The short introduction to Incoherent Scatter (IS) Theory

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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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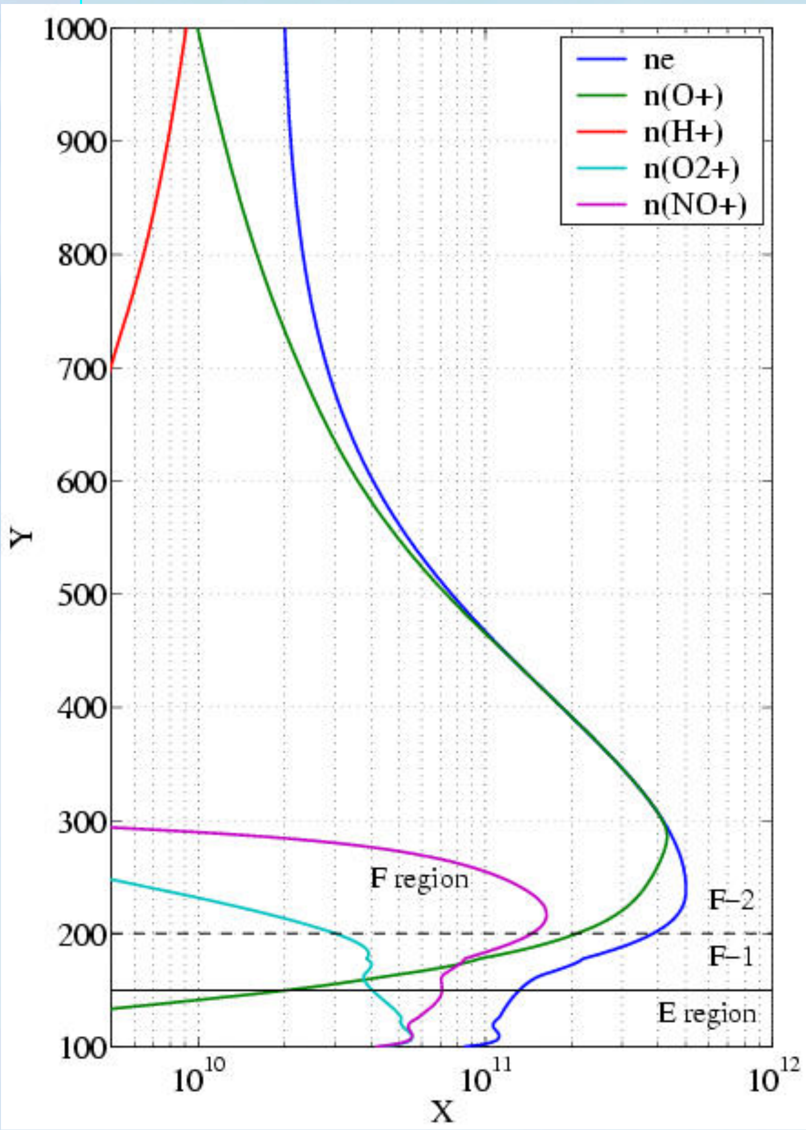
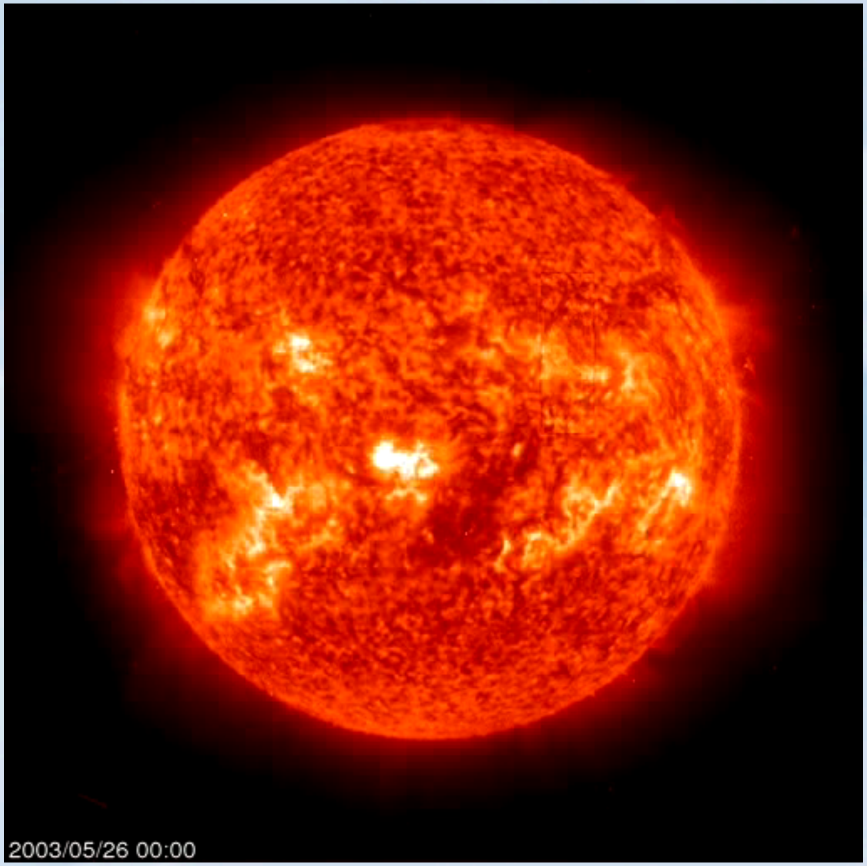
- **Media: Incoherent=Incomprehensible**

