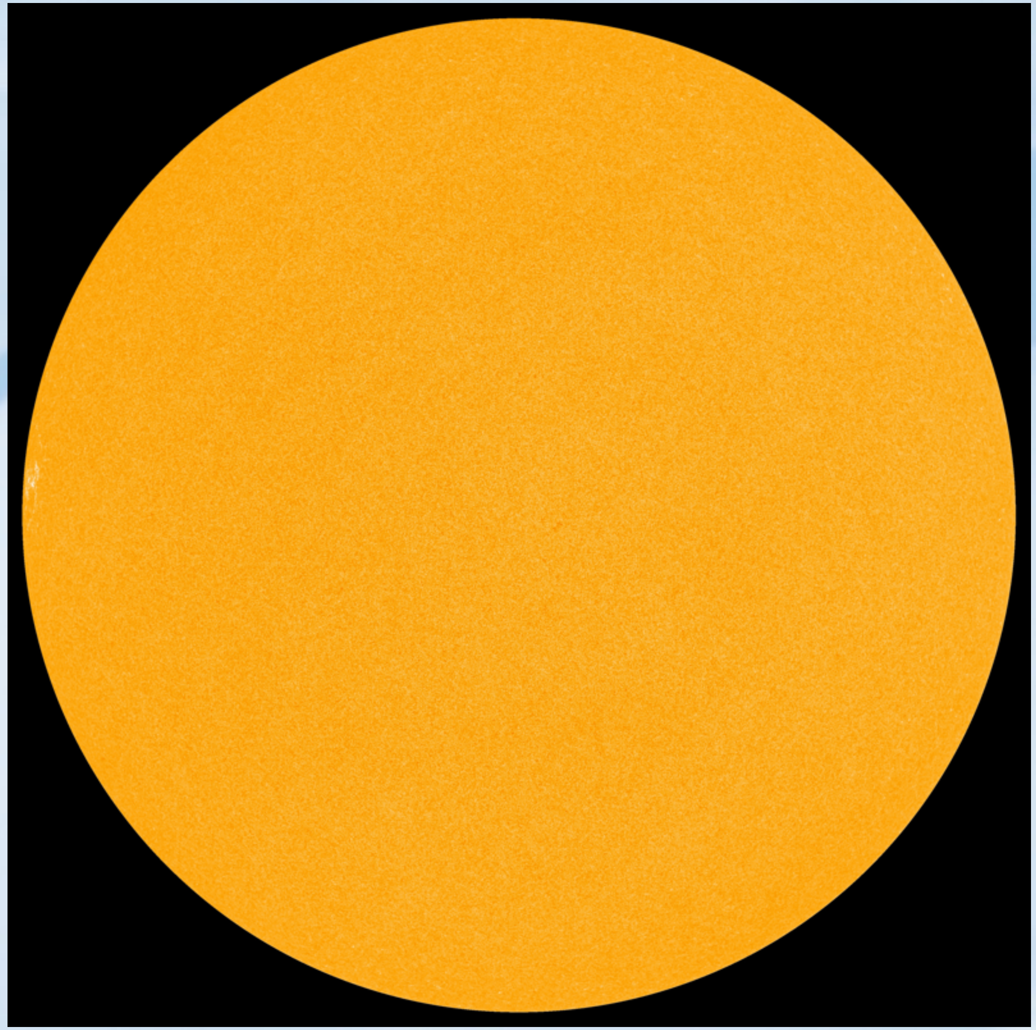


The Sun is an active star!

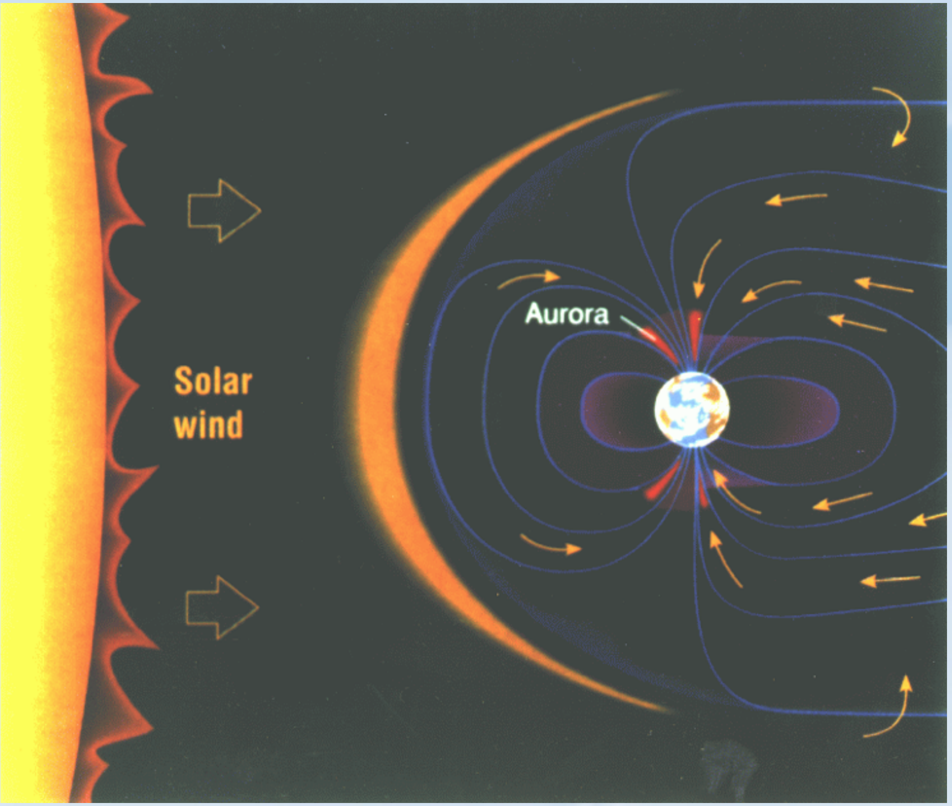




The Sun is an active star... Most days...!



At high latitudes electron (and proton) with solar wind origin creates additional ionization, seen as aurora borealis/australis dispays



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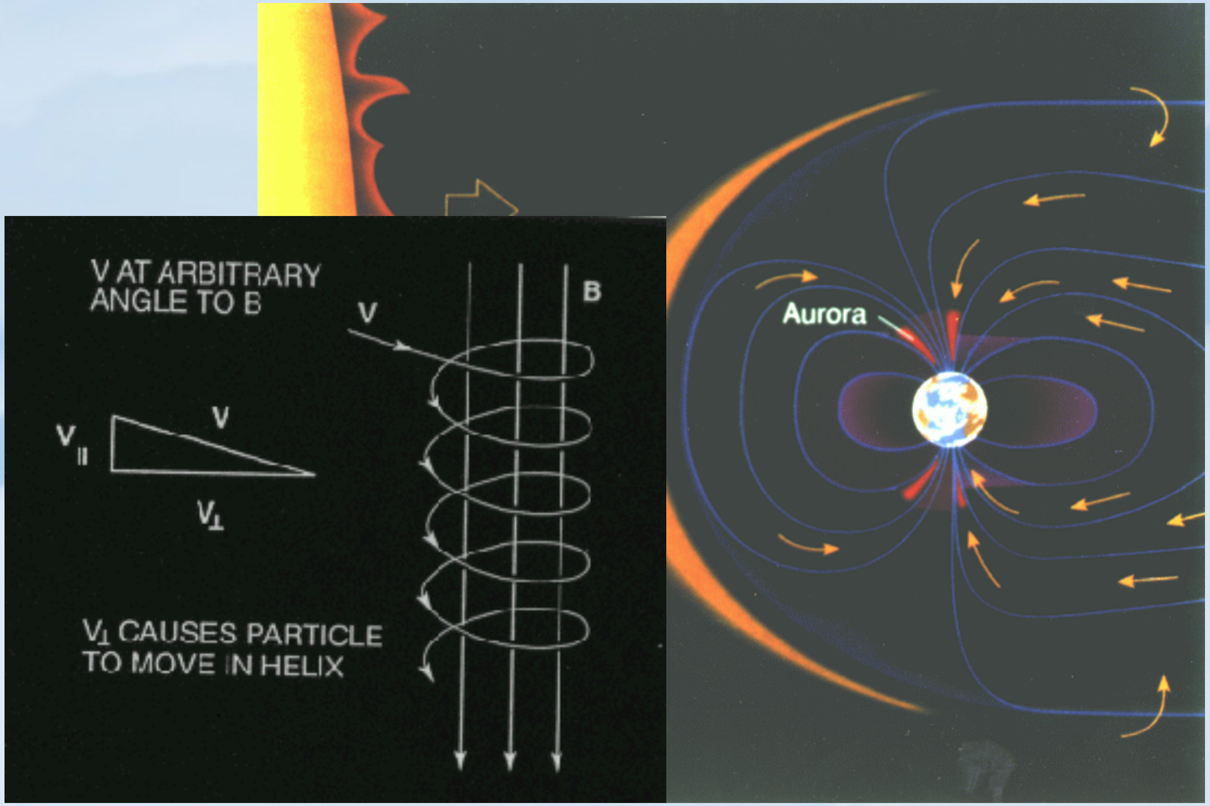

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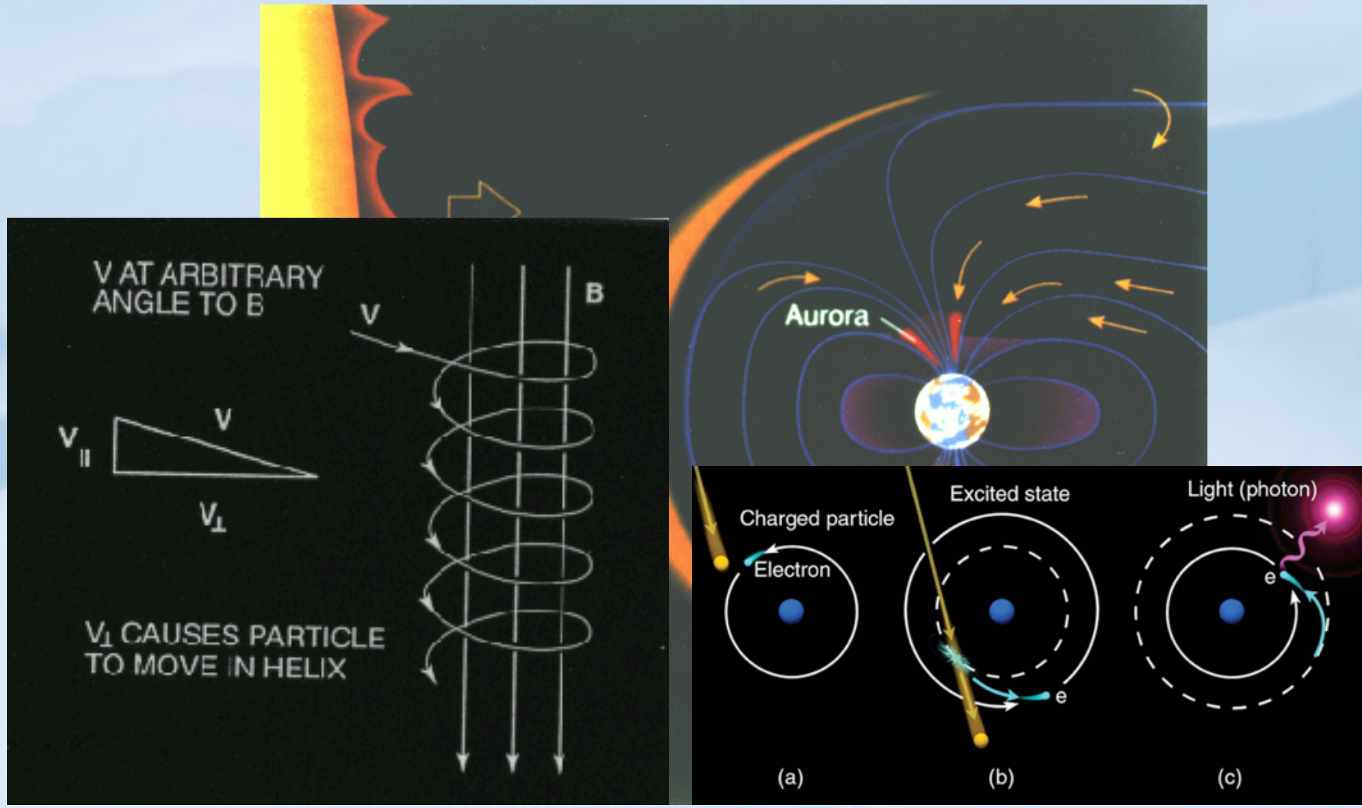

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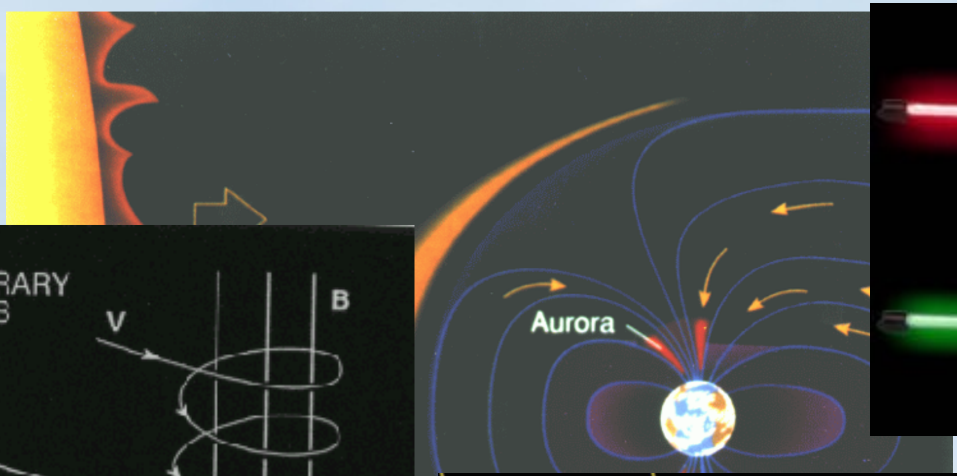