Incoherent scatter is neither incoherent nor incomprehensible

First: We need an Ionsophere…

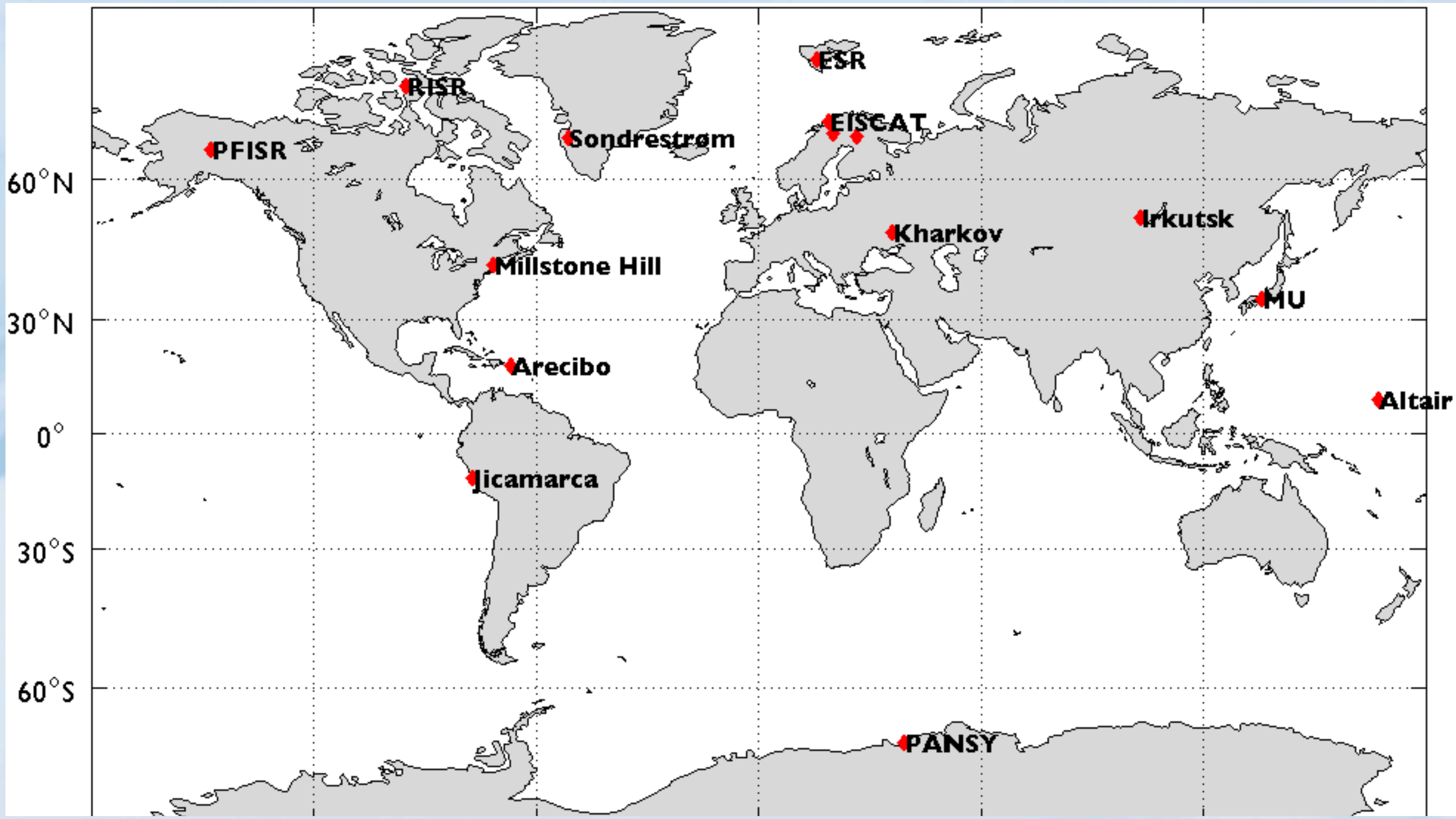
The Earths Ionosphere



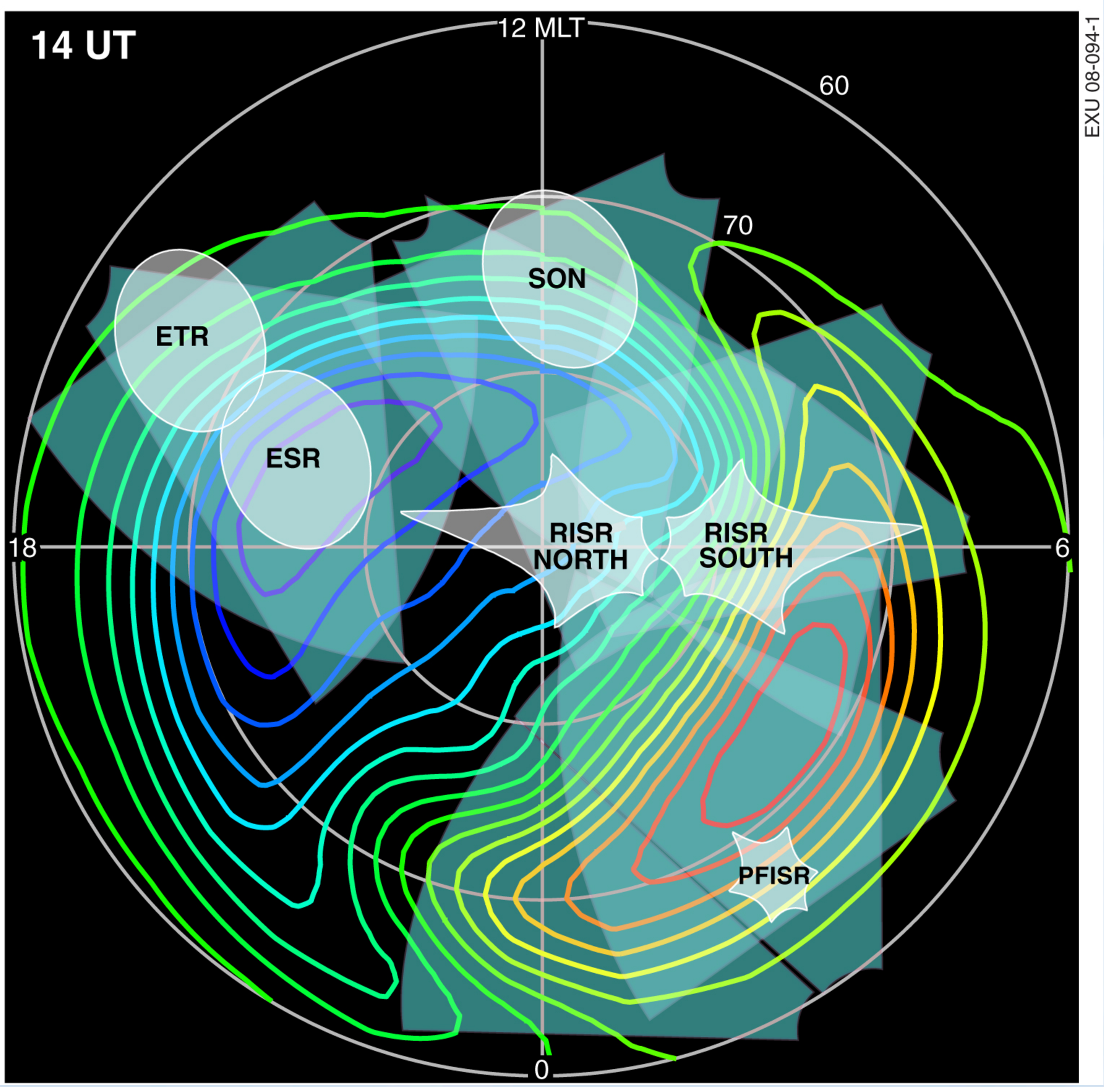


Now we have an ionosphere - let’s add the Incoherent Scatter Radar (ISR) to probe it!

Incoherent Scatter Radars of the World



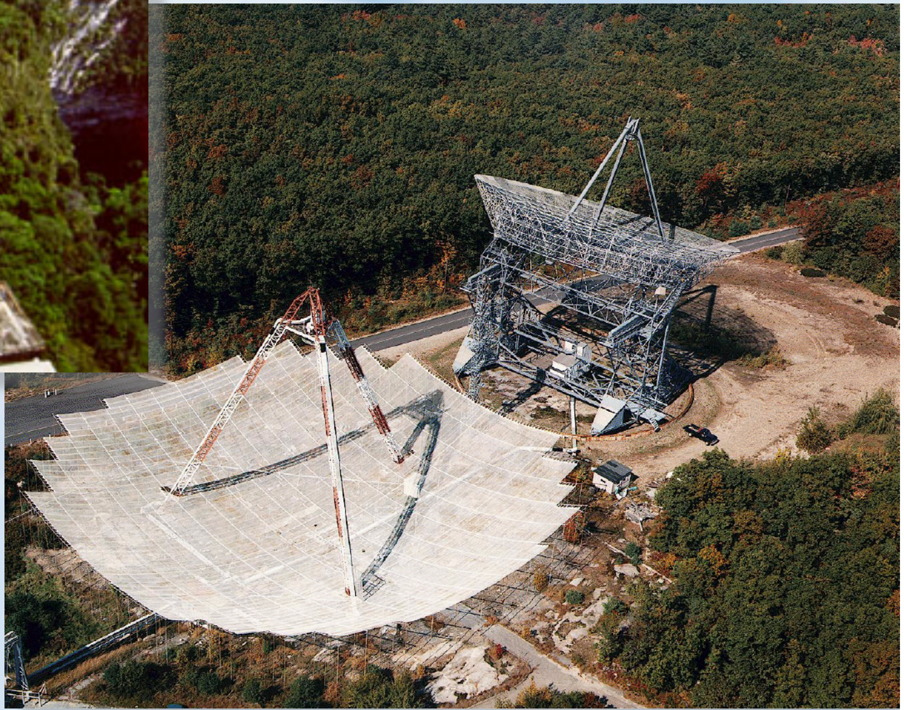
Map of the north…



High latitude Incoherent Scatter Radars….

PFISR (Poker Flat Incoherent Scatter Radar) and RISR-N (Resolute Bay Incoher… AMISRs curre…

Mid-Latitude Incoherent Scatter Radars

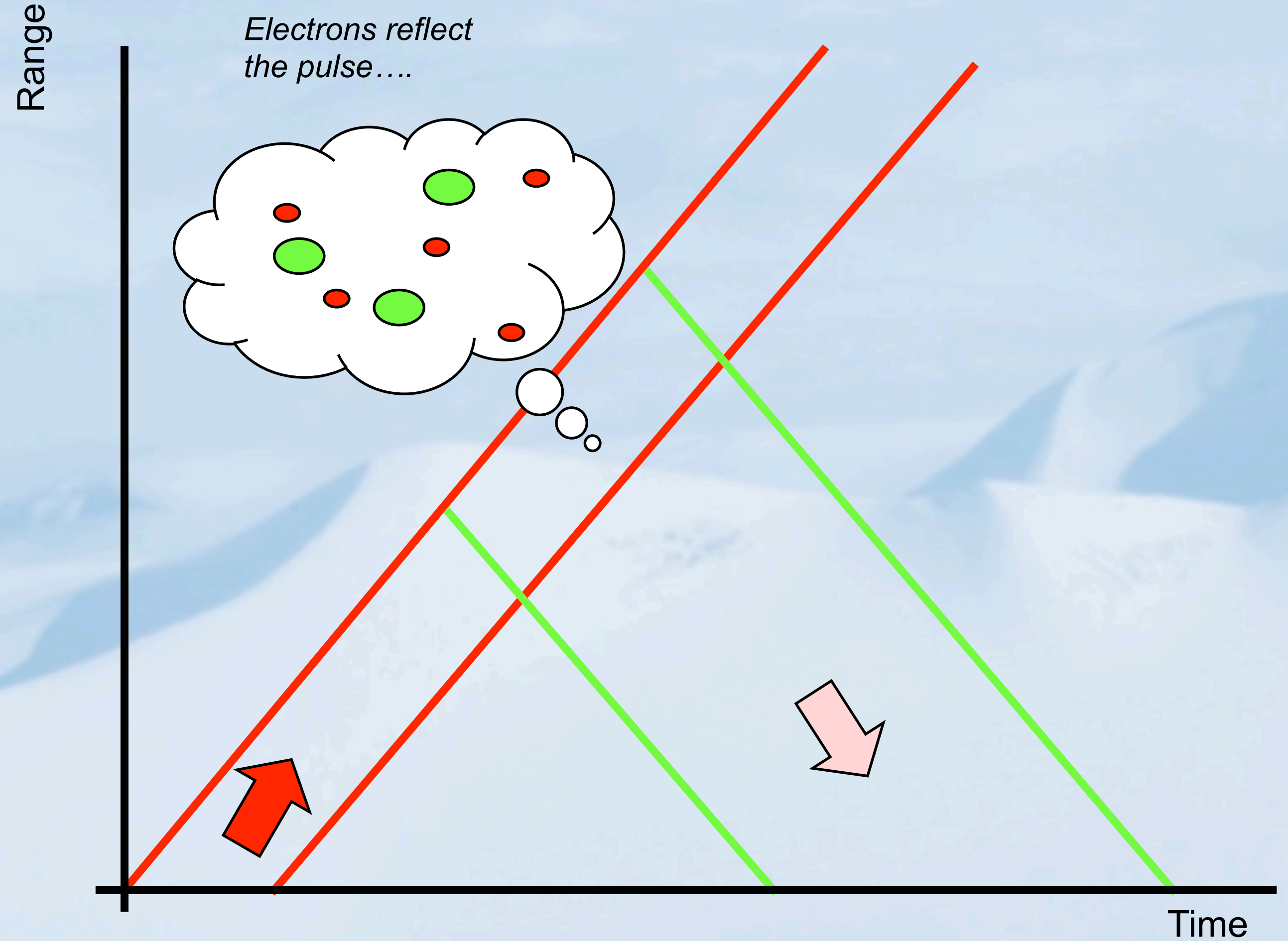


Low-Latitude Incoherent Scatter Radars

Questions you might have now:

- Why are incoherent scatter radars (ISRs) so big? Is it a status-thing?
- Why is it called *incoherent* scattering?
- What do the ISR returns look like and why?
- What can ISRs measure?
- Can we get through this before lunch?