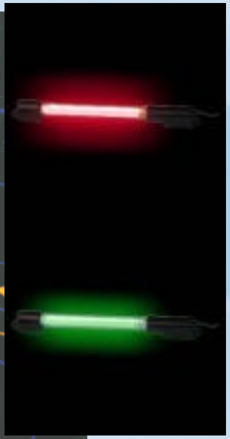

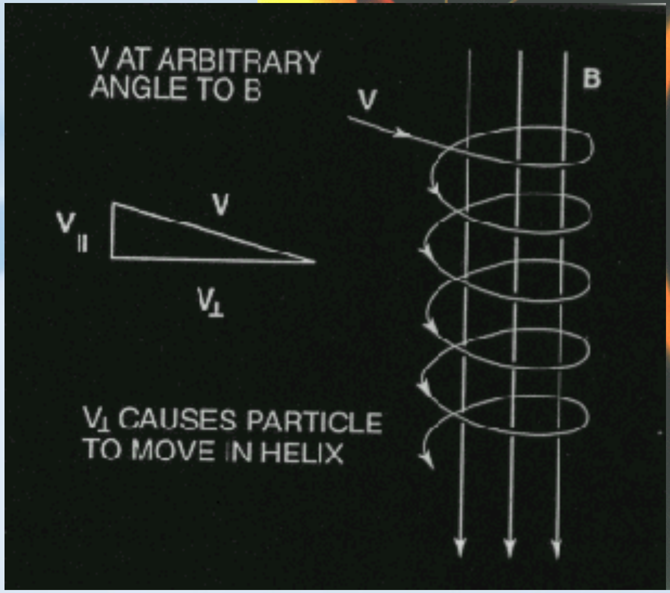

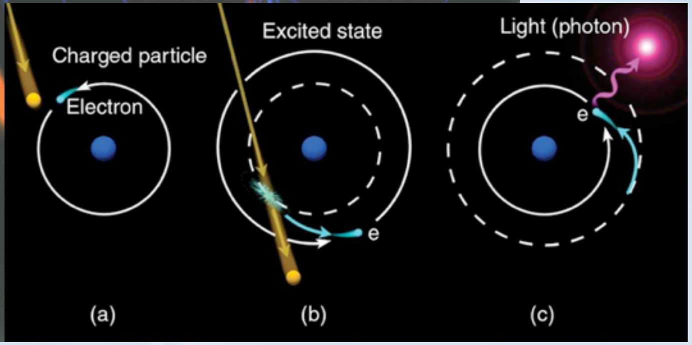

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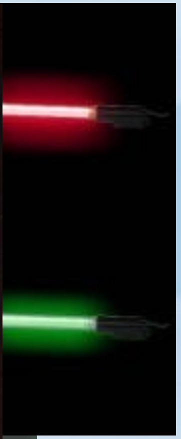
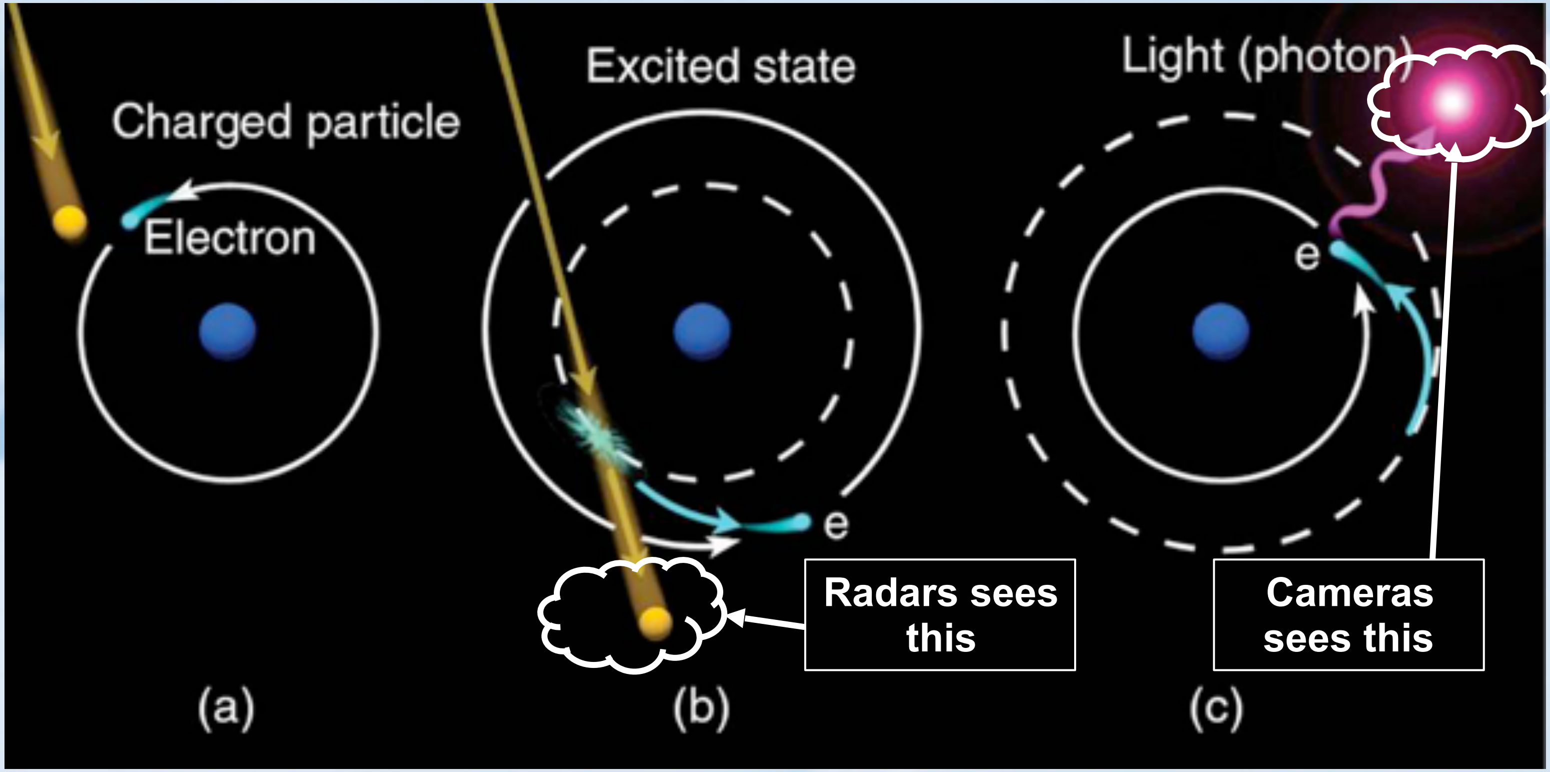
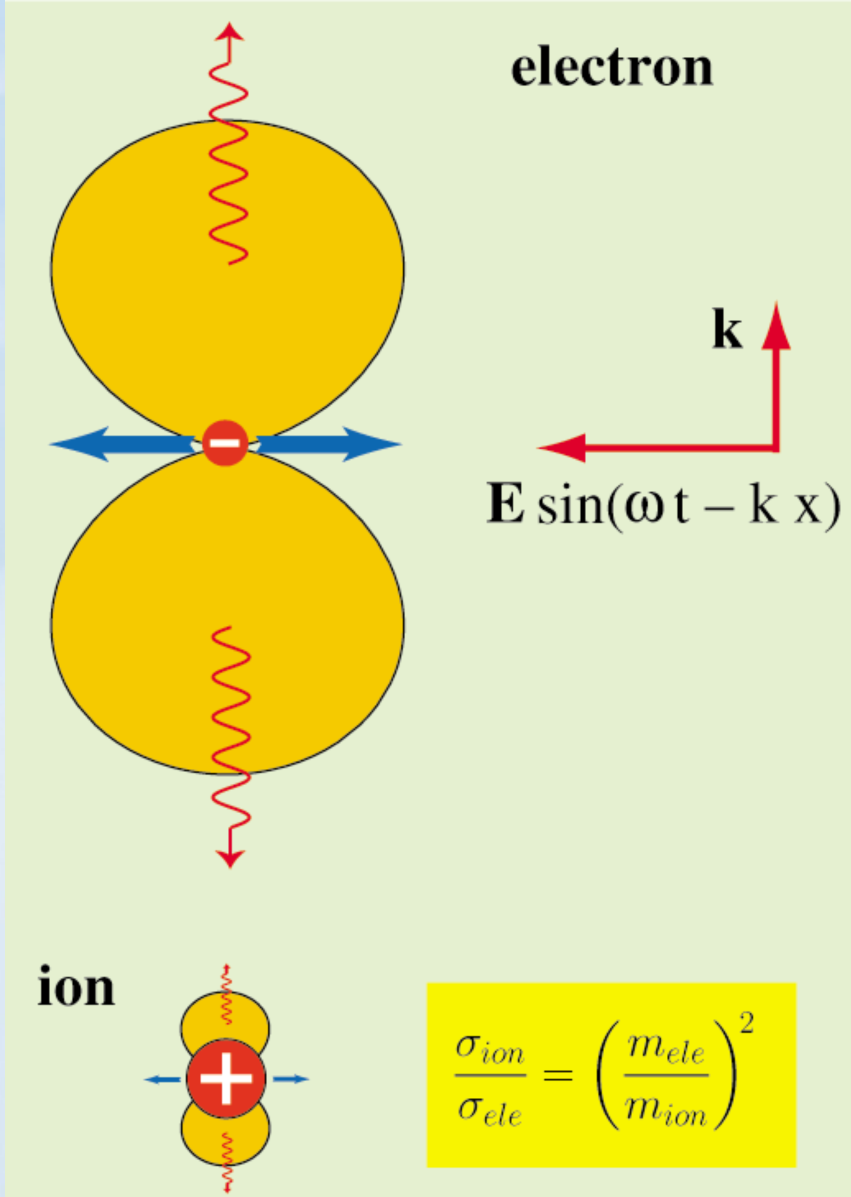


Optical versus Radar Aurora



Scattering from charged particles

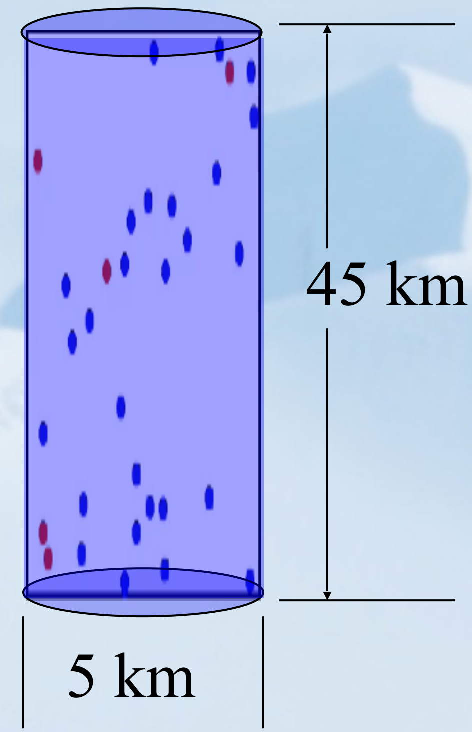
- When a charged paraticle is subjected to an electriomagnetic wave, it start occilating with the wave
- When a charged particle occilates it emitts an electromagnetic wave
- So by radiating an electron with a radar wave, the electron becomes a tiny antenna itself and radiates power in all directions



$$\frac{\sigma_{ion}}{\sigma_{ele}} = \left(\frac{m_{ele}}{m_{ion}}\right)^2$$

Total cross section estimate:

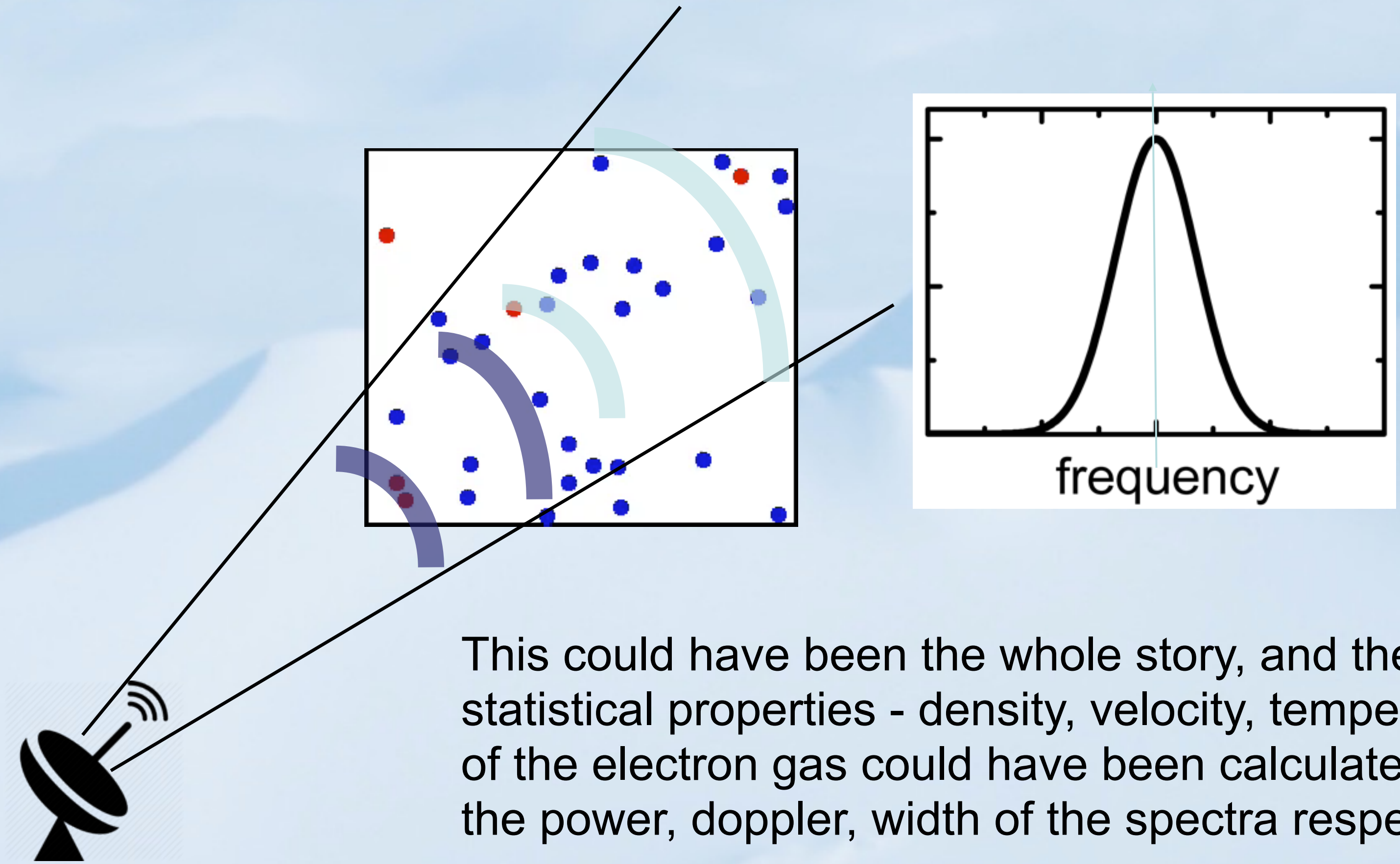
Consider an antenna with a 1-degree beam measuring the ionospheric plasma at 300 km range and using a 300 microsecond pulse.
If the electron density is 10^{12} m^{-3}, the total number of electrons scattering into a given measurement is ~8.8×10^{23}. This yields a total cross-section of 88 mm^2 – we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



"The possibility that incoherent scattering from electrons in the ionosphere, vibrating independently, might be observed by radar techniques has apparently been considered by many workers although seldom seriously because of the enormous sensitivity required…"

K.L. Bowles [Cornell PhD 1955], Observations of vertical incidence scatter from the ionosphere at 41 Mc/sec. *Physical Review Letters* 1958:

Thermal fluctuating electrons
"Incoherent Scattering"



This could have been the whole story, and the statistical properties - density, velocity, temperature - of the electron gas could have been calculated from the power, doppler, width of the spectra respectively...

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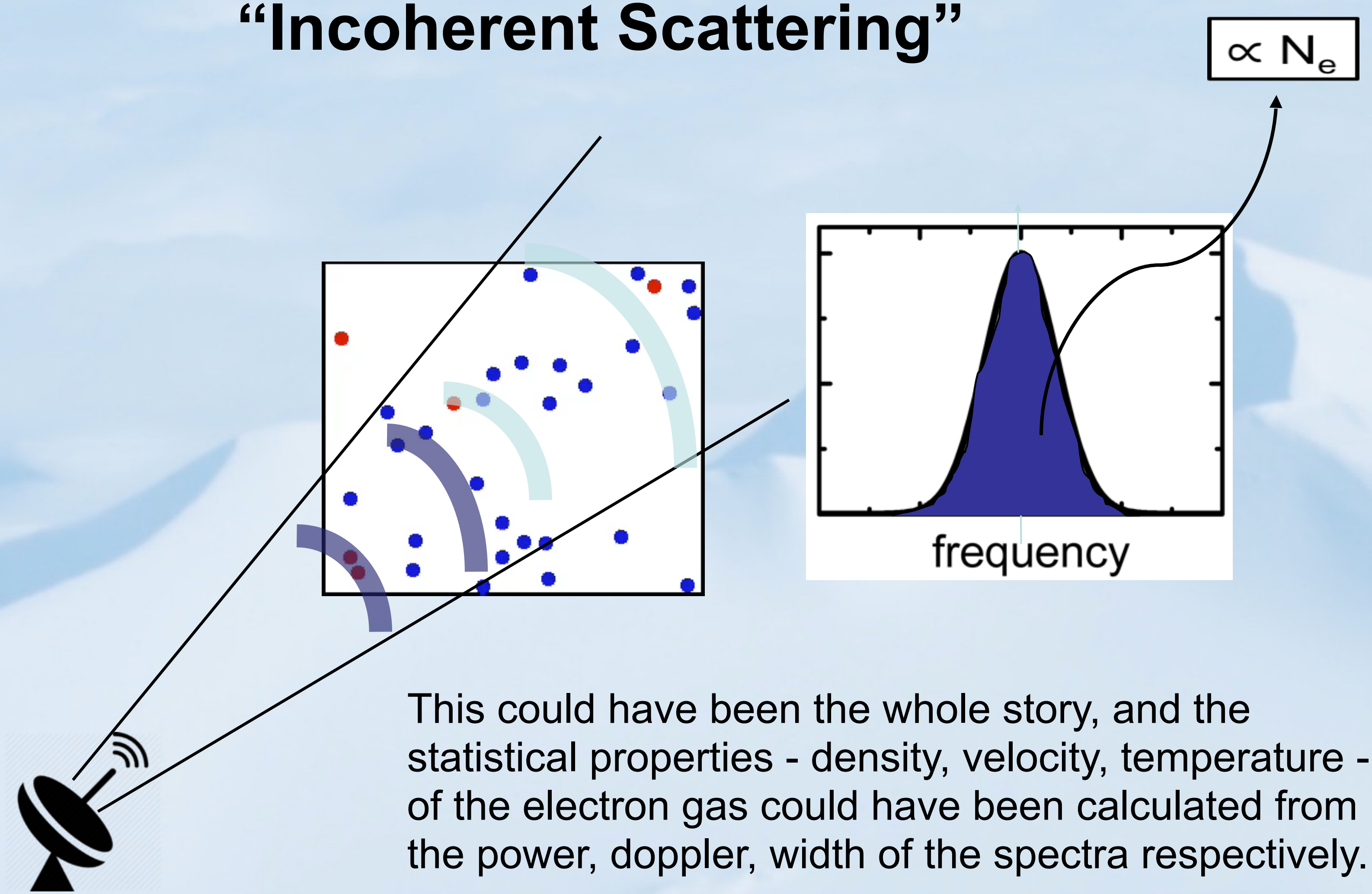

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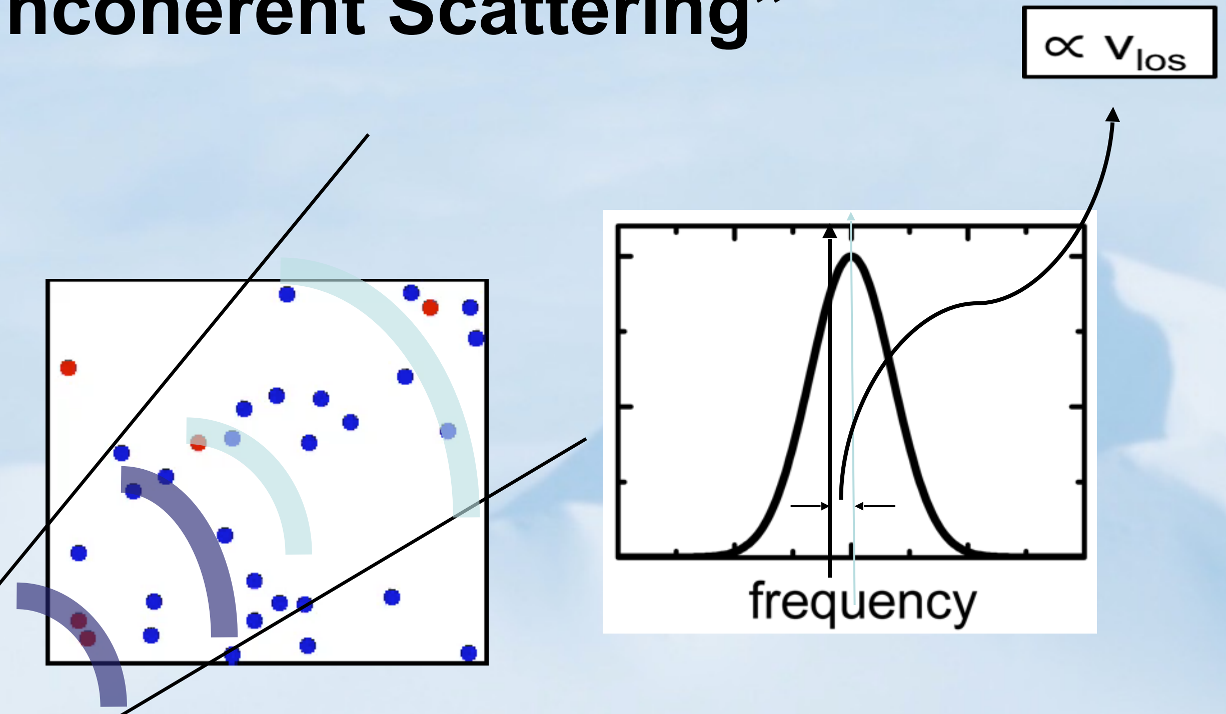

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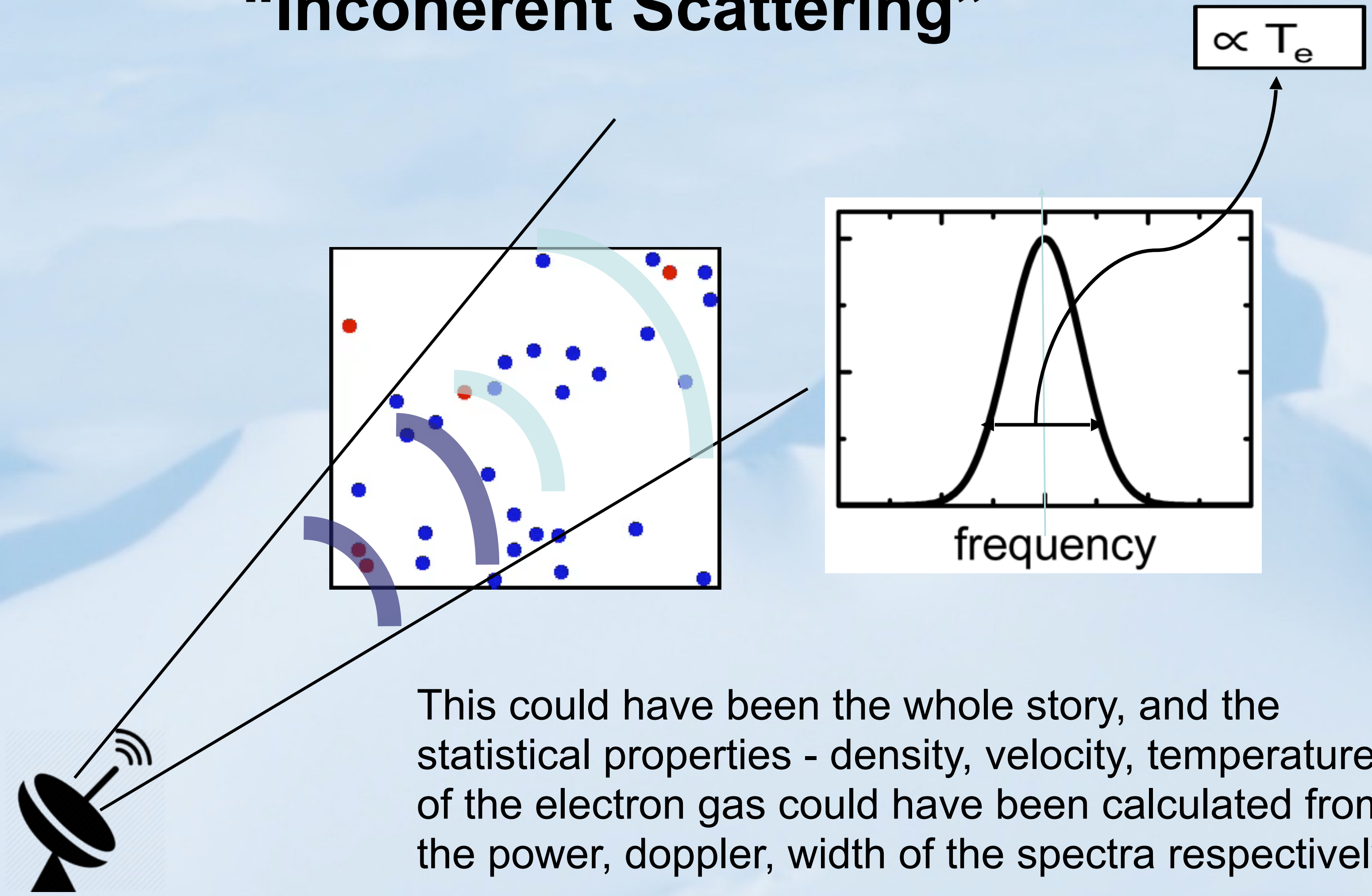

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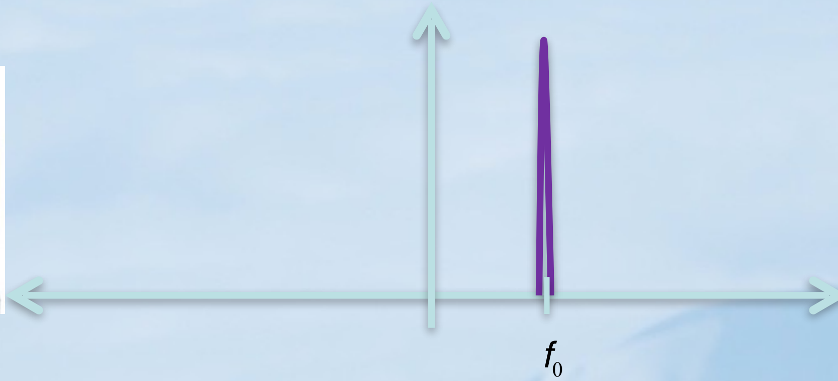
In order to detect this you need Arecibo

What if there are colletive behaviours in the ionospheric plasma....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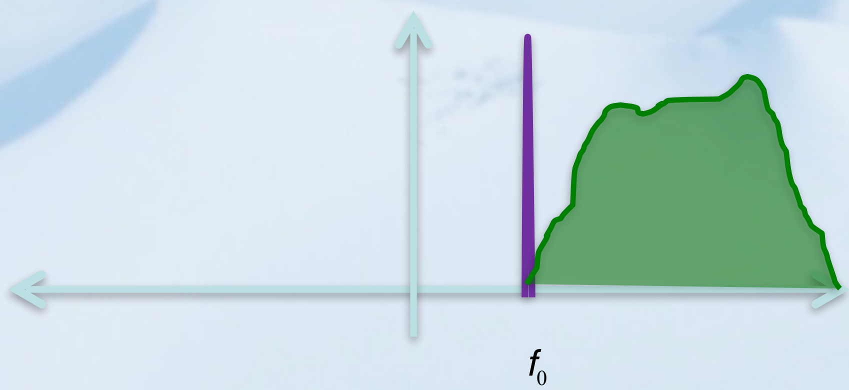
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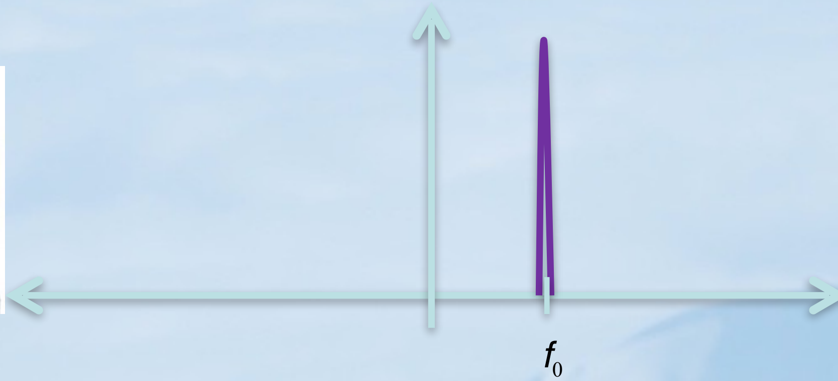
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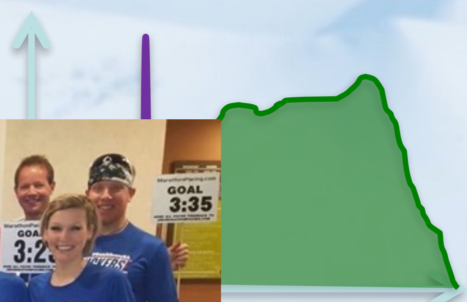


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START
START


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GOAL TIME 3:30
GOAL TIME 4:45
SNICKERS 26.2
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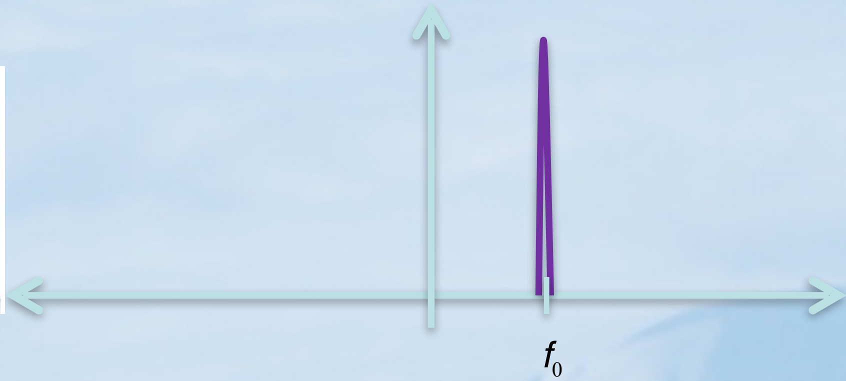
GOAL 4:20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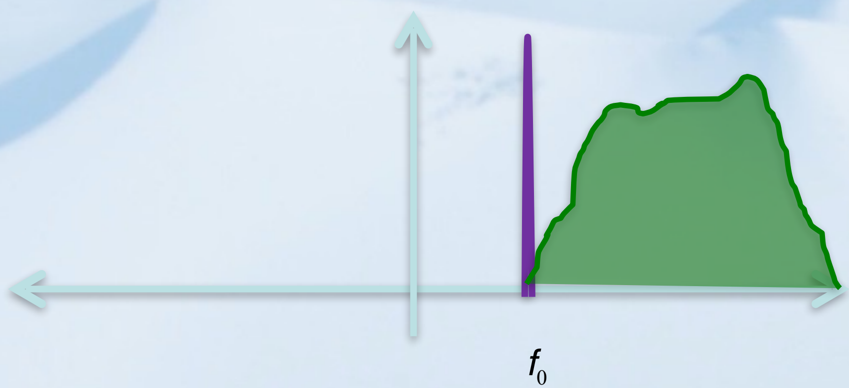
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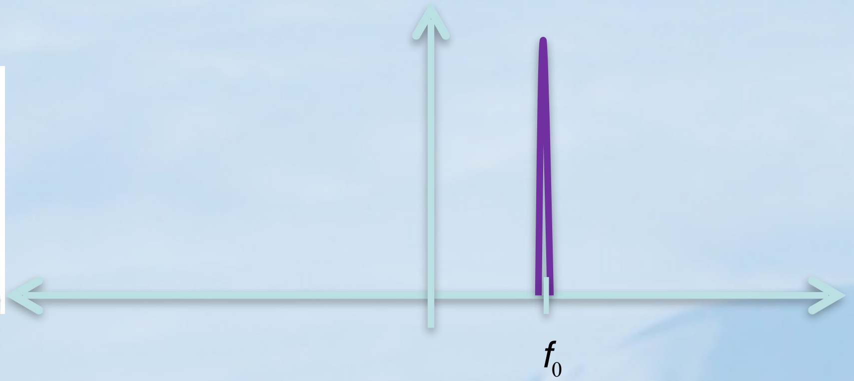
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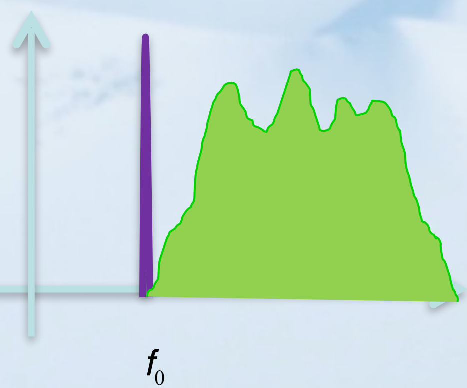
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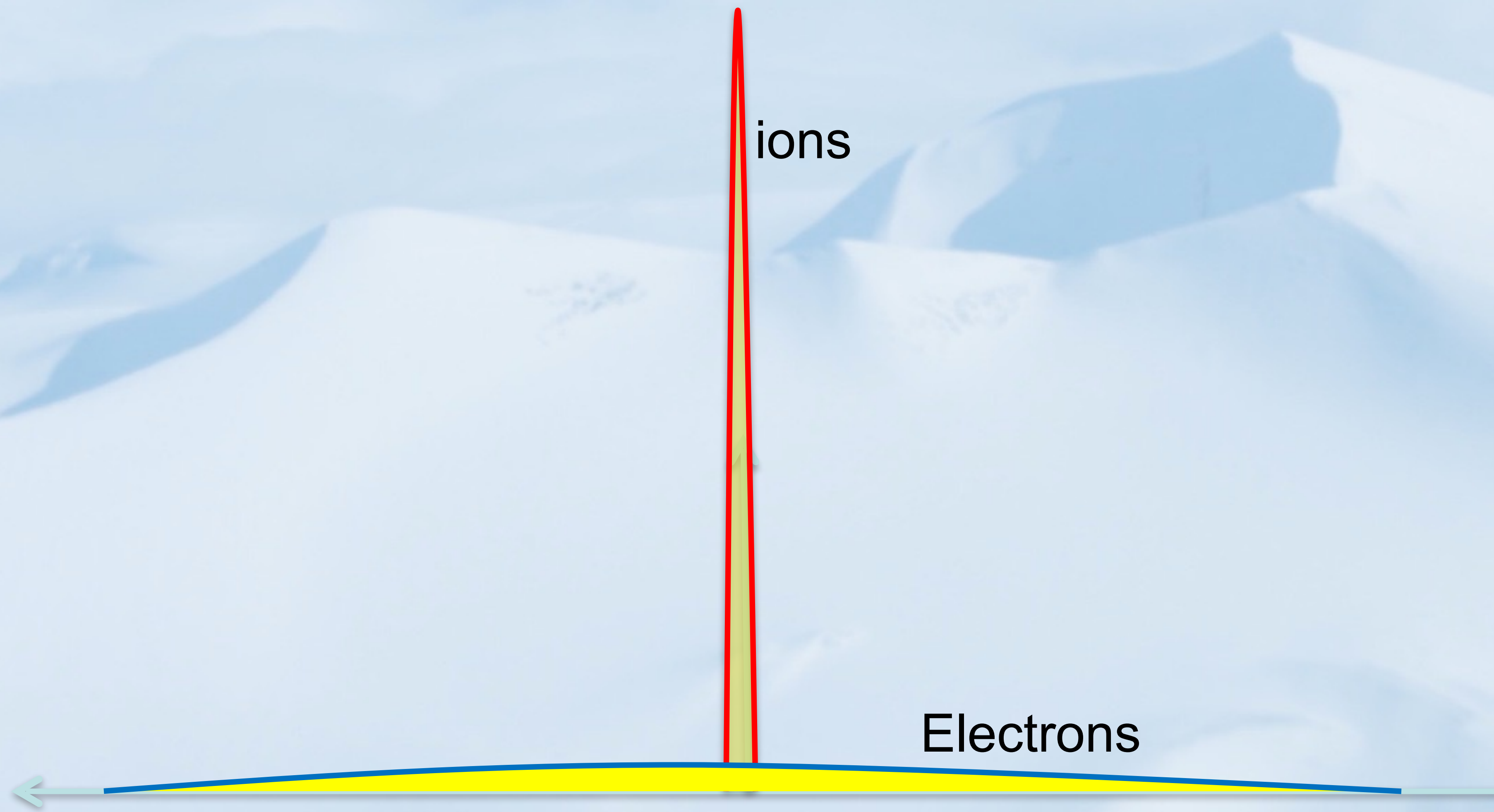
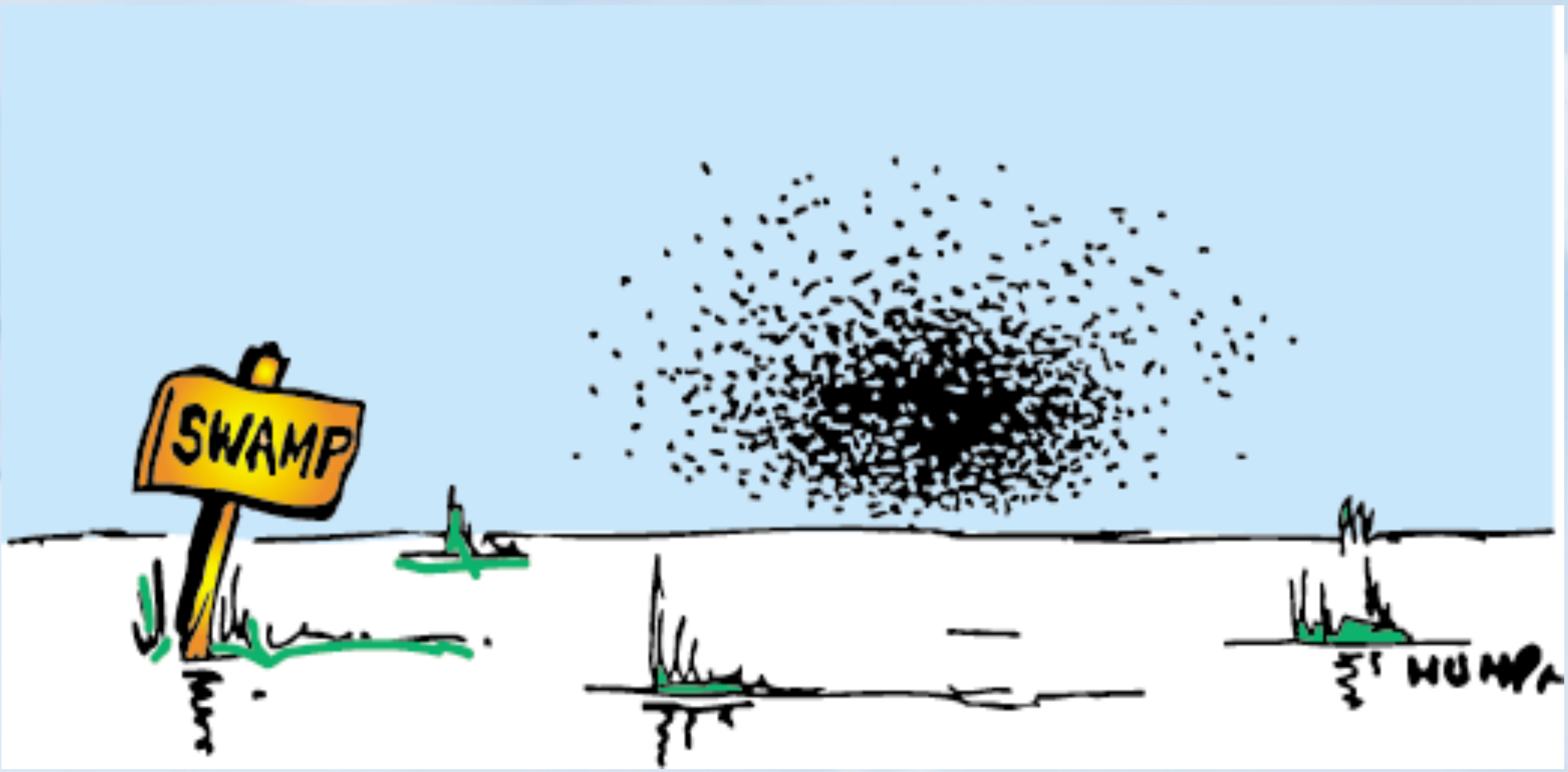
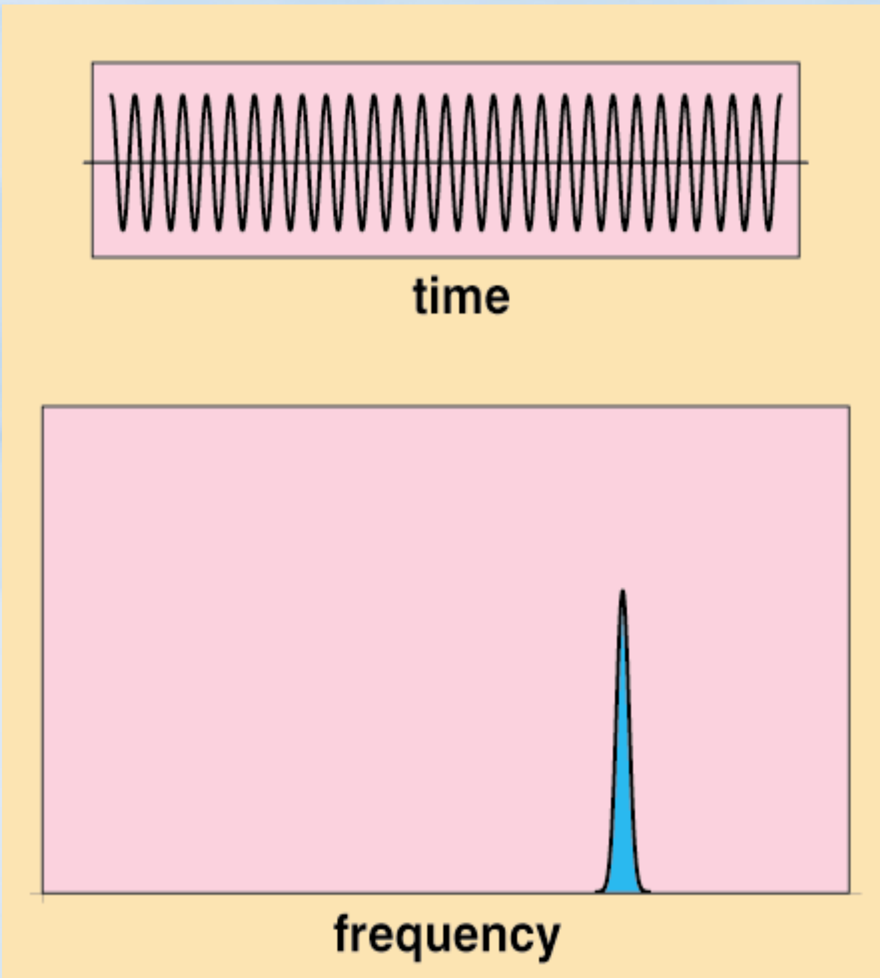
The ionospheric ions acts as slooooow pacers for the electron gas