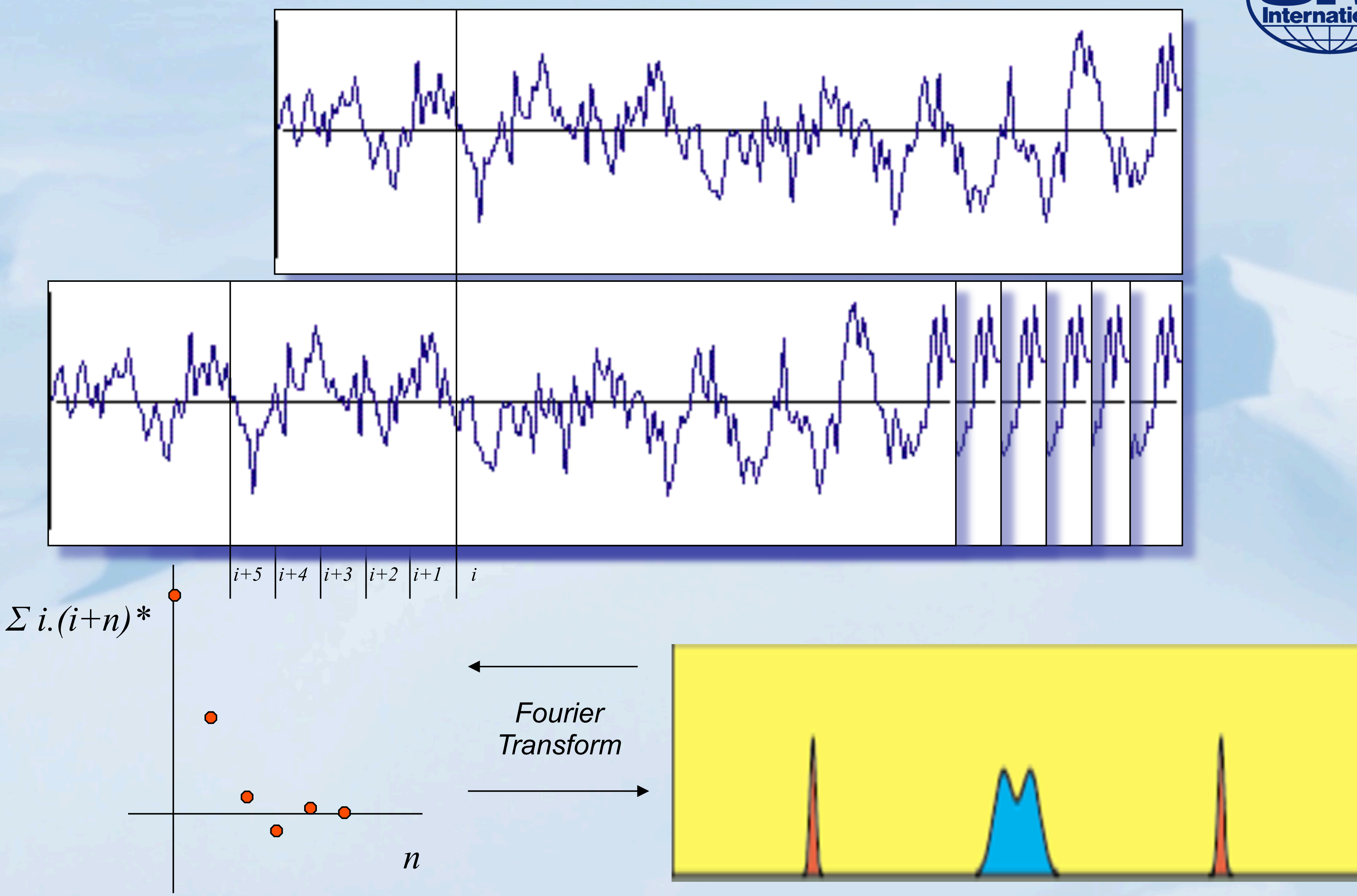
How ISRs work...

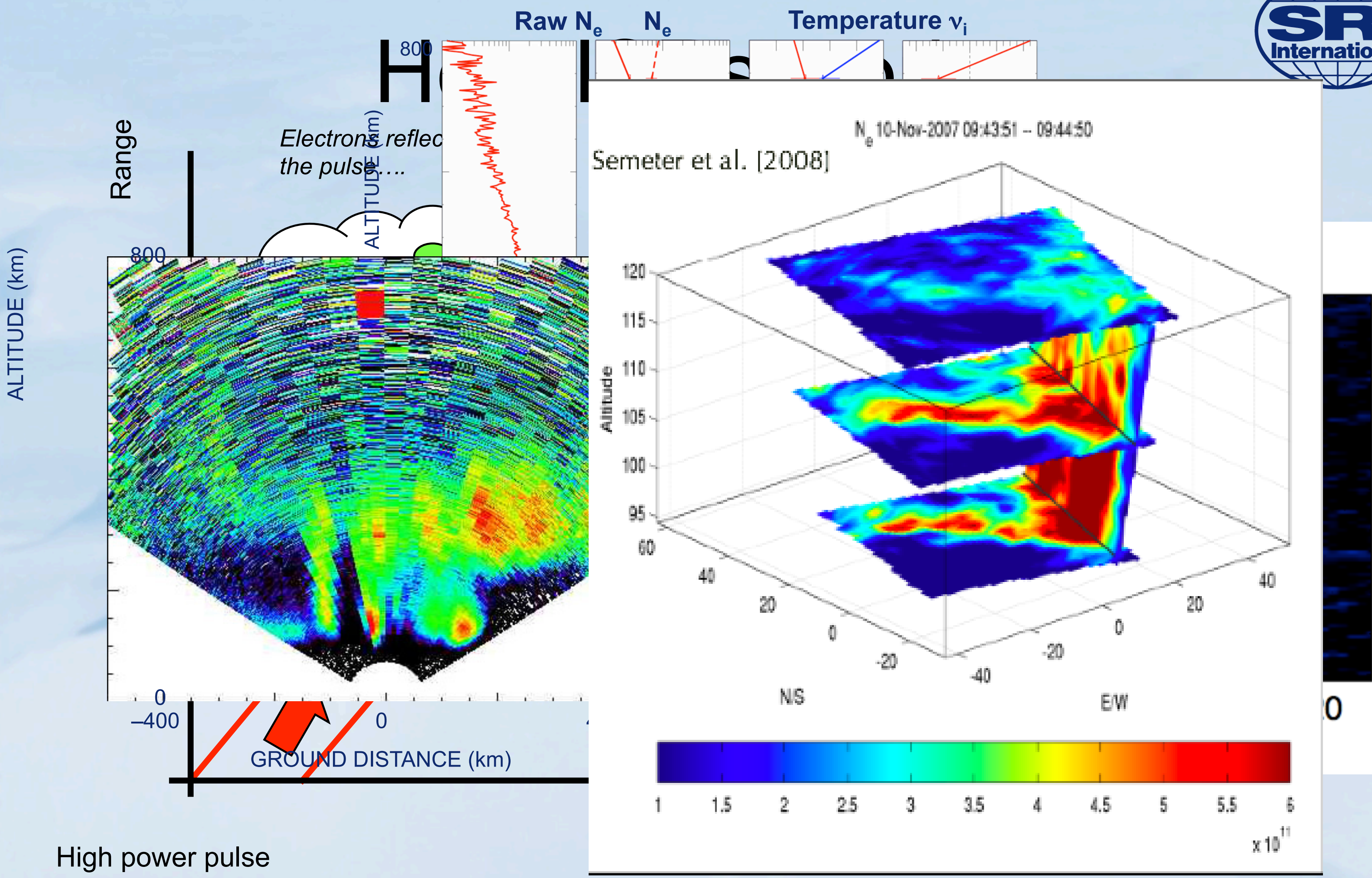


High power pulse

Very sensitive receiver

Only ~0.000000000000000001% of the transmitted power is returned!