Incoherent scattering - the short story



Incoherent scattering - the short story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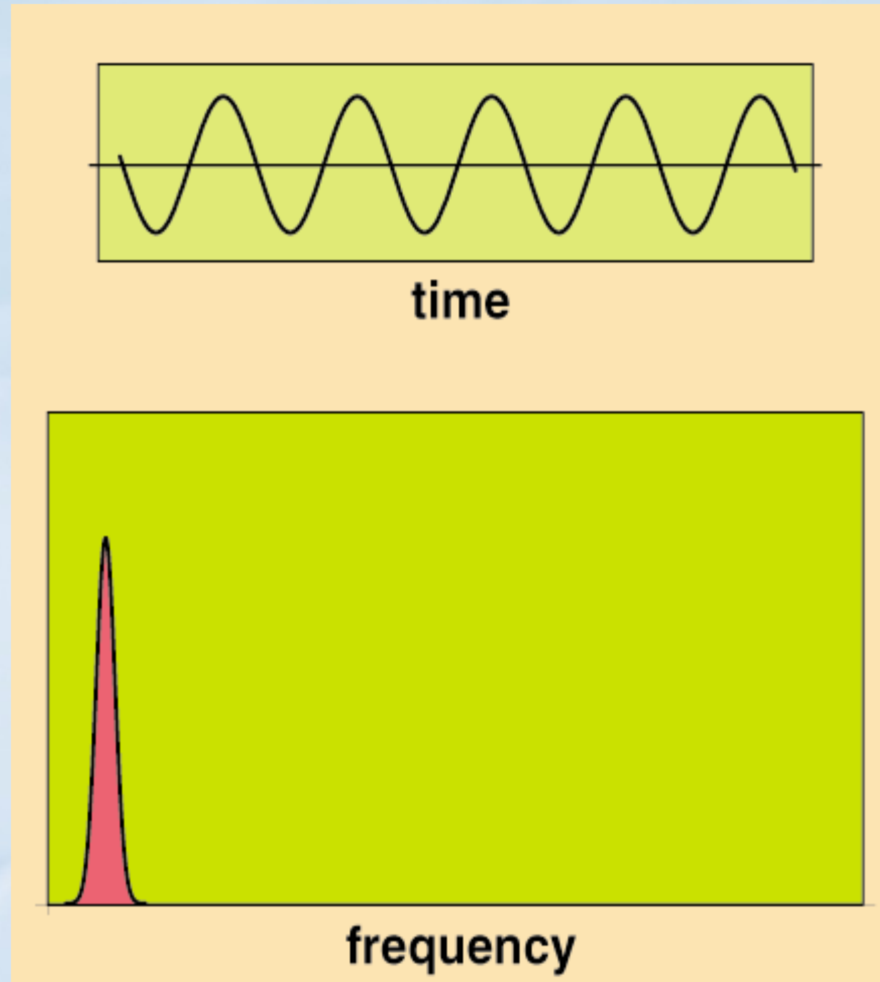
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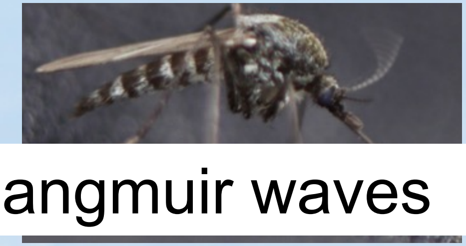
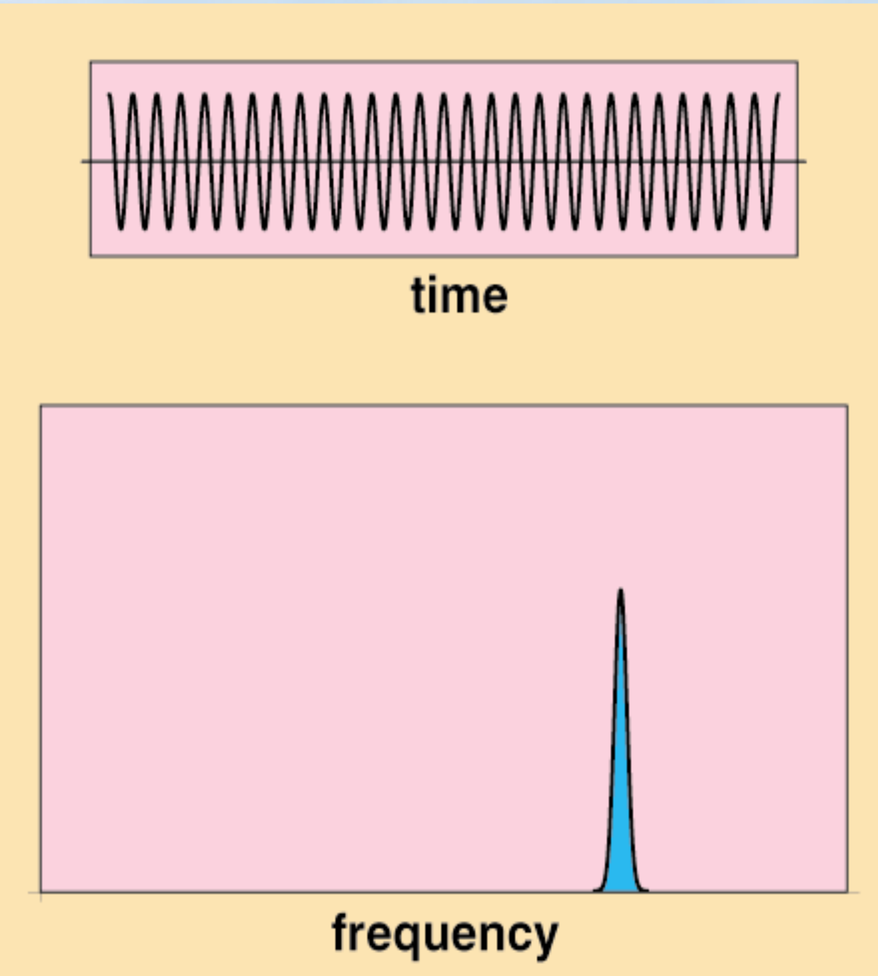
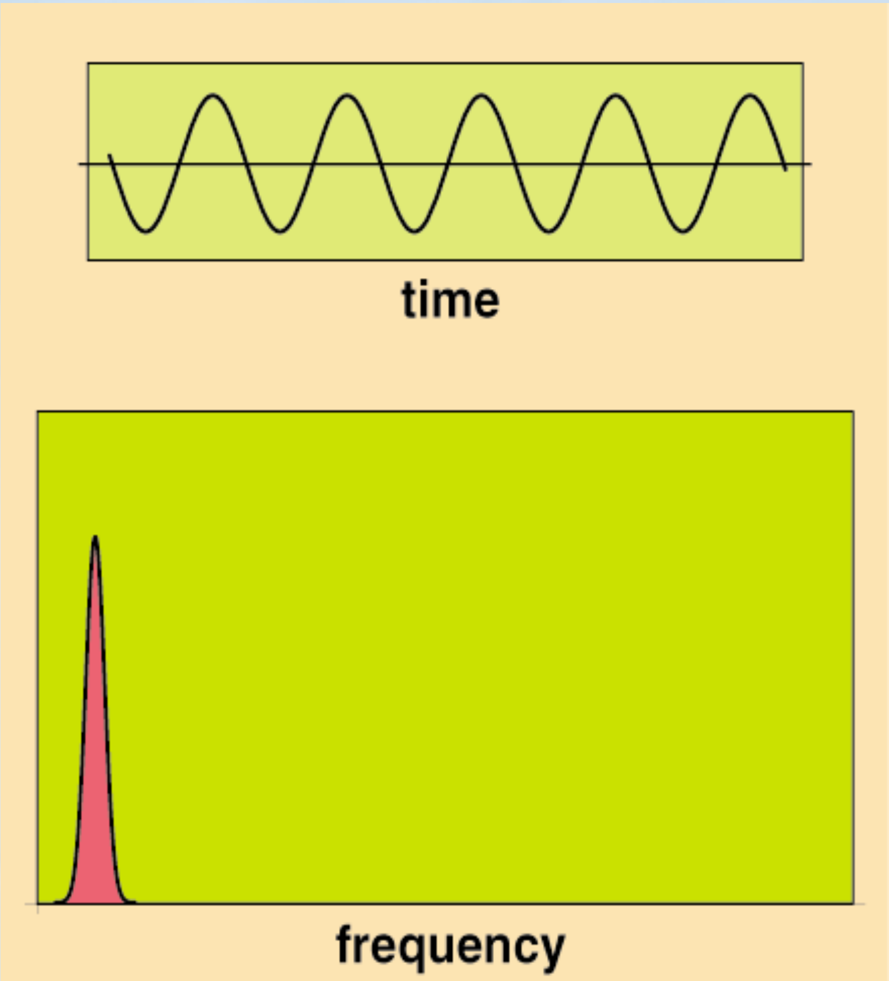
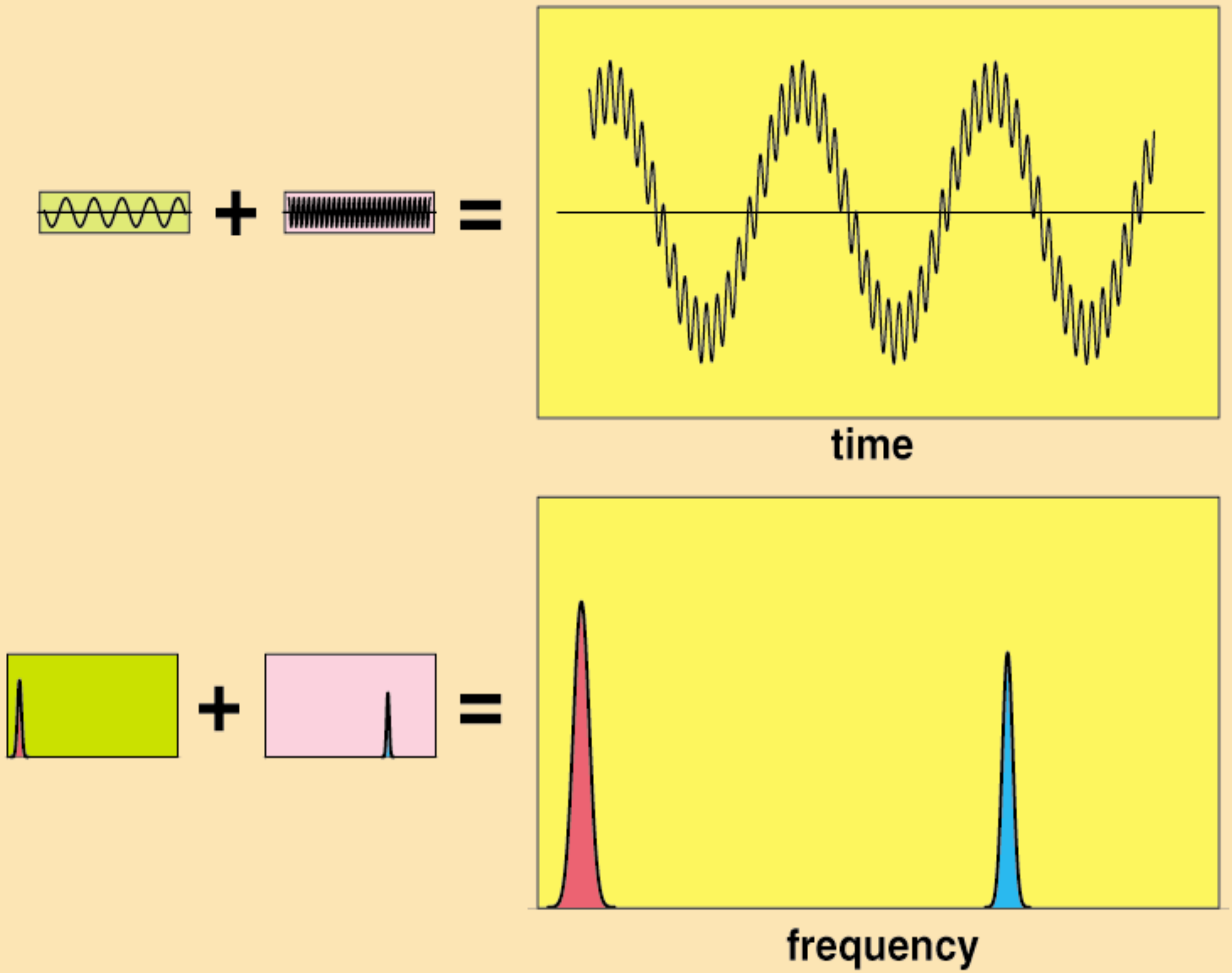


Langmuir waves

Ion acoustic waves



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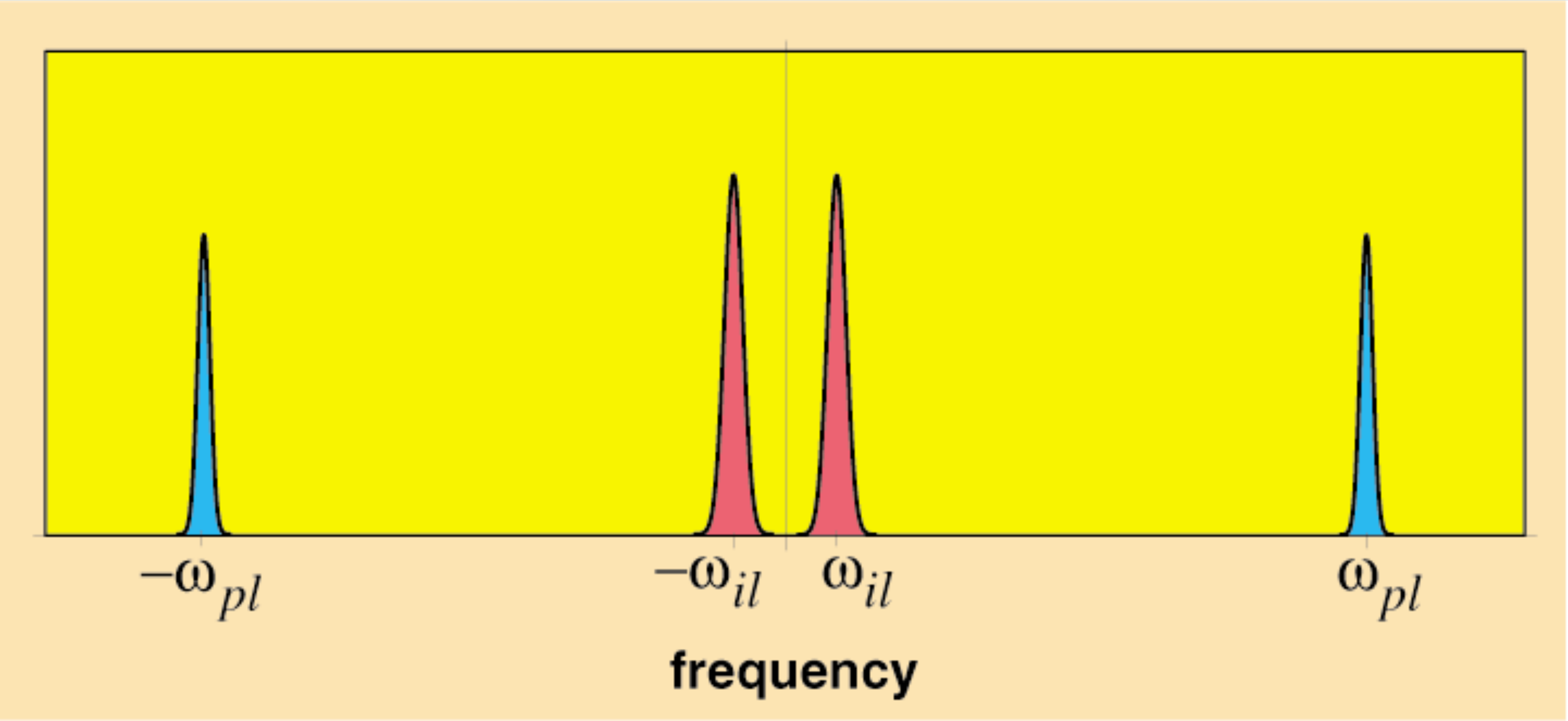
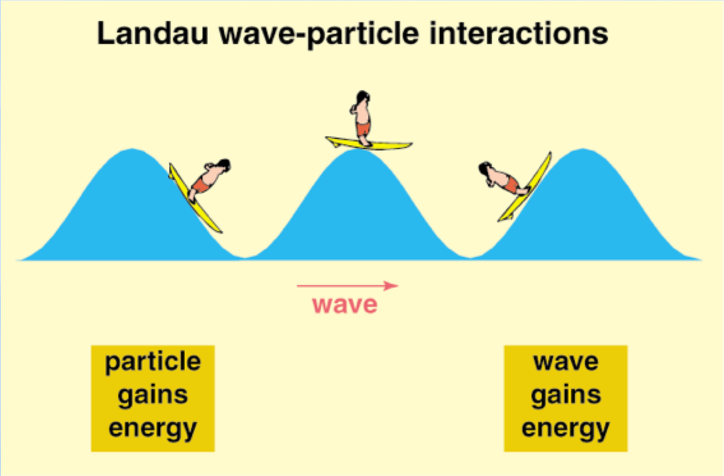
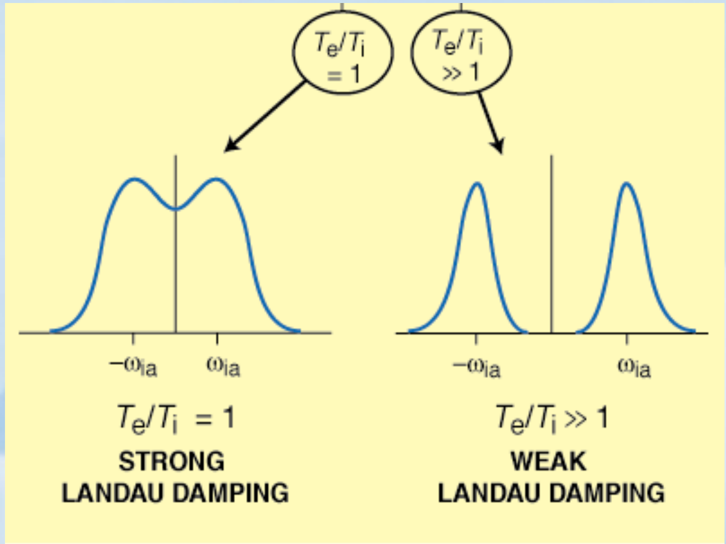
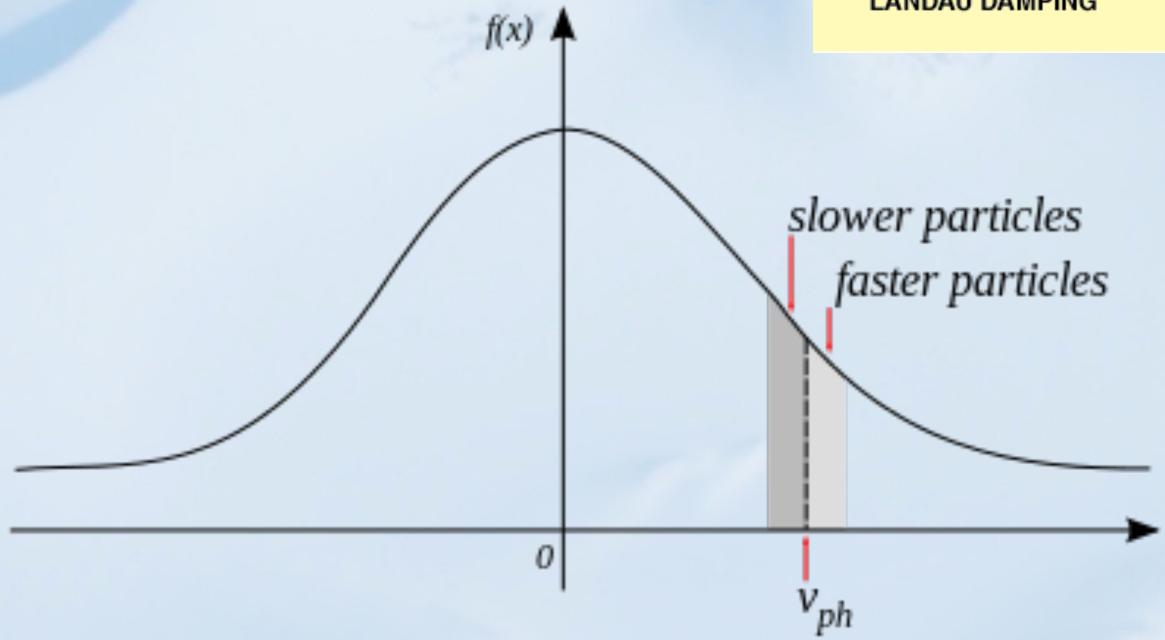
Plasma Wave Approach (cont'd)