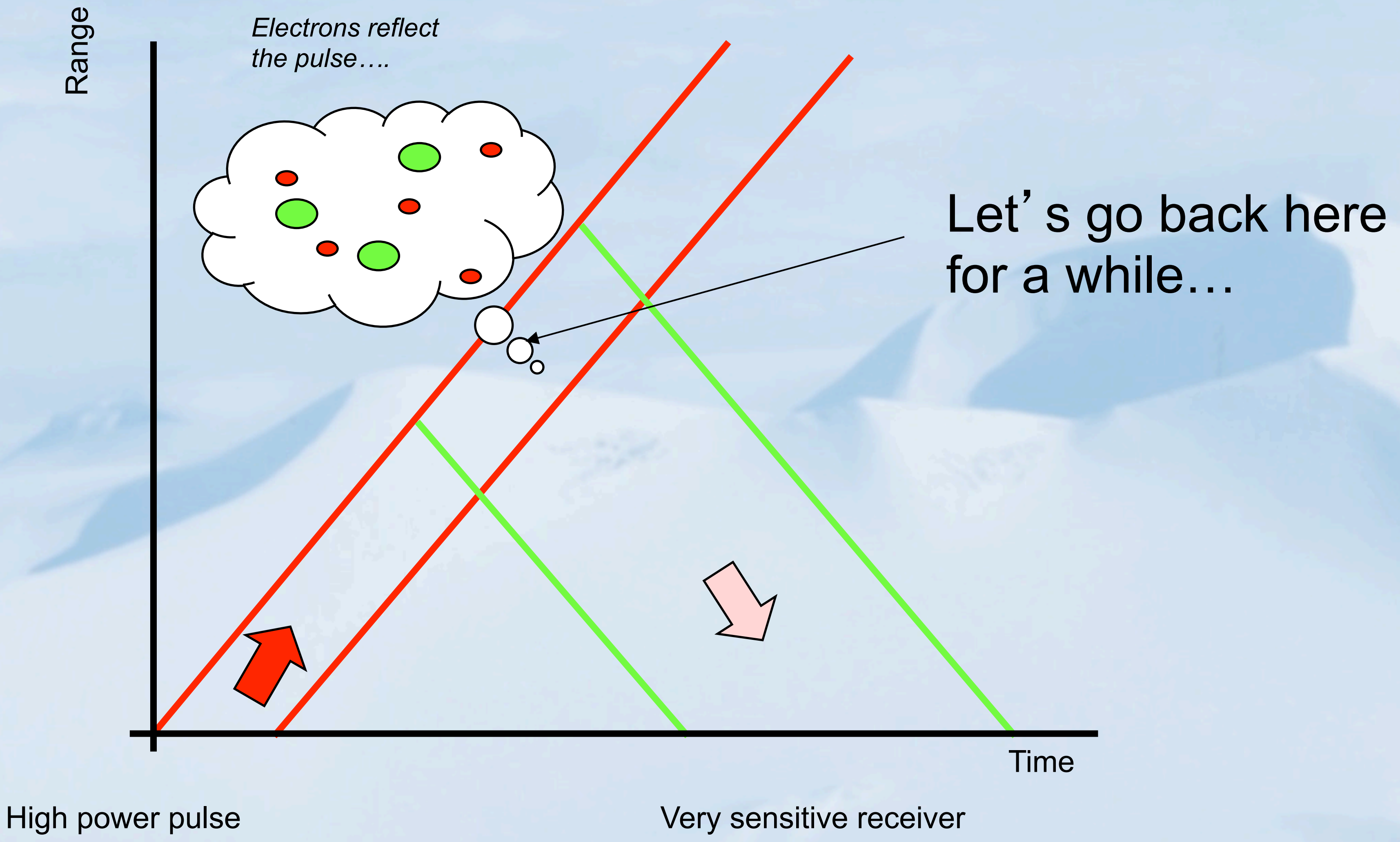

i+5
i+4
i+3
i+2
i+1
i
Σ i.(i+n)*
n
Fourier
Transform

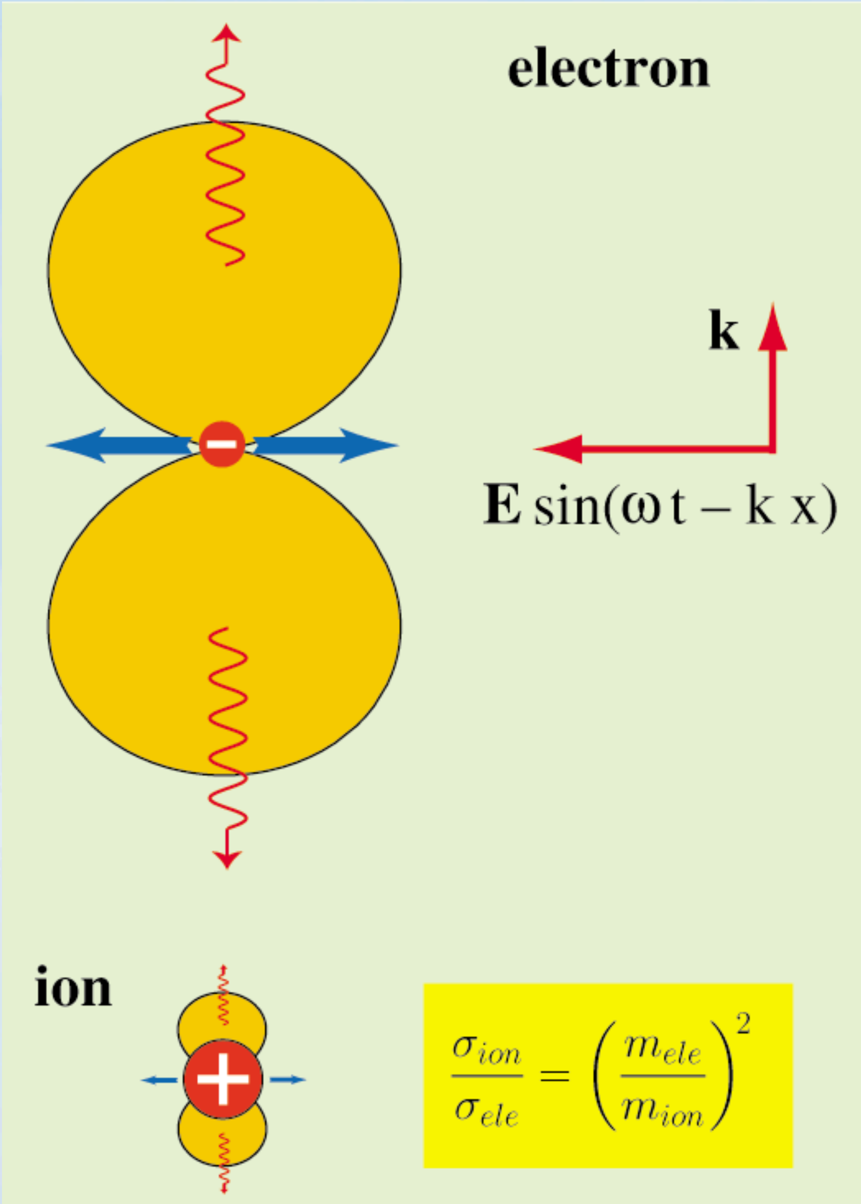


High power pulse

Only ~0.0000000000000000001% of the transmitted power is returned!

How ISRs work...

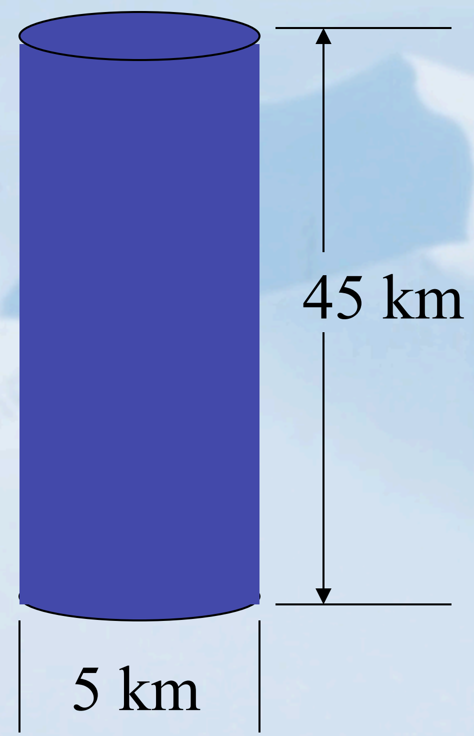




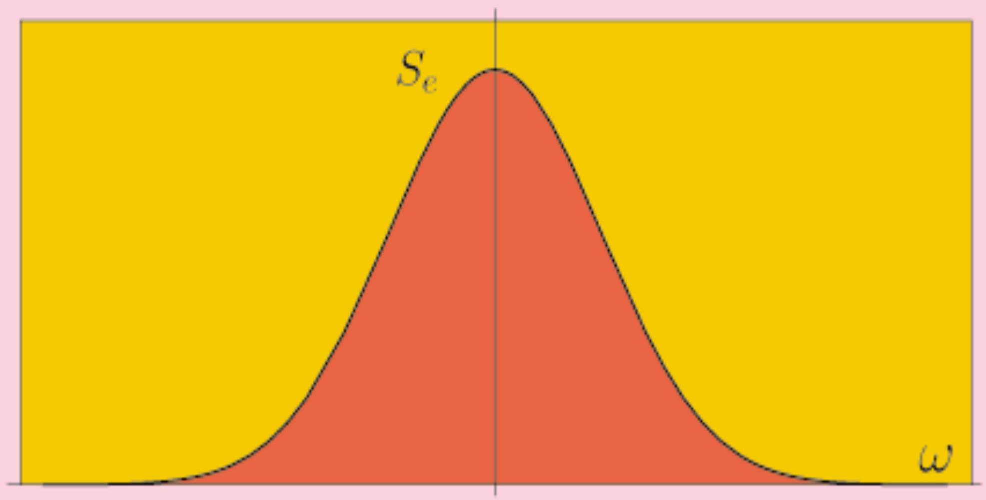
electron
k
E sin(ω t – k x)
ion
$\frac{\sigma_{ion}}{\sigma_{ele}} = \left(\frac{m_{ele}}{m_{ion}}\right)^2$

Total Cross-Section Estimate

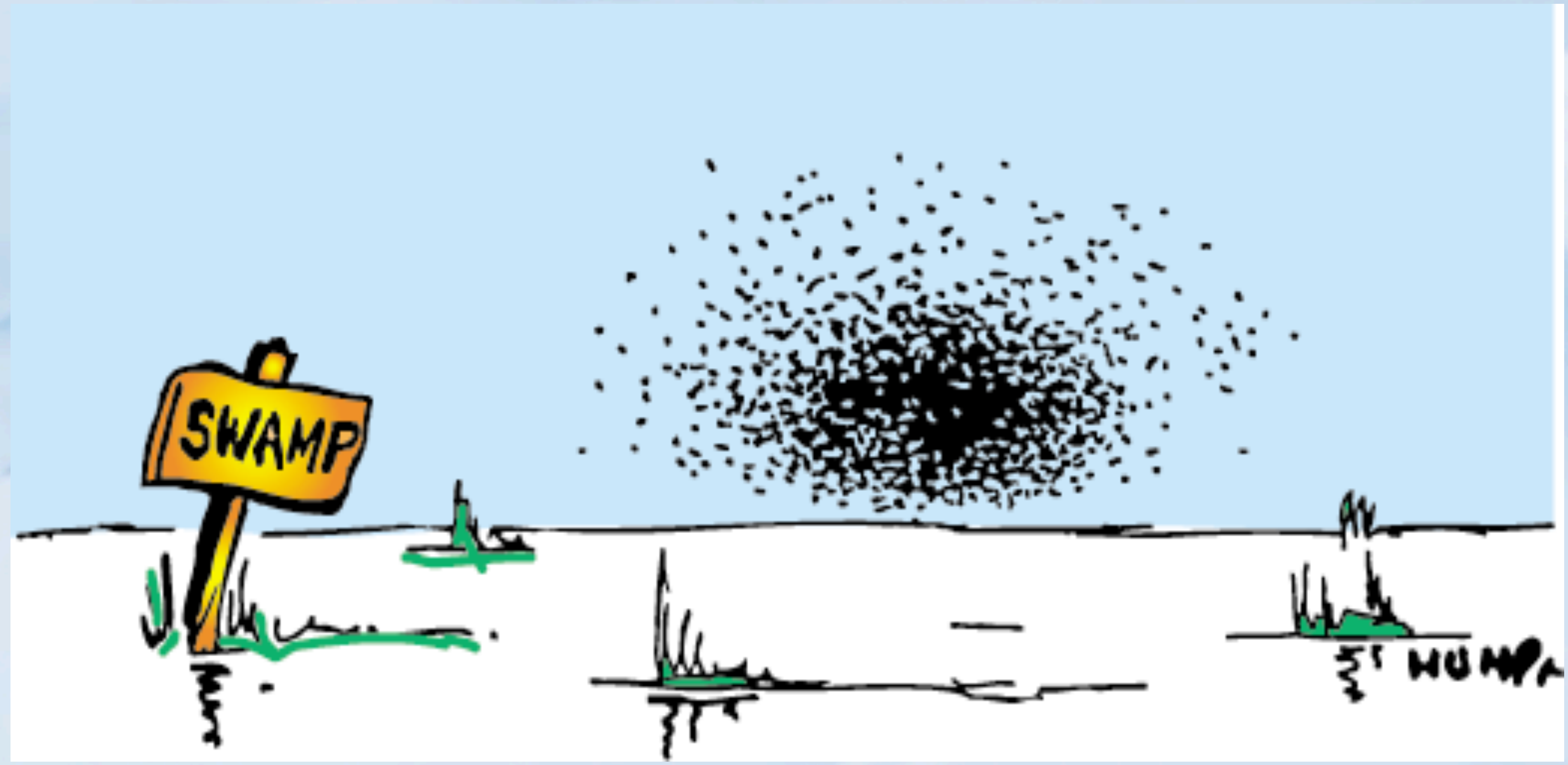
Consider an antenna with a 1-degree beam measuring the ionospheric plasma at 300 km range and using a 300 microsecond pulse.
If the electron density is 10^{12} m^{-3}, the total number of electrons scattering into a given measurement is ~8.8×10^{23}. This yields a total cross-section of 88 mm^2 – we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