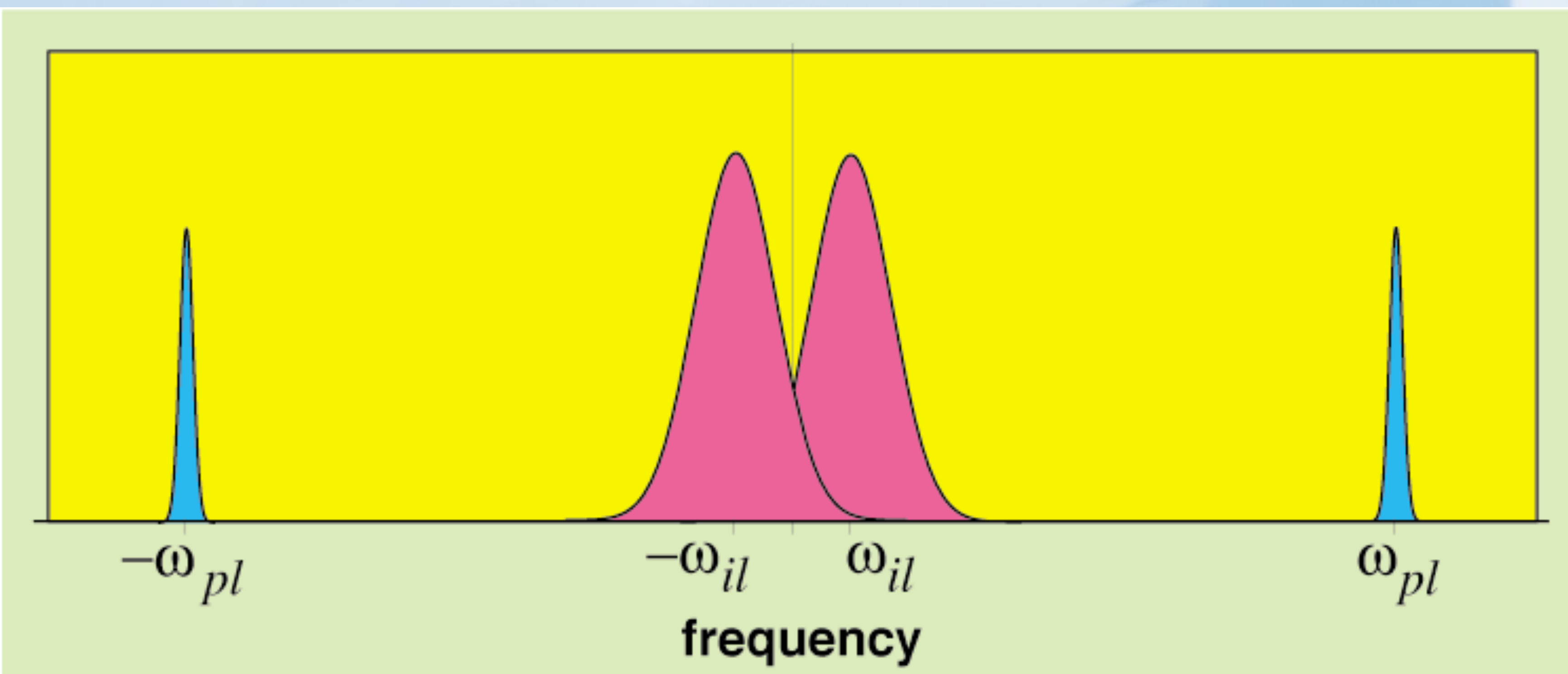


Landau damping









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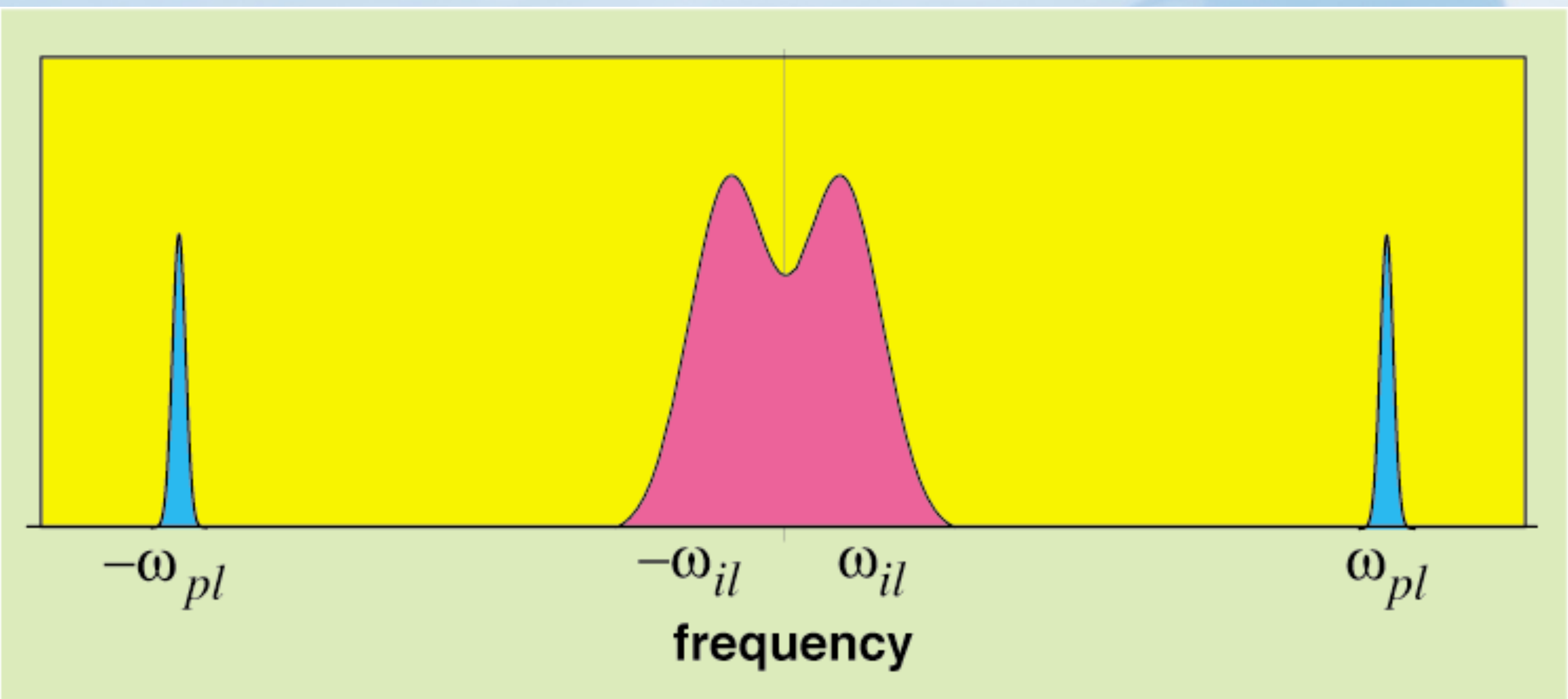
ω pl
frequency



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

Incoherent Scattering Spectrum

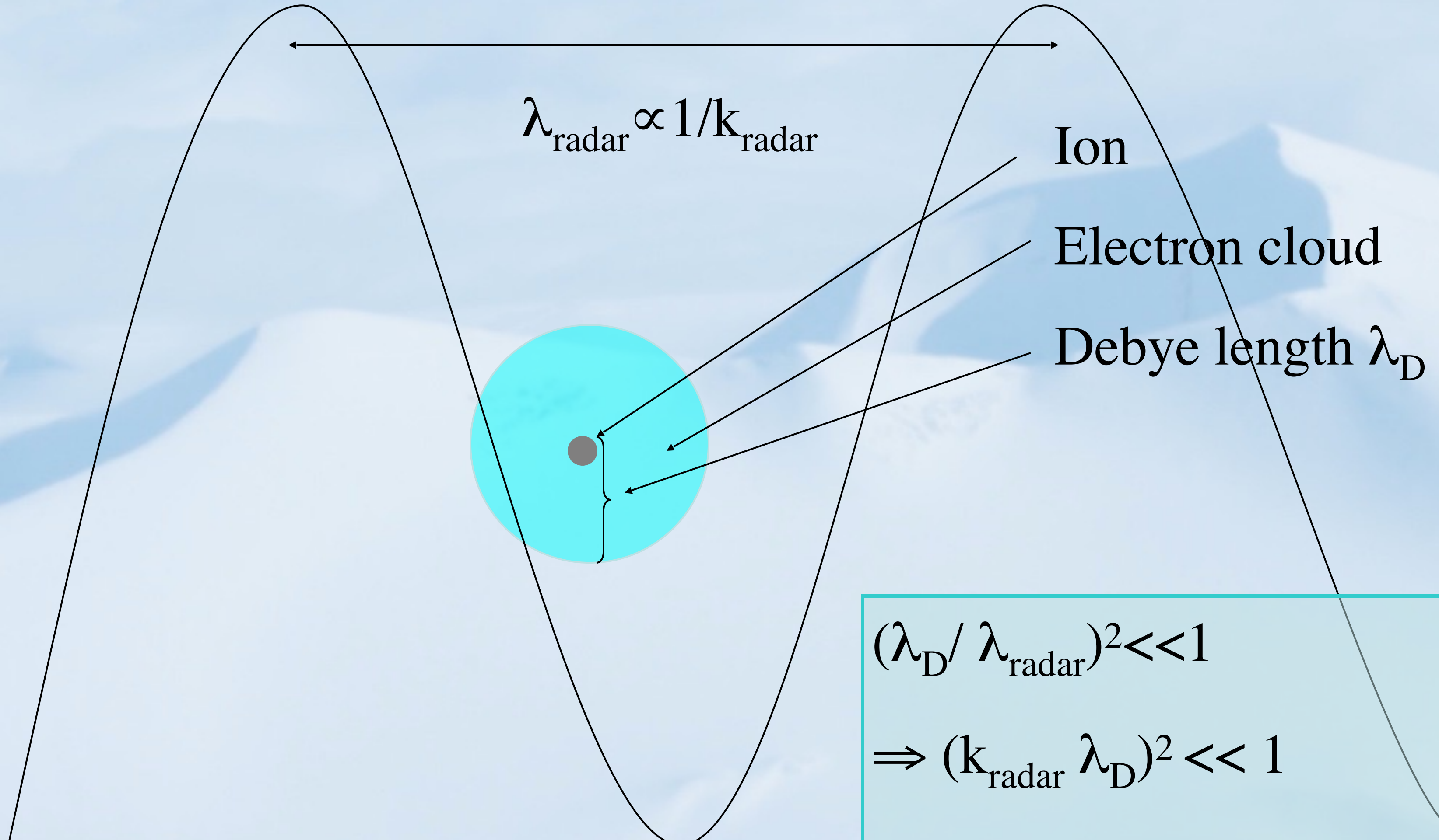
$$S_e(\mathbf{k},\omega) = N_e\left|1-\frac{\chi_e(\mathbf{k},\omega)}{\epsilon(\mathbf{k},\omega)}\right|^2\int d\mathbf{v}\, f_e(\mathbf{v})\,\delta(\omega-\mathbf{k}\cdot\mathbf{v}) + N_i\left|\frac{\chi_e(\mathbf{k},\omega)}{\epsilon(\mathbf{k},\omega)}\right|^2\int d\mathbf{v}\, f_i(\mathbf{v})\,\delta(\omega-\mathbf{k}\cdot\mathbf{v})$$

Plasma line

Ion line

electric susceptibility	$\chi_{e,i}(\mathbf{k},\omega)$
dielectric constant function	$\epsilon(\mathbf{k},\omega)$
velocity distribution function	$f_{e,i}(\mathbf{v})$

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

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

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

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

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

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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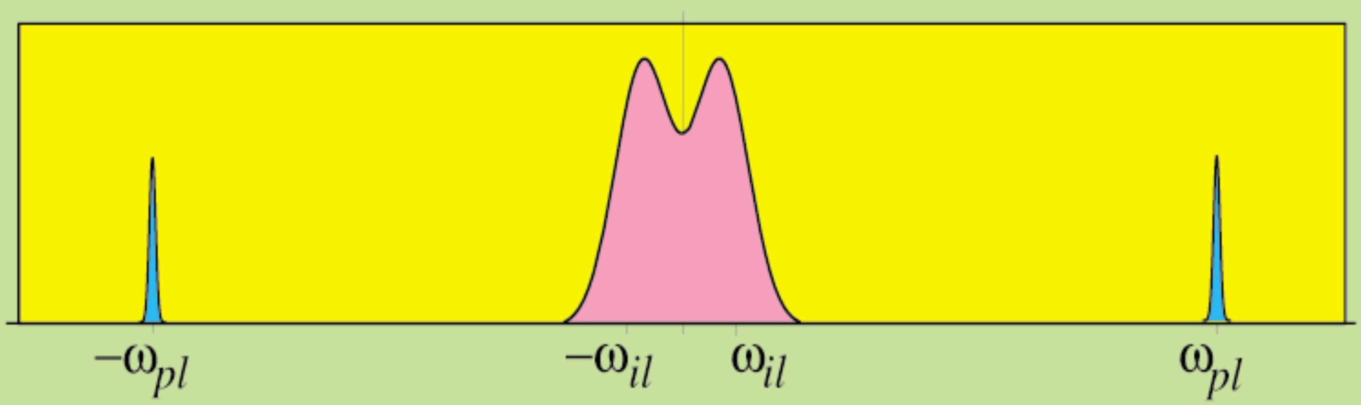
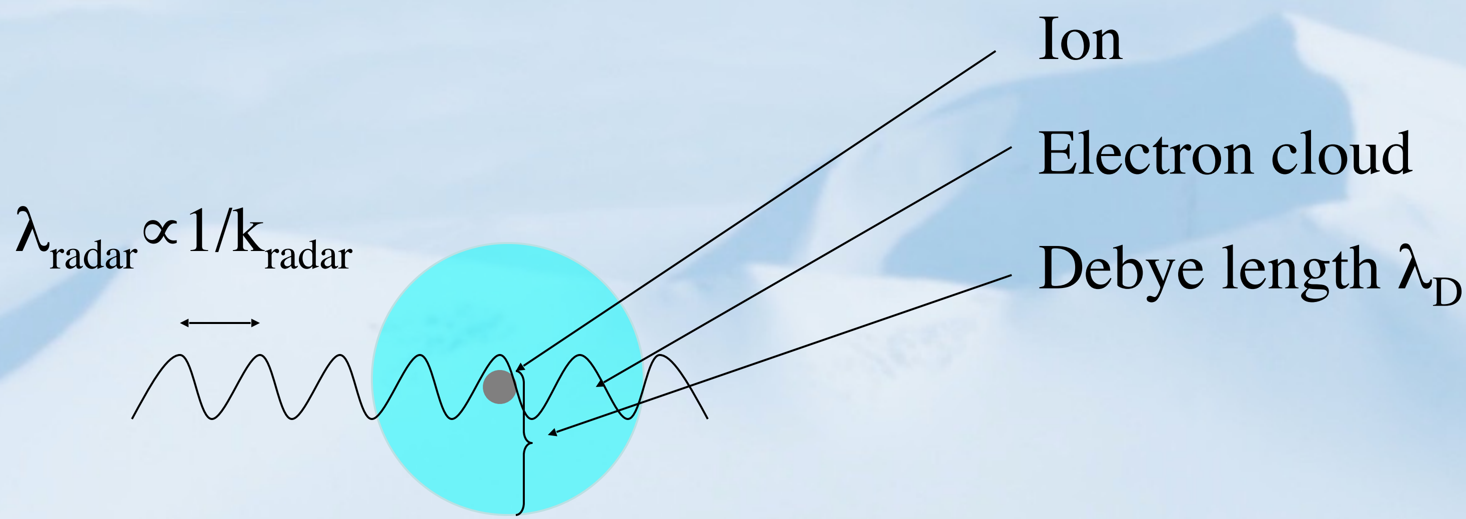