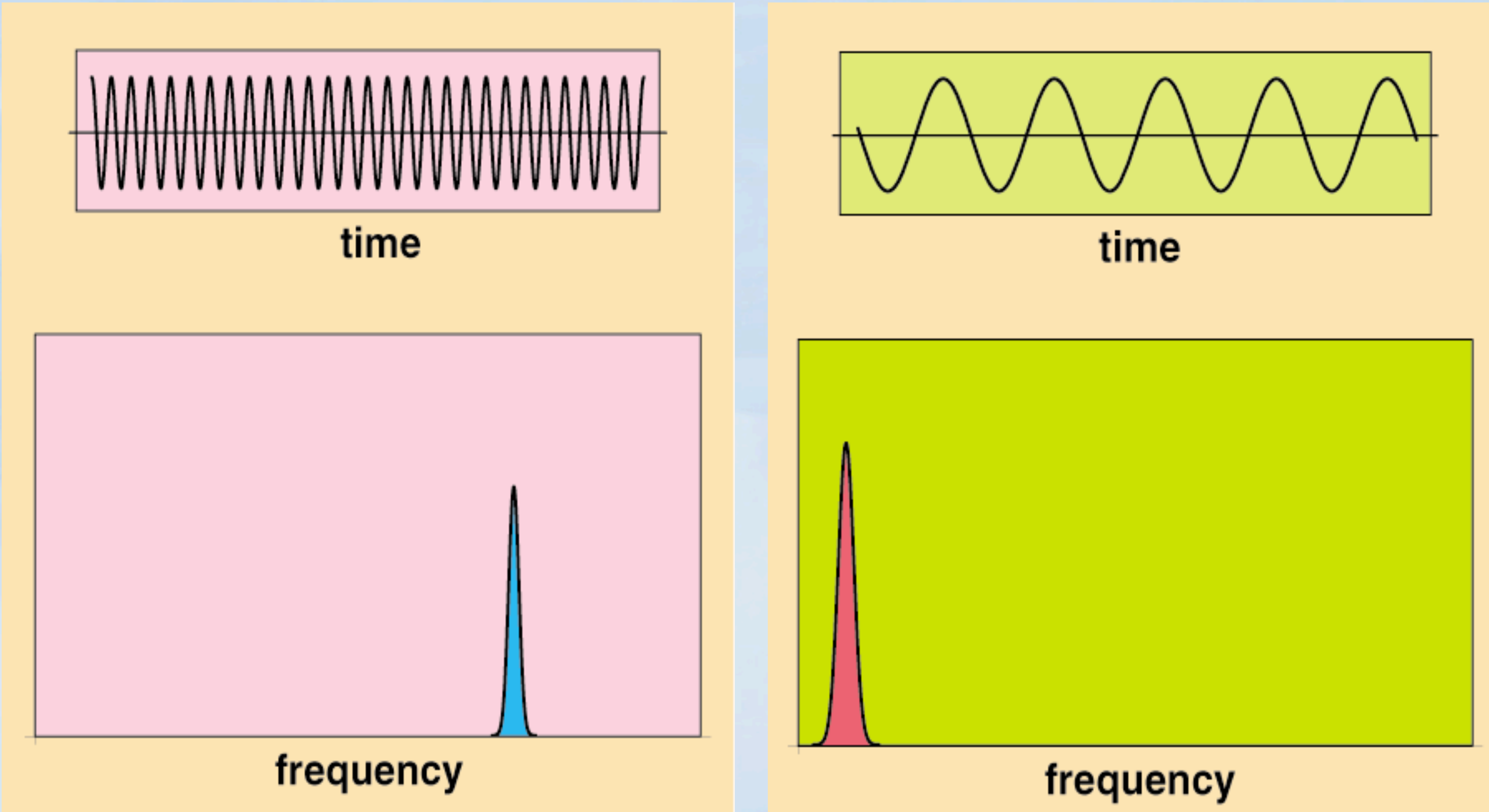
$$S_e(\mathbf{k}, \omega) = N_e \int d\mathbf{v}\, f_e(\mathbf{v}) \delta(\omega - \mathbf{k} \cdot \mathbf{v})$$