Debye length dependence



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

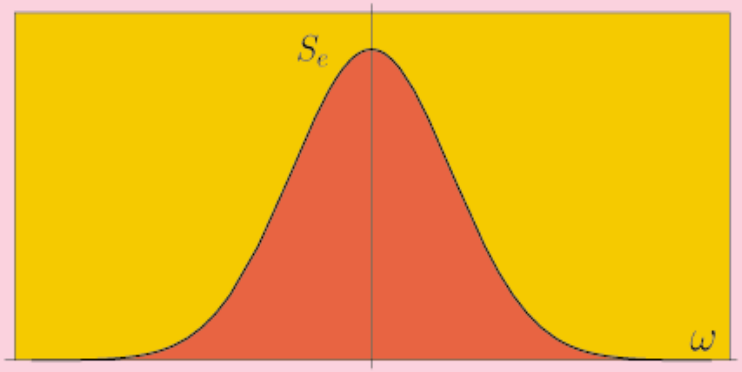
$\Rightarrow (k_{radar}\, \lambda_D)^2 > 1$

$\Rightarrow$ No collective interactions

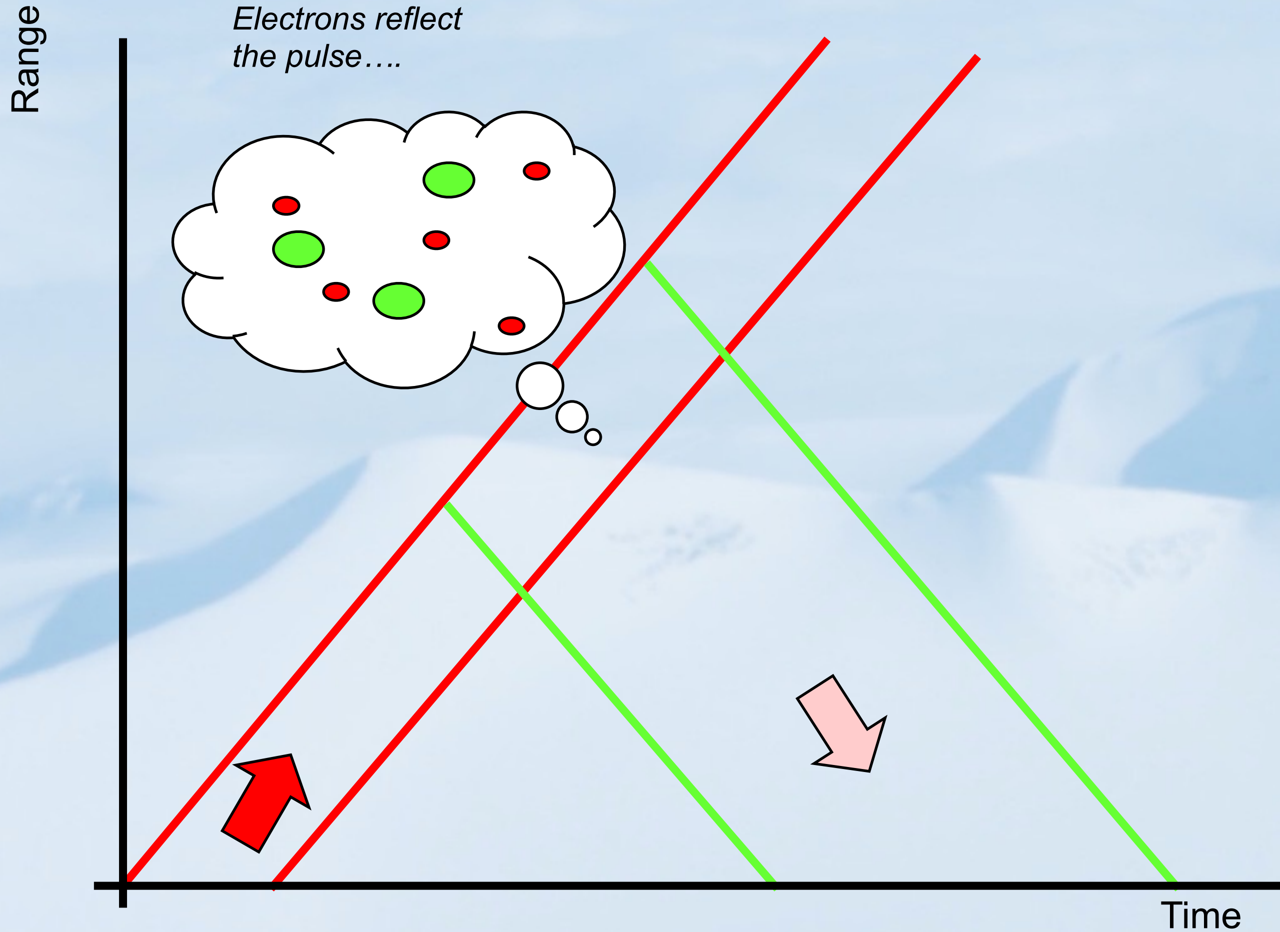
no collective interactions

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

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



How ISRs work...

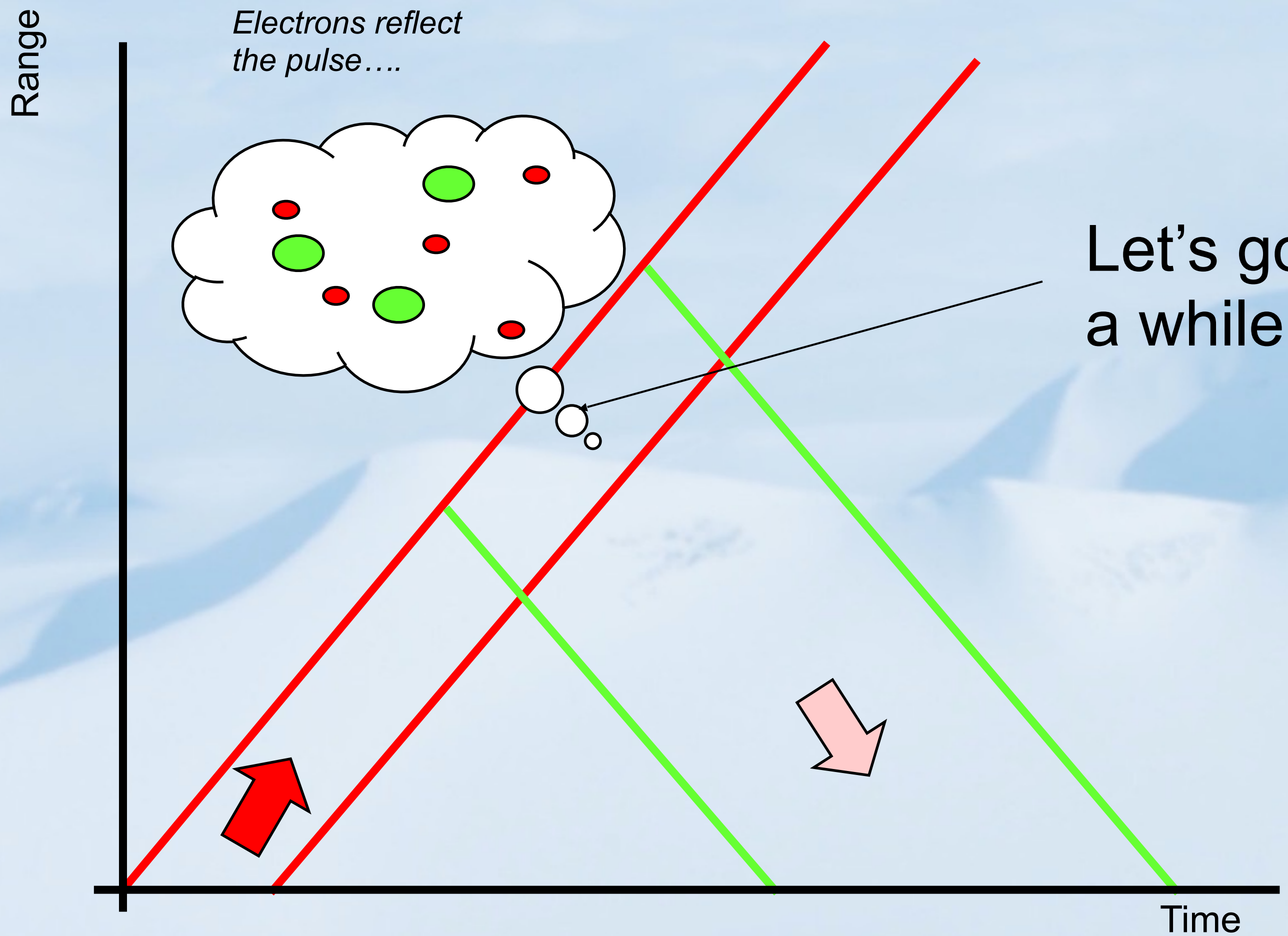


High power pulse

Very sensitive receiver

Only ~0.00000000000000000001% of the transmitted power is returned!

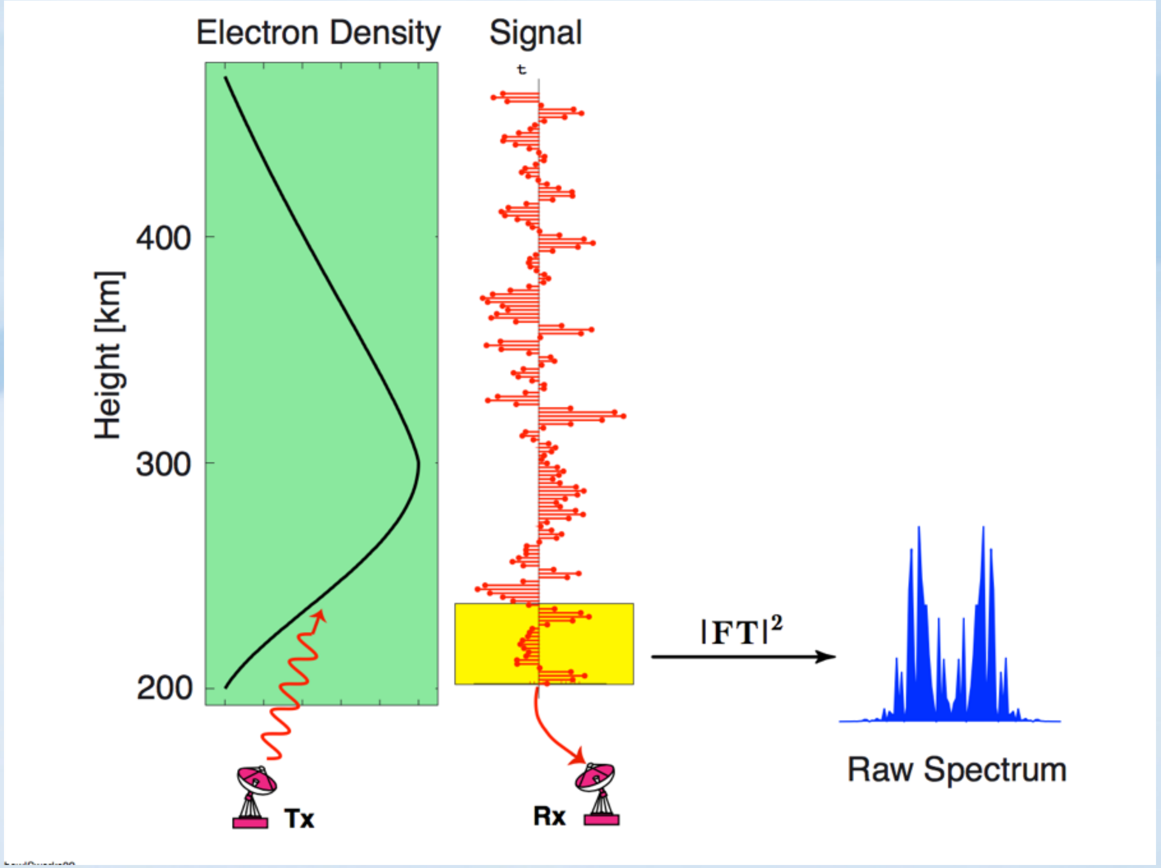
How ISRs work...