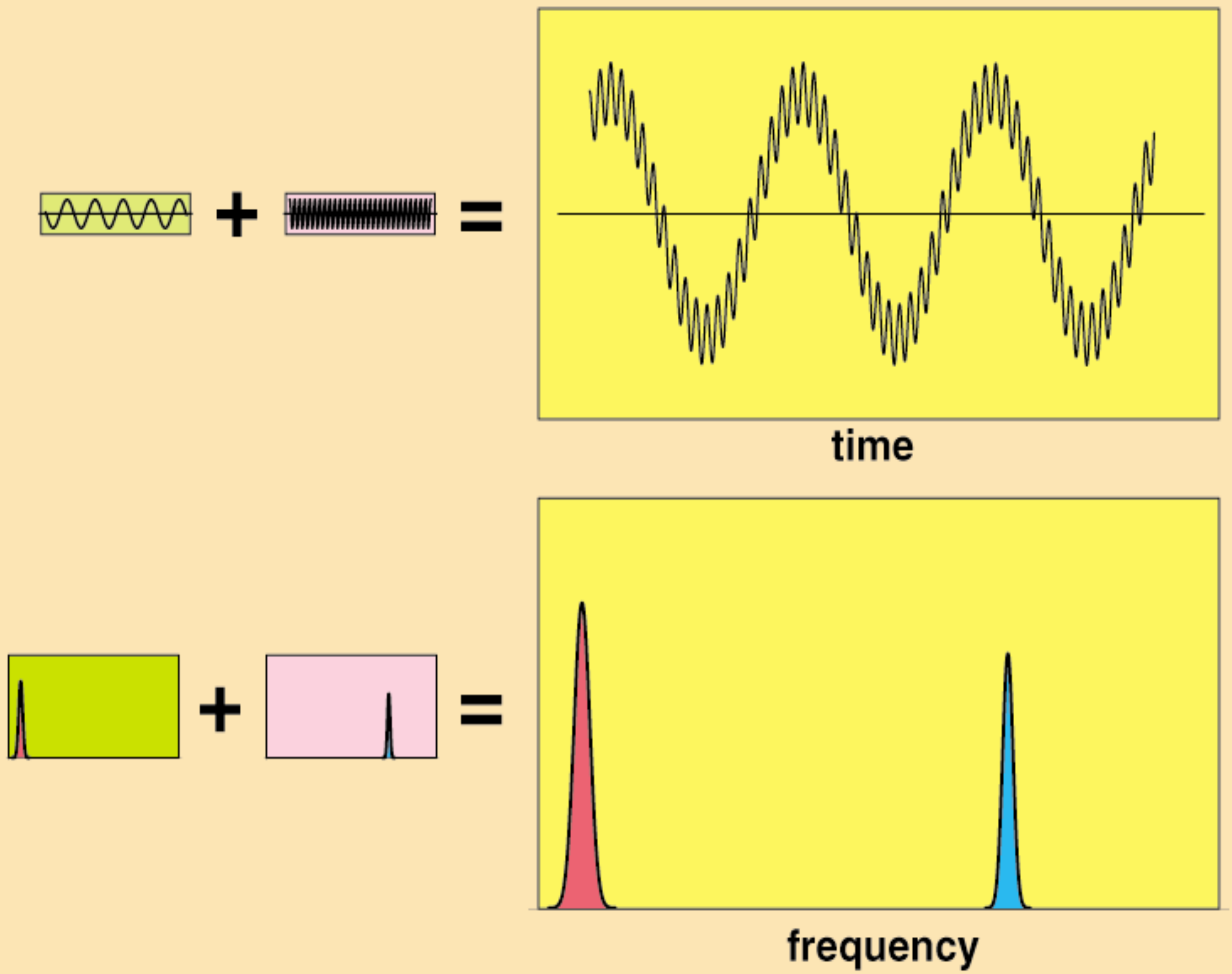
Incoherent scattering - the short story



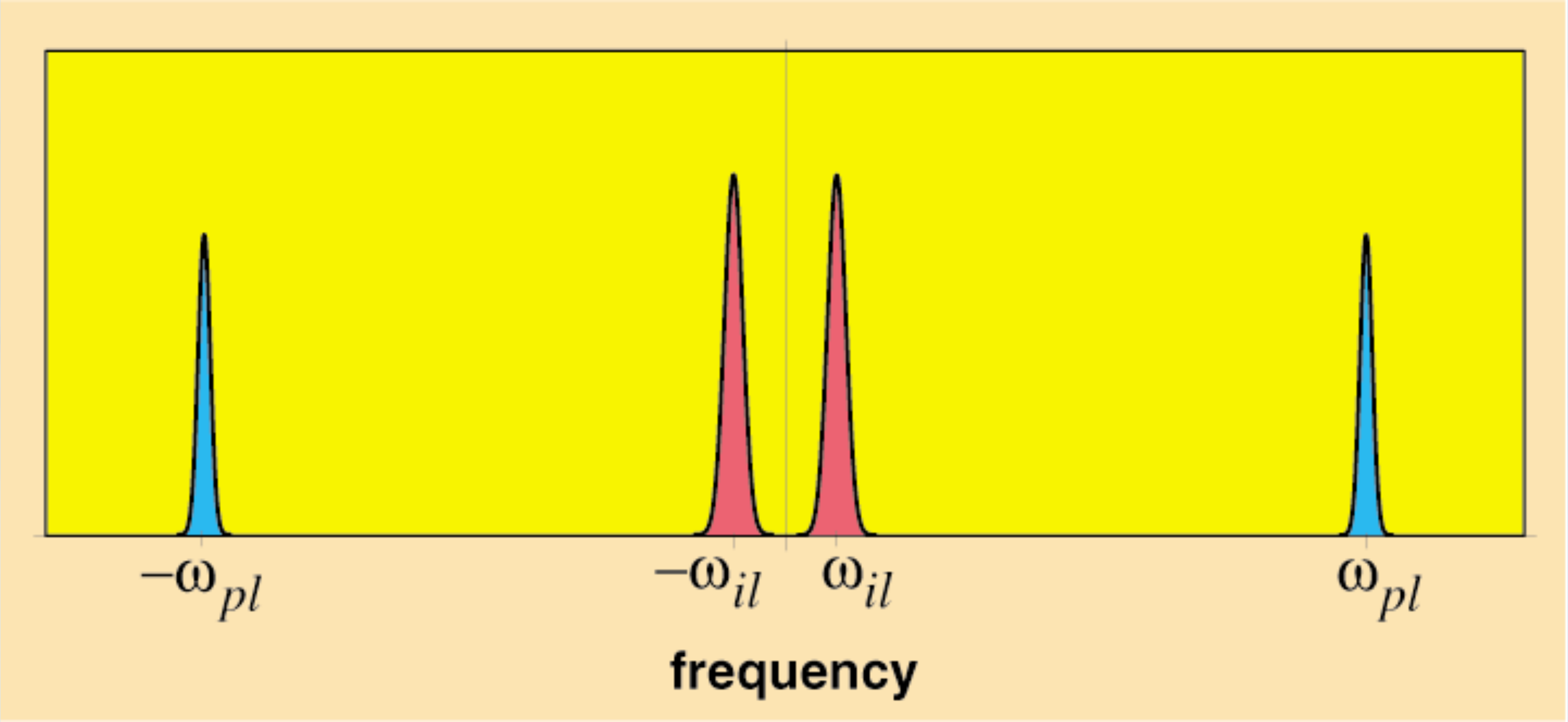
Incoherent scattering - the short story



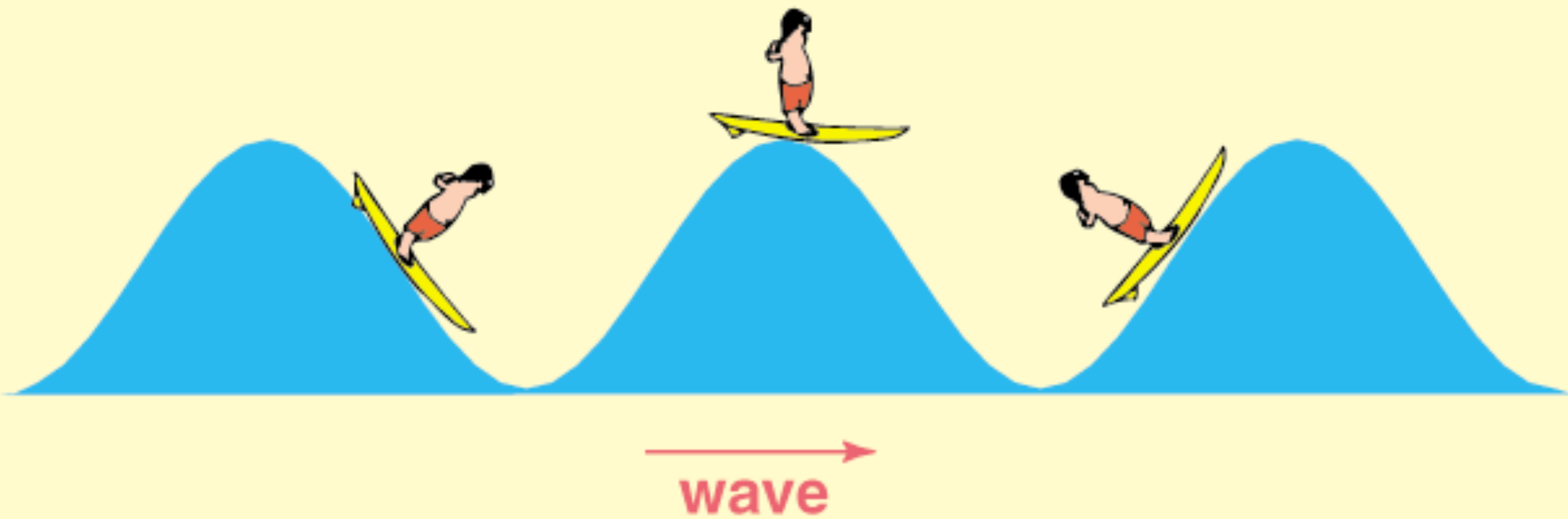
time
frequency
time
frequency


time
frequency

Plasma Wave Approach (cont'd)

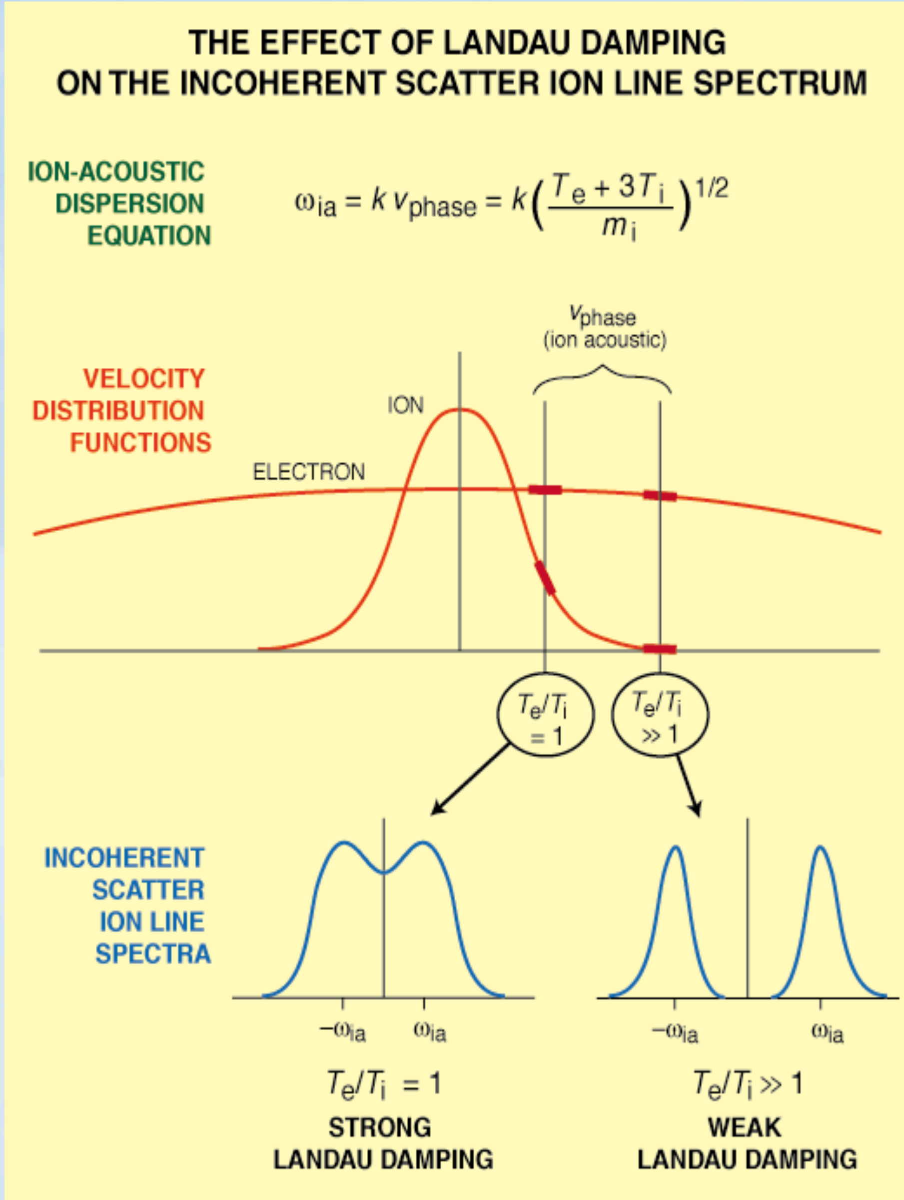


Landau wave-particle interactions

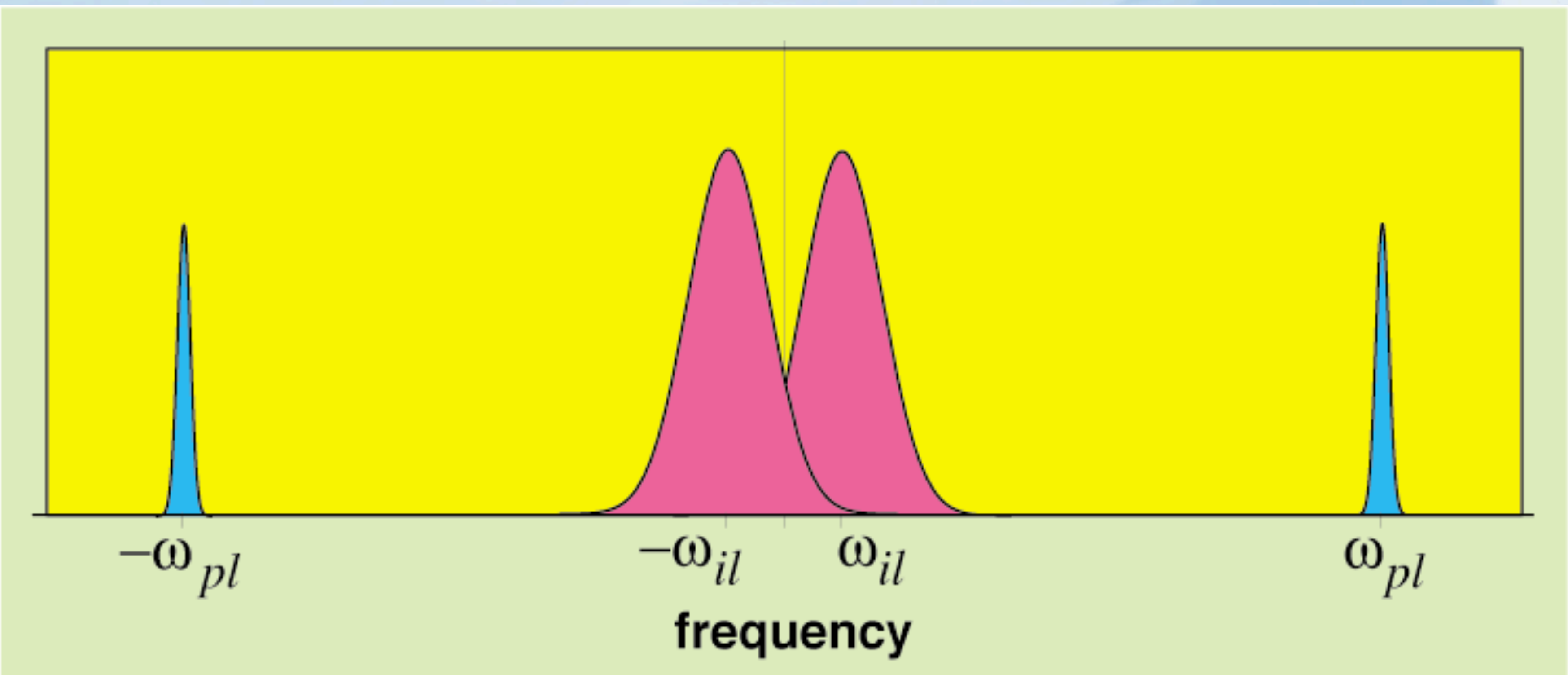


particle gains energy

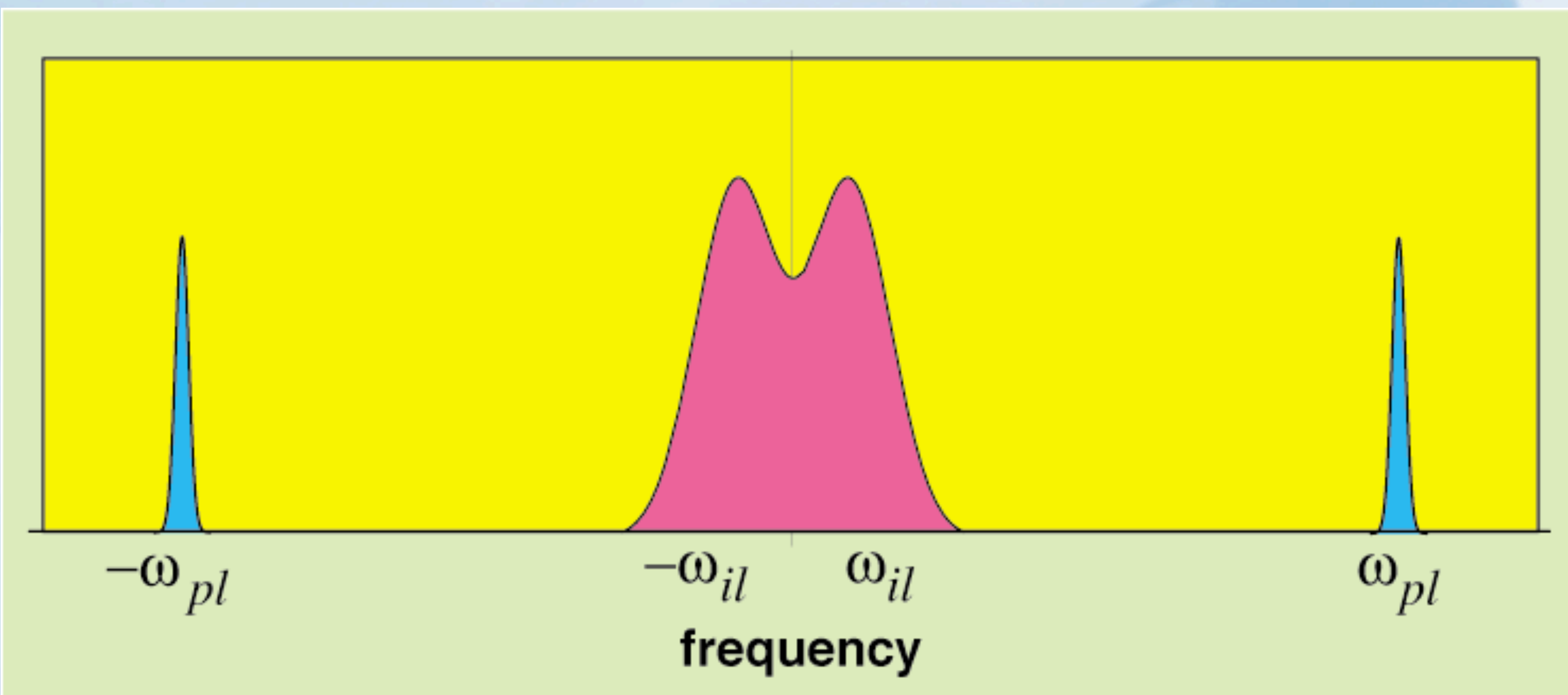
wave gains energy



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
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

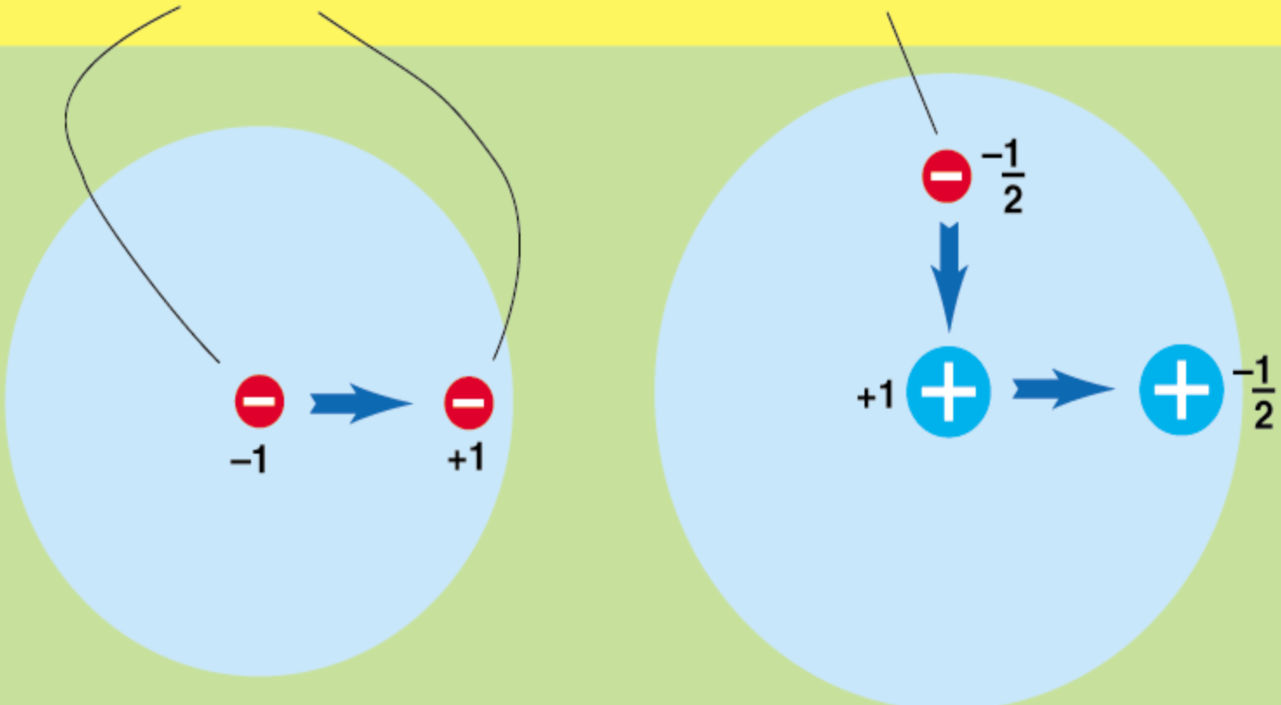
$$S_e(\mathbf{k},\omega) = N_e \left|1 - \frac{\chi_e(\mathbf{k},\omega)}{\epsilon(\mathbf{k},\omega)}\right|^2 \int d\mathbf{v}\, f_e(\mathbf{v})\delta(\omega - \mathbf{k}\cdot\mathbf{v}) + N_i \left|\frac{\chi_e(\mathbf{k},\omega)}{\epsilon(\mathbf{k},\omega)}\right|^2 \int d\mathbf{v}\, f_i(\mathbf{v})\delta(\omega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

Plasma line — Ion line

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

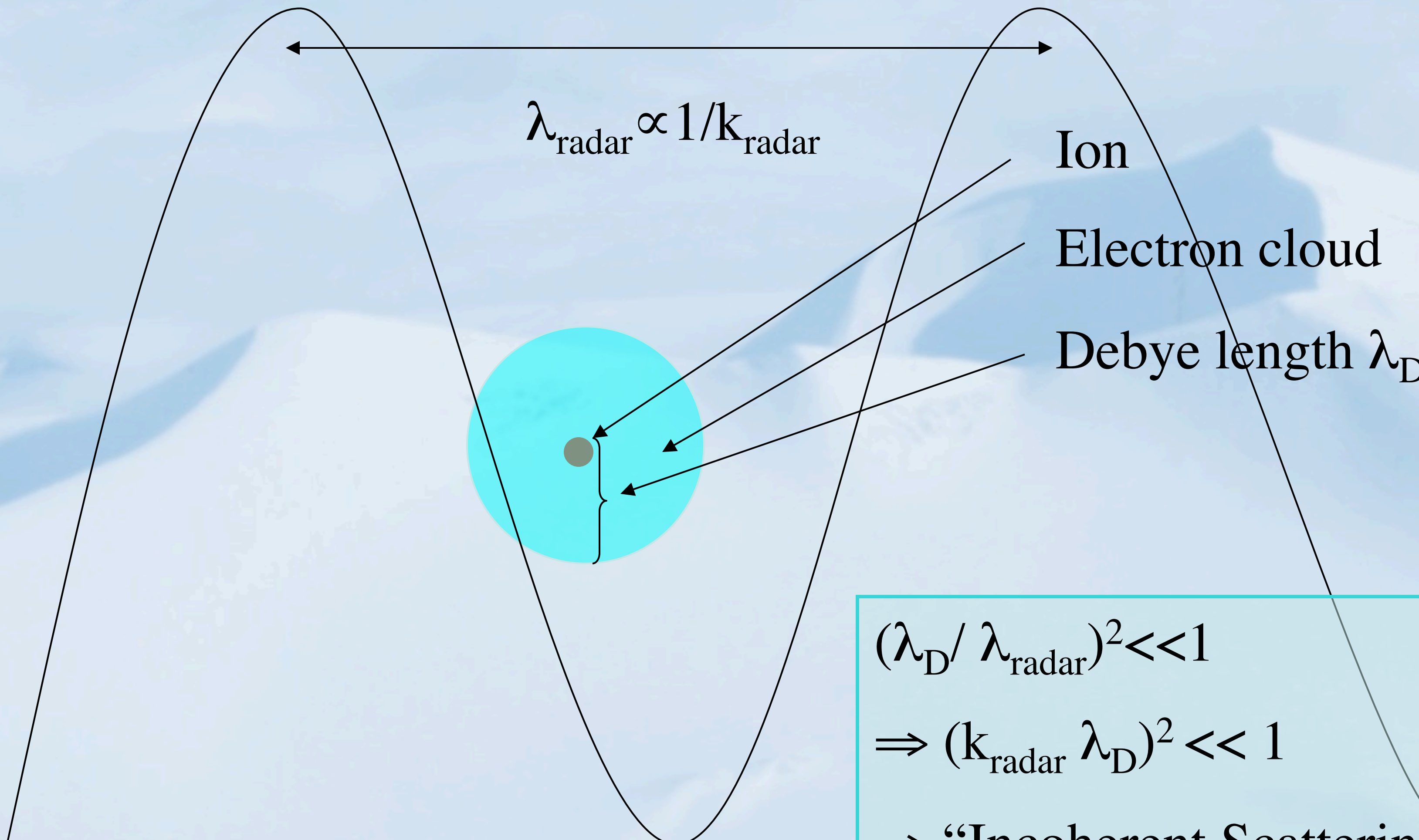
Plasma Line $S_{PL}(\mathbf{k},\omega)$ **Ion Line** $S_{IL}(\mathbf{k},\omega)$