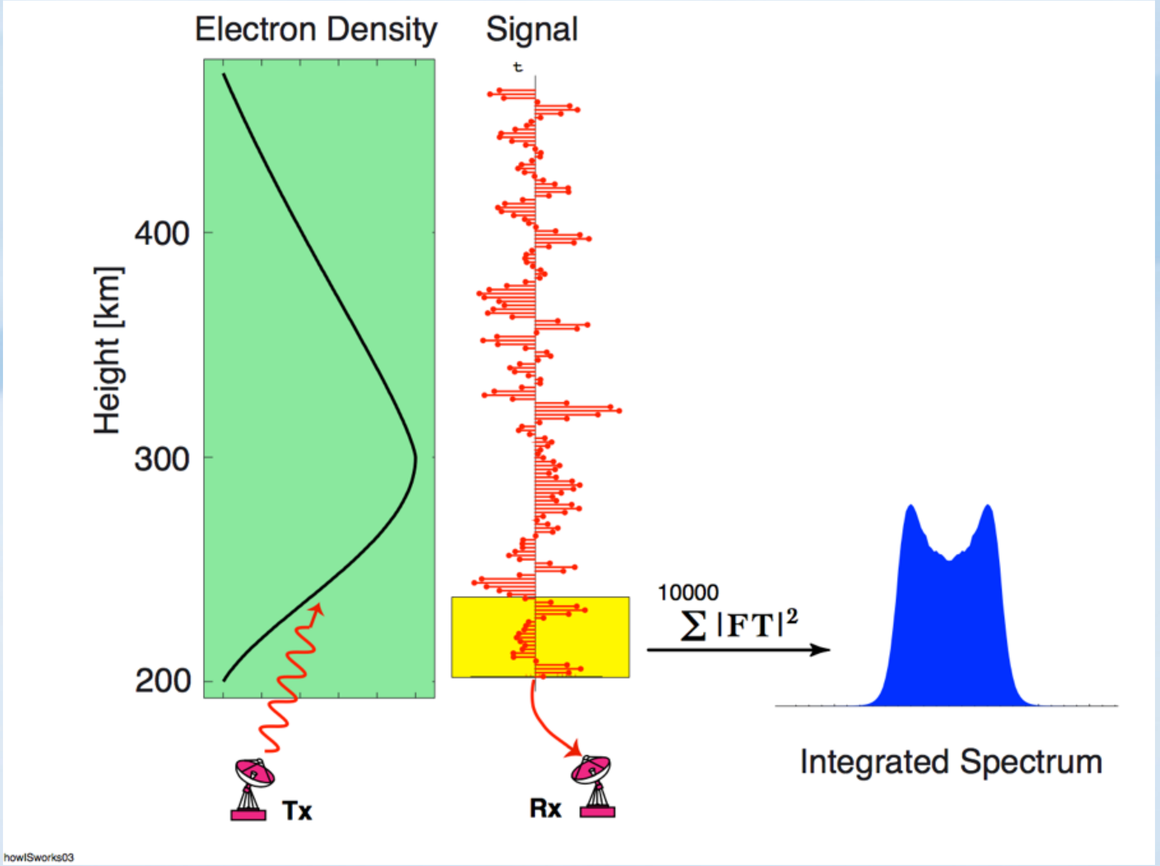
Let’s go back here for a while…

High power pulse

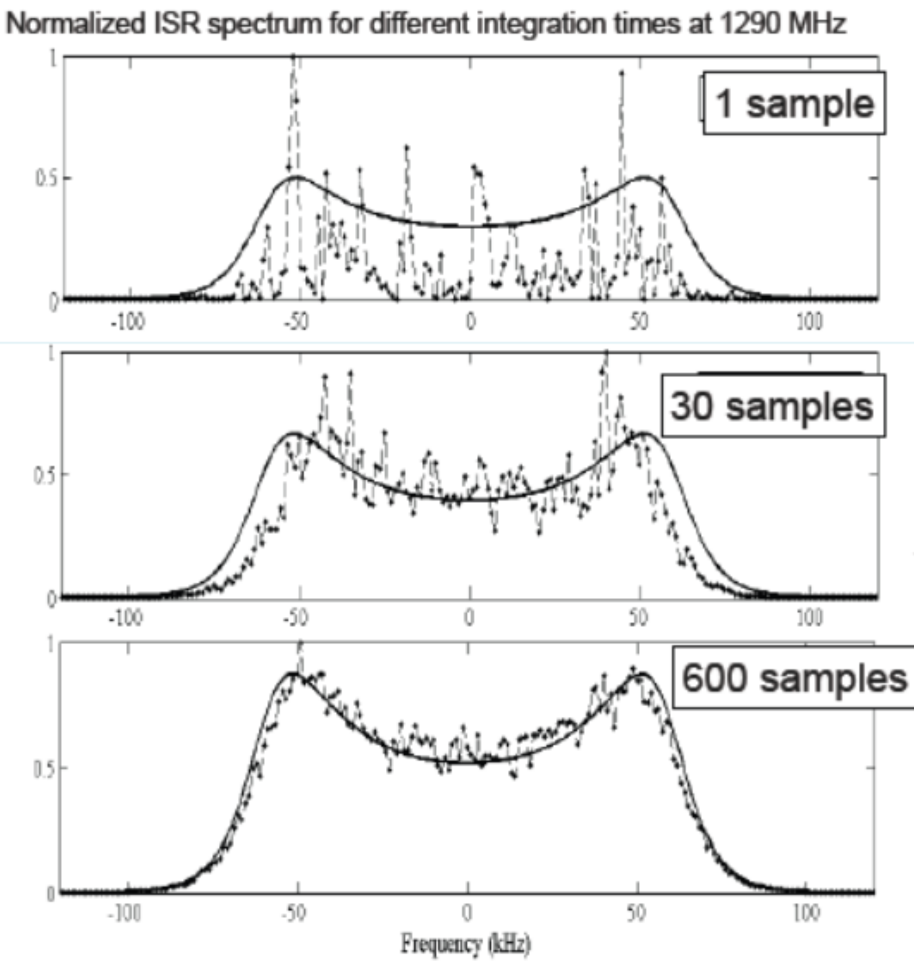
Very sensitive receiver



Electron Density
Signal
t
Height [km]
400
300
200
Tx
Rx
|FT|²
Raw Spectrum

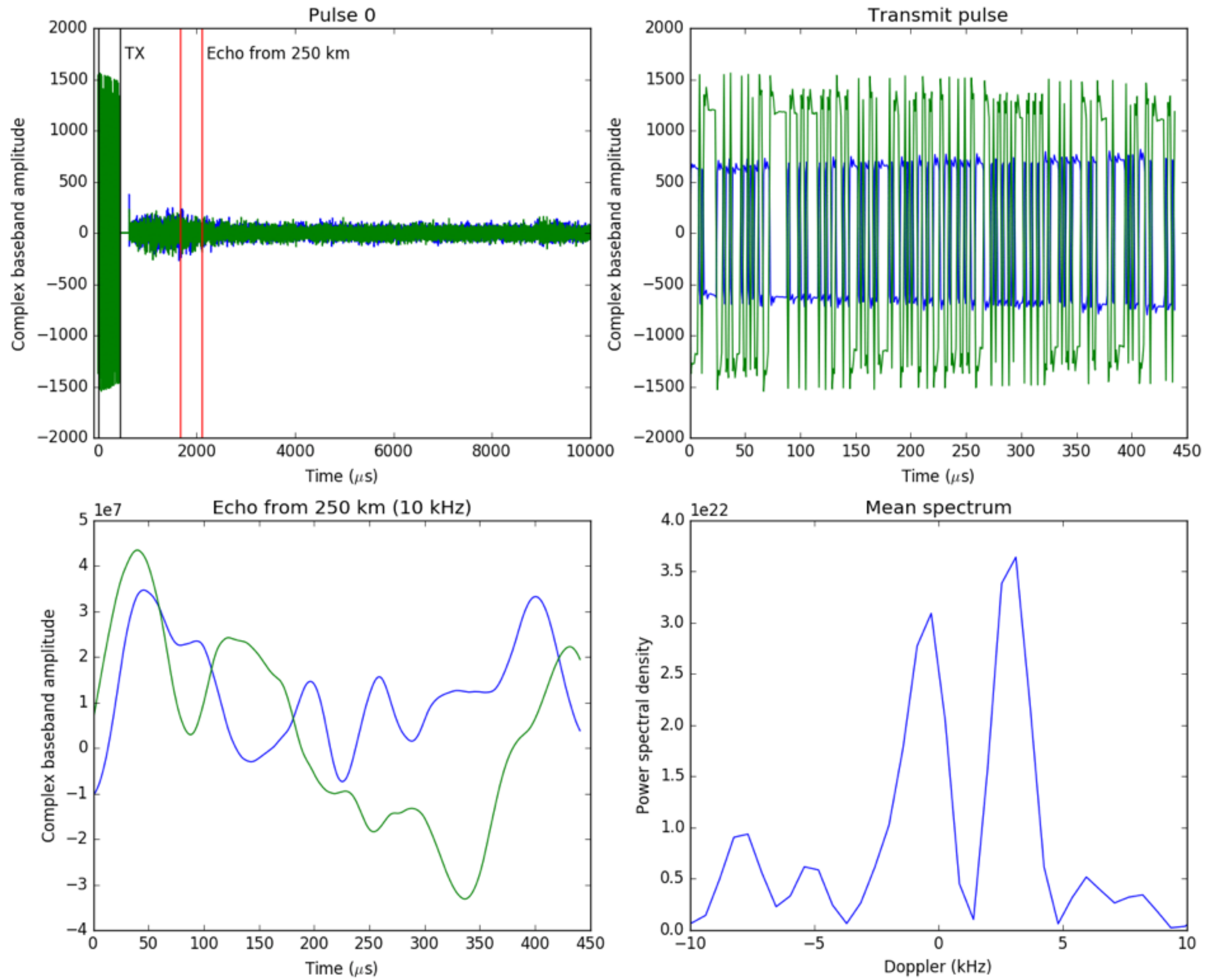

Electron Density
Signal
Height [km]
400
300
200
Tx
Rx
10000
$\sum |FT|^2$
Integrated Spectrum
howISworks03

Incoherent Averaging

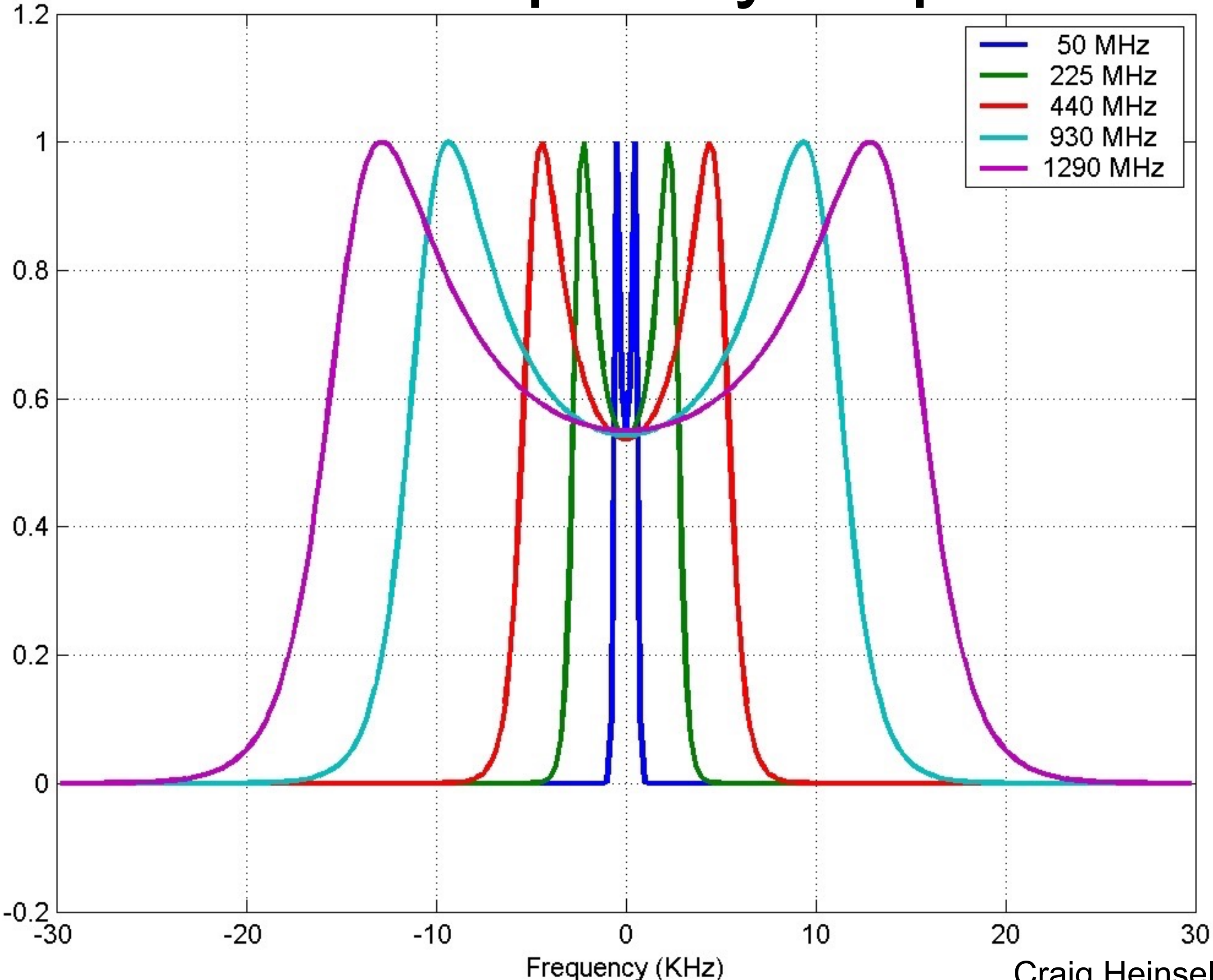


We are seeking to estimate the power spectrum of a Gaussian random process. This requires that we sample and average many independent “realizations” of the process.

$$\text{Uncertainties} \propto \frac{1}{\sqrt{\text{Number of Samples}}}$$


Pulse 0
TX
Echo from 250 km
Complex baseband amplitude
Time (μs)
Transmit pulse
Complex baseband amplitude
Time (μs)
Echo from 250 km (10 kHz)
1e7
Complex baseband amplitude
Time (μs)
Mean spectrum
1e22
Power spectral density
Doppler (kHz)

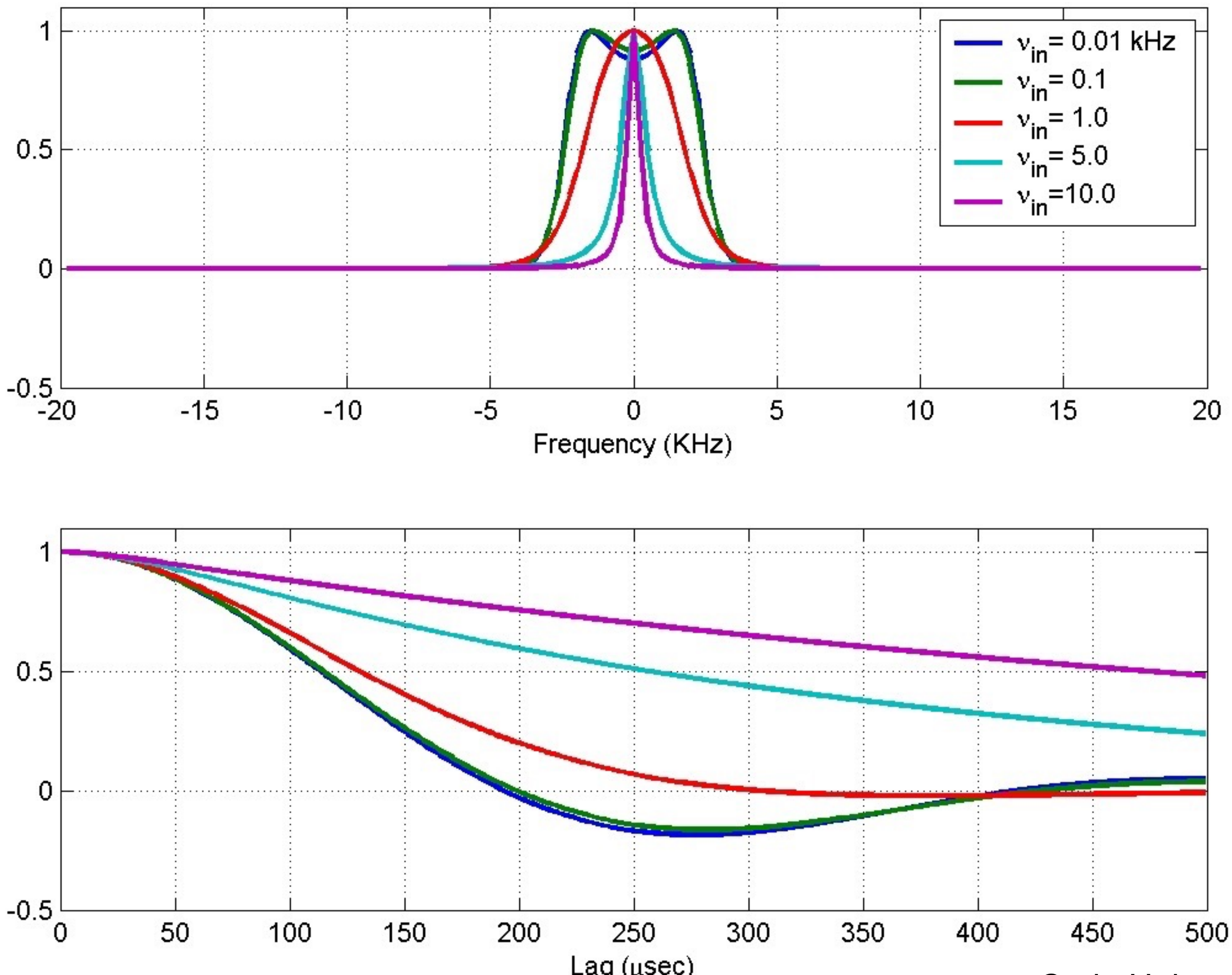
Radar Frequency Dependencies



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

Craig Heinselman

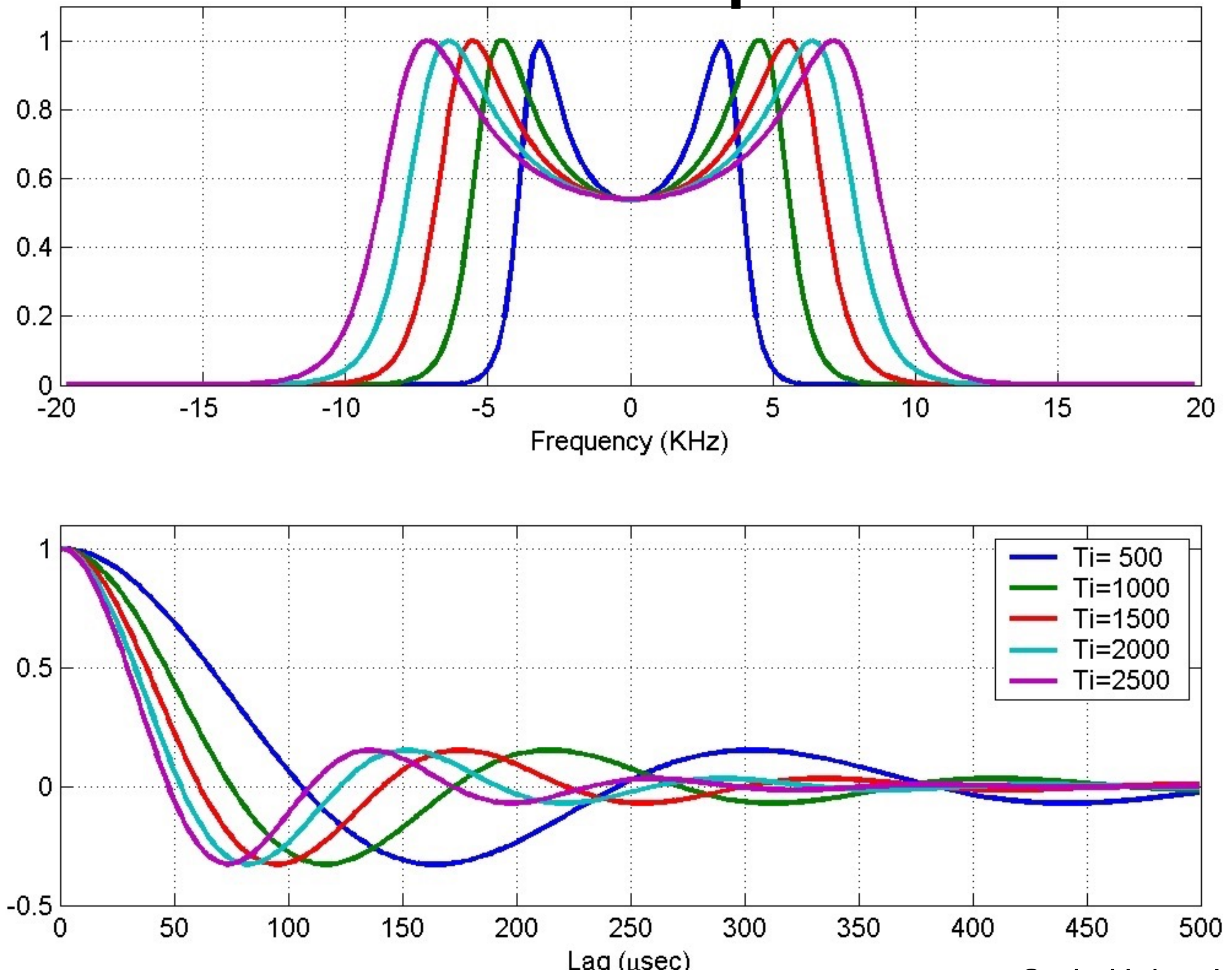
Ion-Neutral Collision Frequency



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

Craig Heinselman

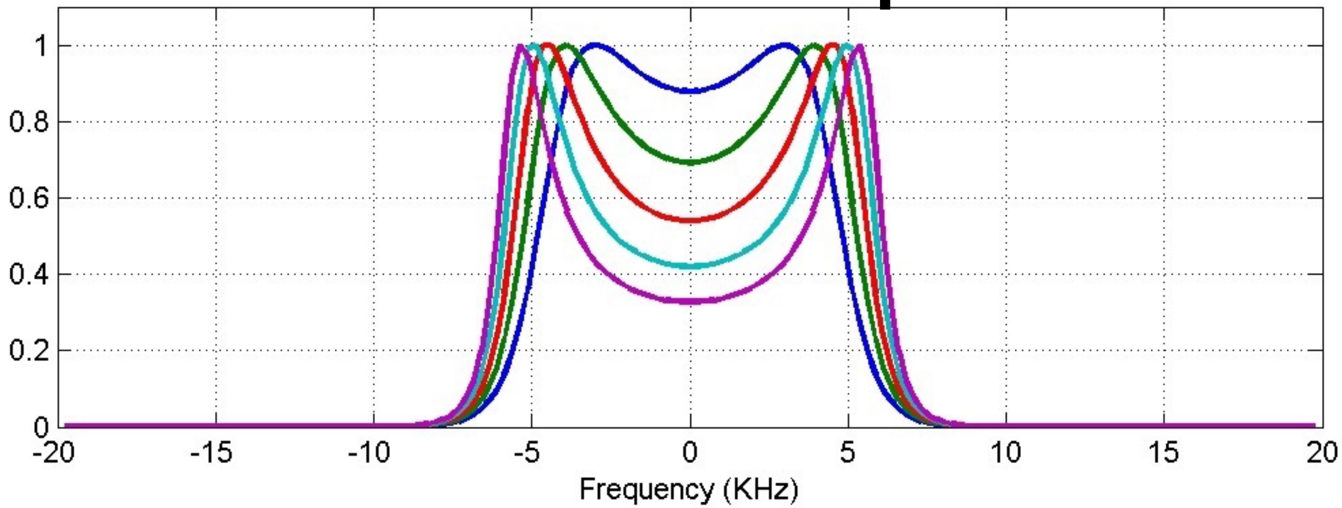
Ion Temperature



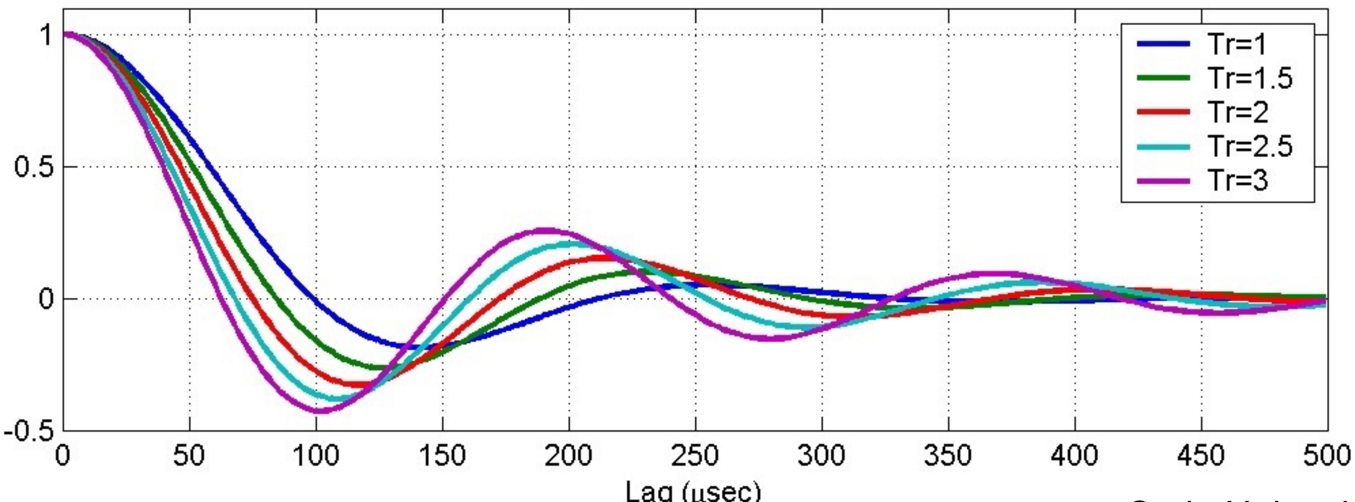
Parameters
Freq: 449 MHz
Ne: 10^{12} m^{-3}
Te: 2*Ti
Comp: 100% O^+
ν_{in}: 10^{-6} KHz

Craig Heinselman

Electron/Ion Temperature Ratio

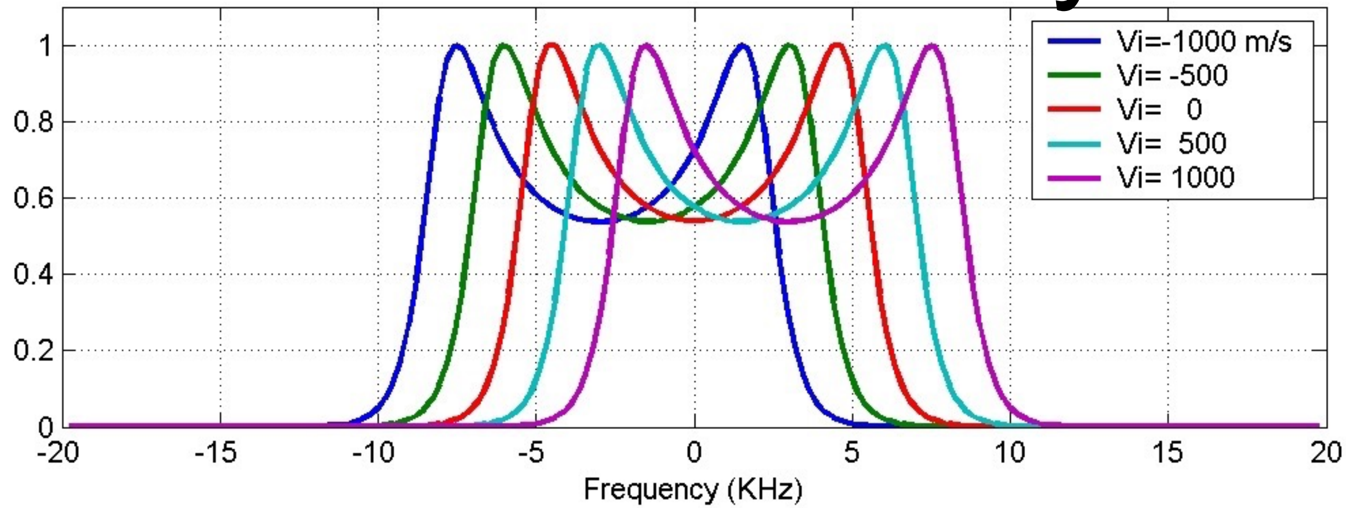


Parameters
Freq: 449 MHz
Ne: 10^{12} m^{-3}
Ti: 1000 K
Comp: 100% O^+
ν_{in}: 10^{-6} KHz

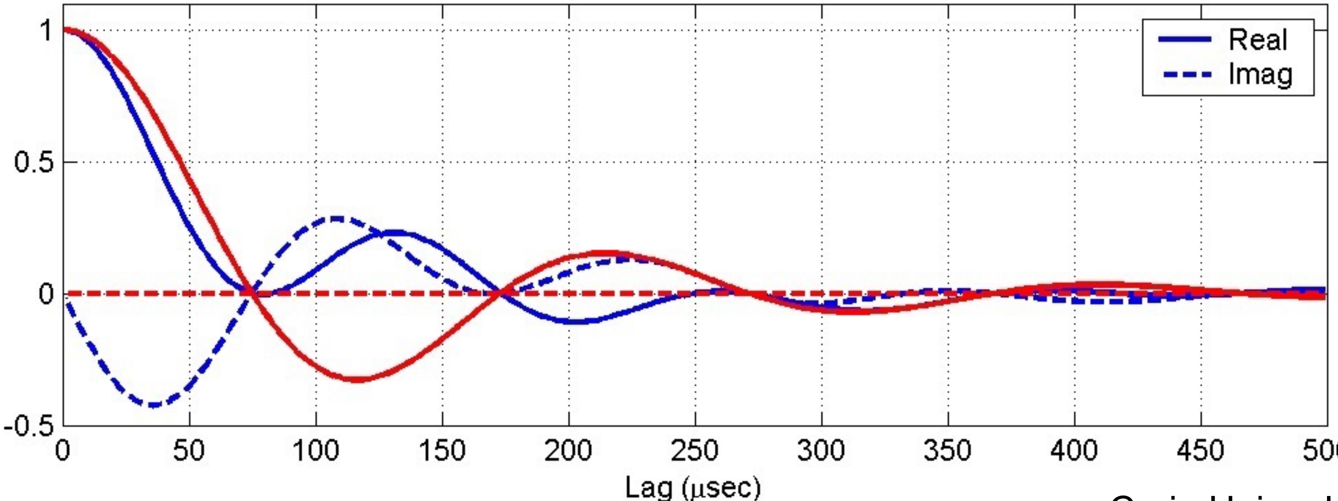


Craig Heinselman

Ion Velocity

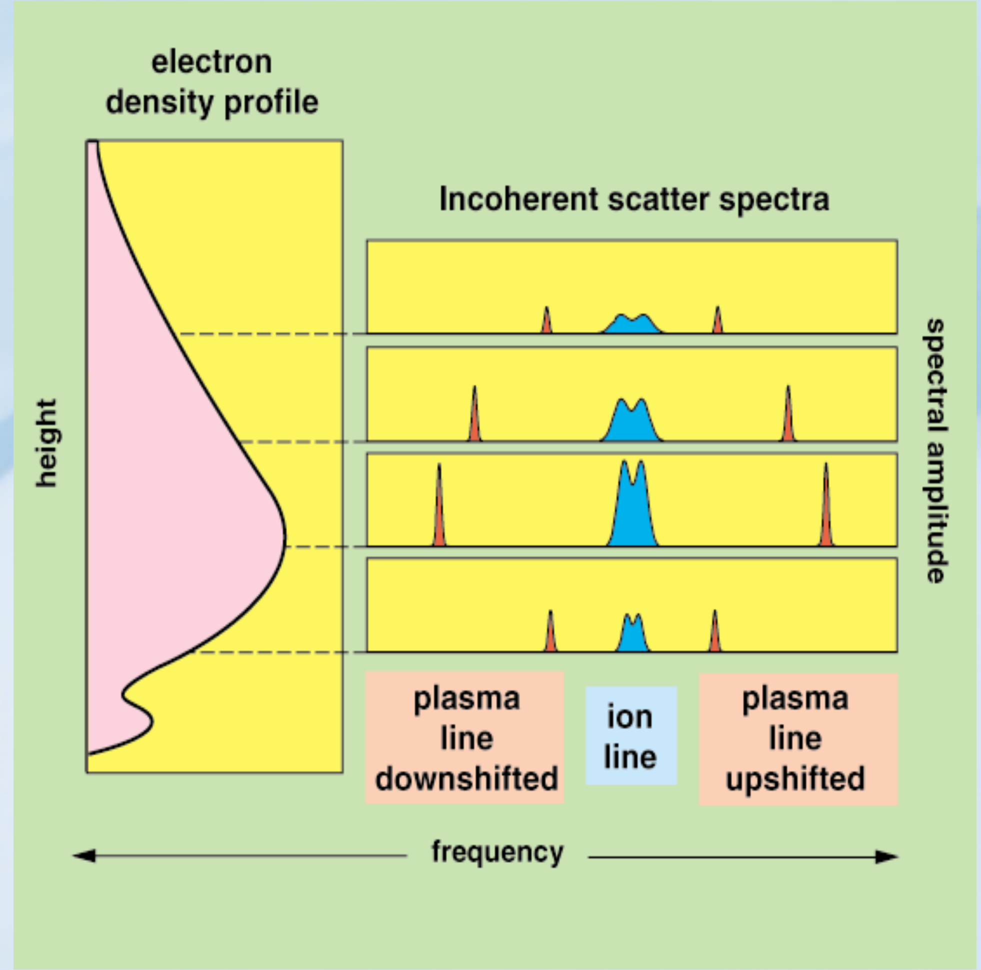


<u>Parameters</u>
Freq: 449 MHz
Ne: 10^{12} m^{-3}
Ti: 1000 K
Te: 2000 K
Comp: 100% O^+
ν_{in}: 10^{-6} KHz

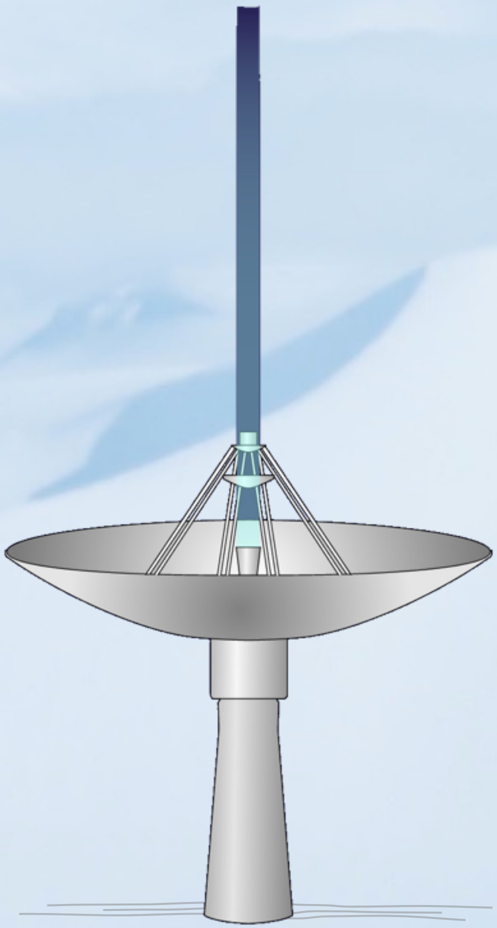


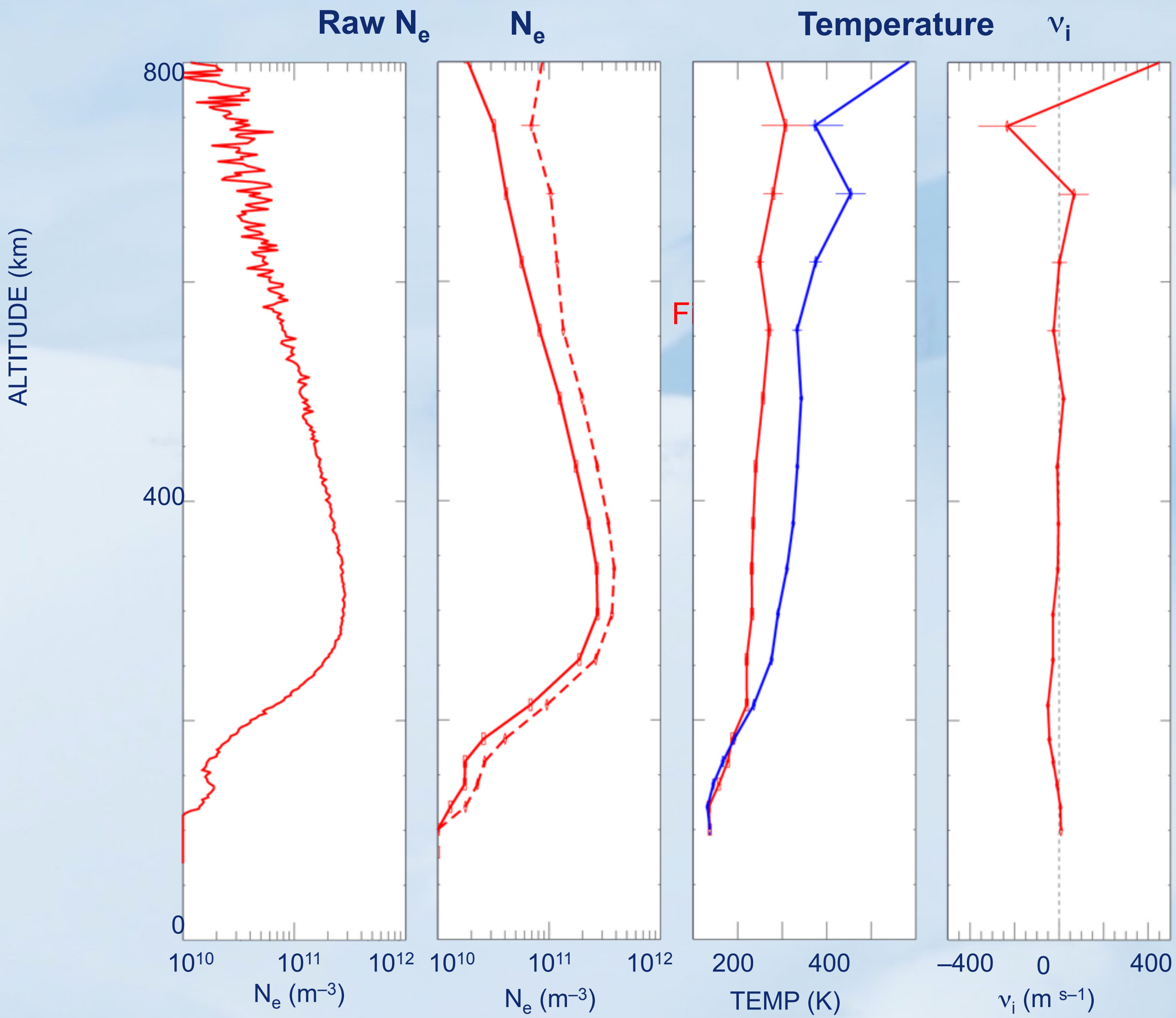
Craig Heinselman

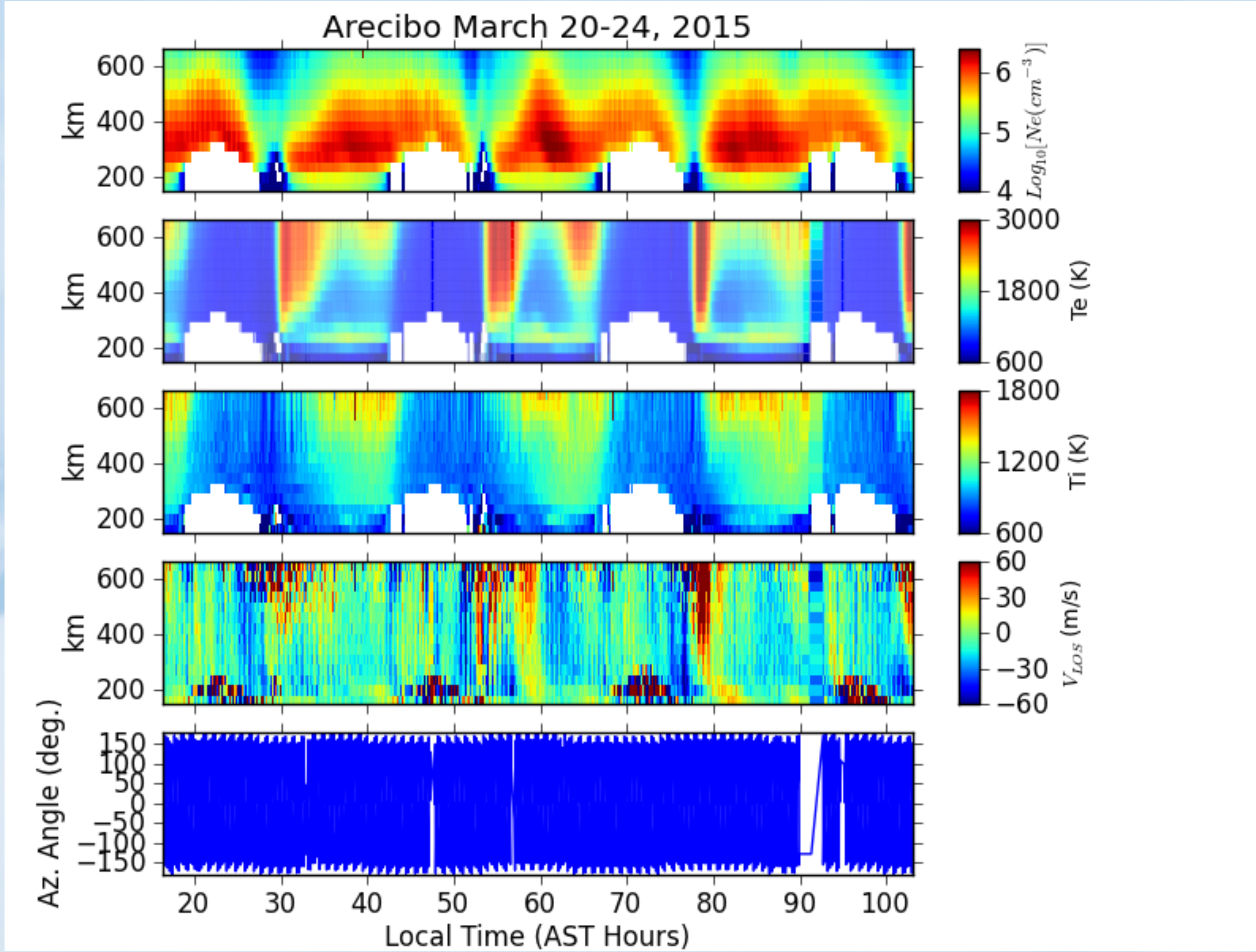
Spectral space as a function of altitude



Plasma Parameter Profile







Arecibo March 20-24, 2015
km
600
400
200
$Log_{10}[Ne(cm^{-3})]$
6
5
4
Te (K)
3000
1800
600
Ti (K)
1800
1200
600
V_{LOS} (m/s)
60
30
0
−30
−60
Az. Angle (deg.)
150
100
50
0
−50
−100
−150
20
30
40
50
60
70
80
90
100
Local Time (AST Hours)

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

Questions you should ask

(...although some might cause facepalming and potential religious wars among the lecturers)

- What is the difference between coherent and incoherent scatter?
- What is the significance of under- versus over-spred targets?
- What is a hard target versus a soft target?
- What is the difference between a beam filling versus a point target?