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



electron with cloud ion with cloud

Debye length dependence



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

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

⇒ "Incoherent Scattering"

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

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

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

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

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

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

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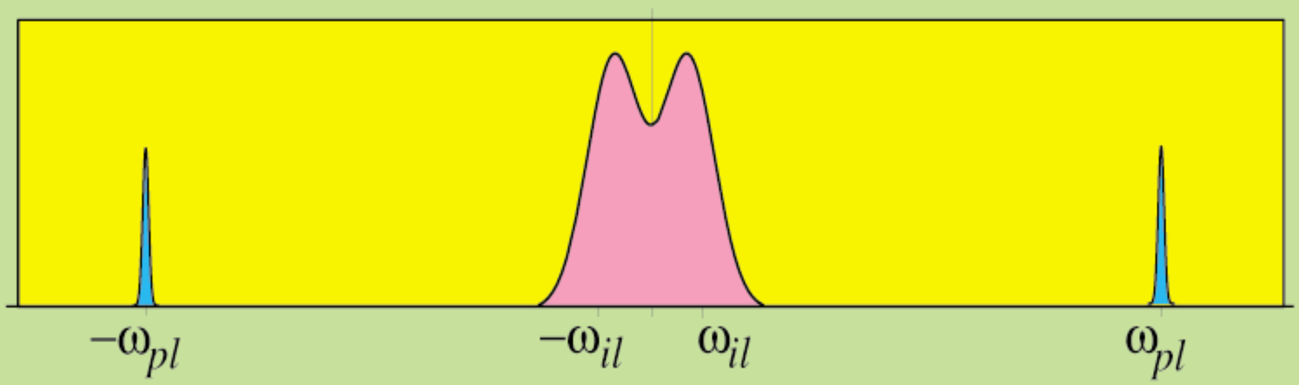
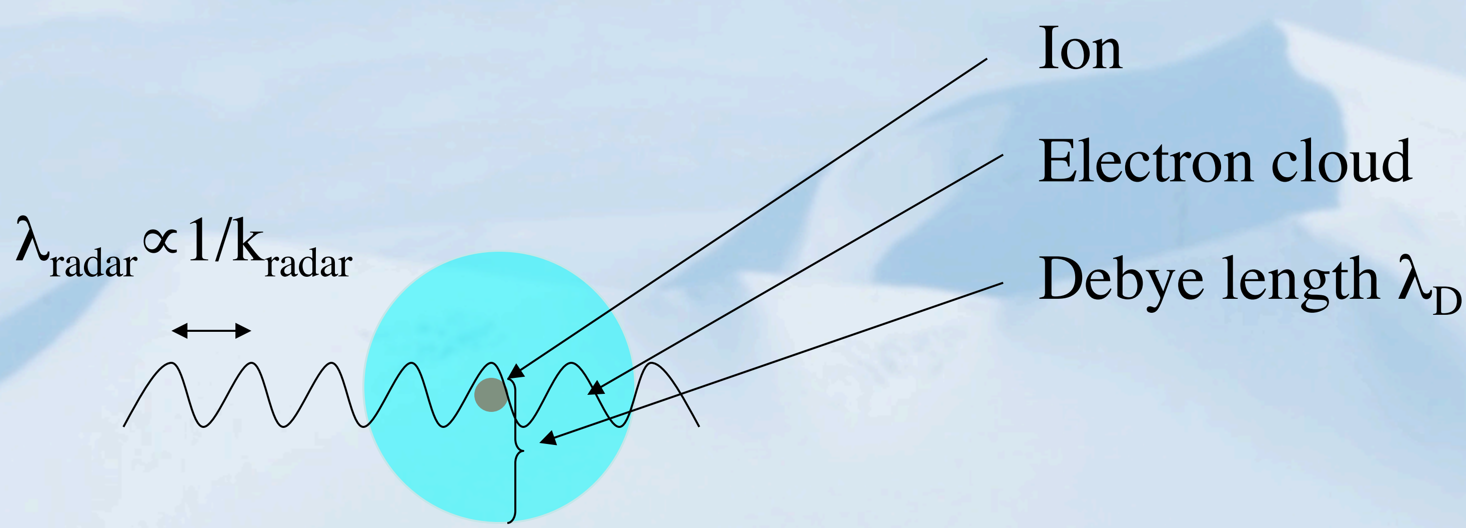


Debye length dependence



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

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

$\Rightarrow$ No collective interactions

no collective interactions

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

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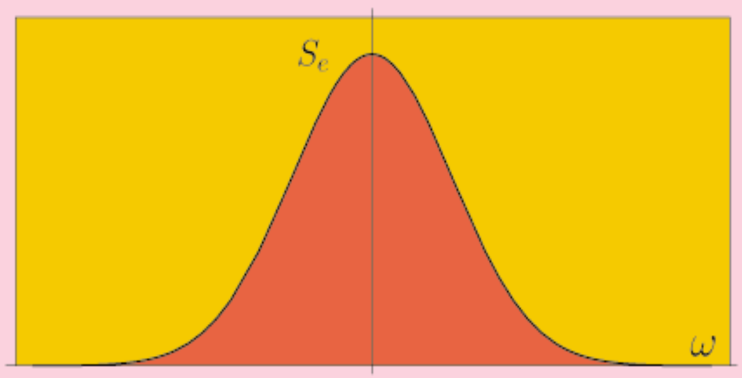
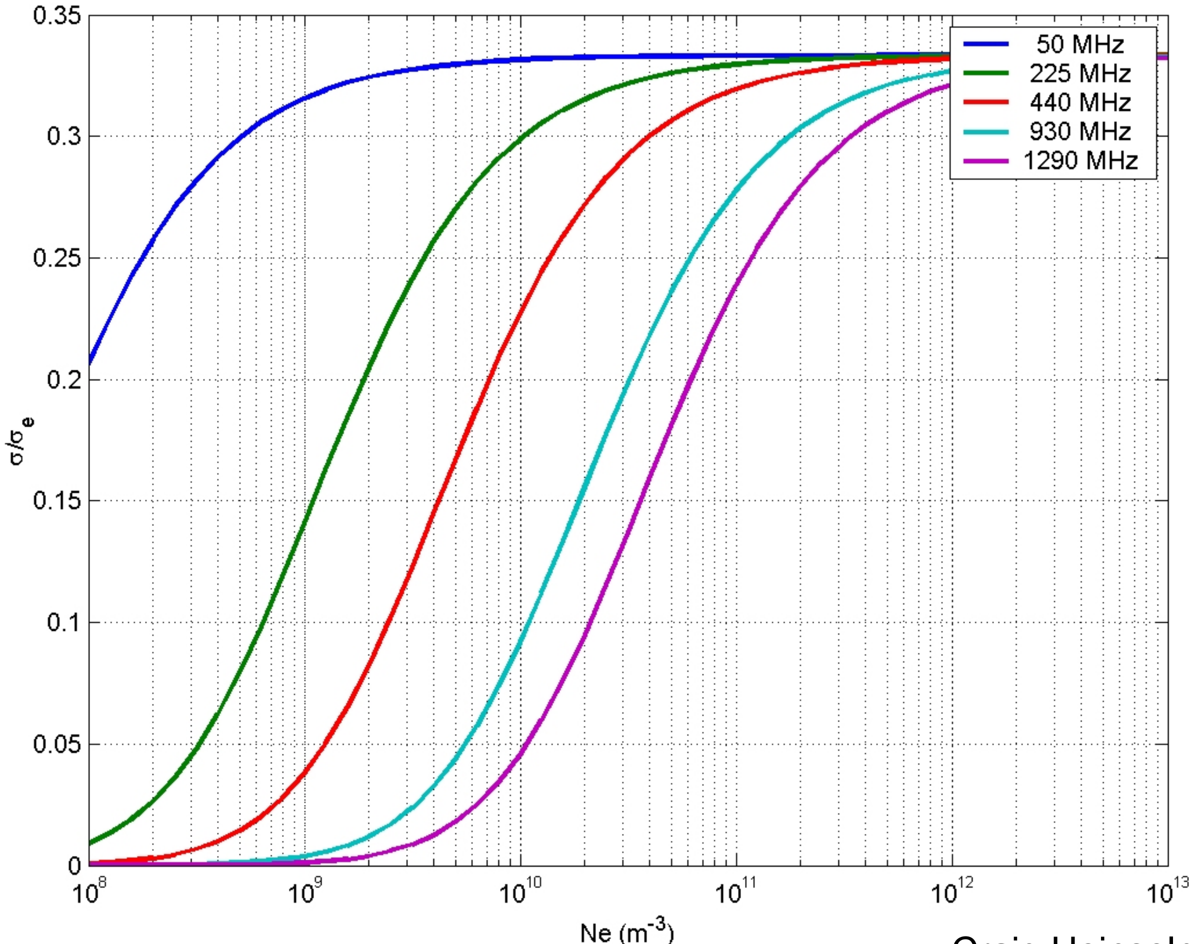


Debye Length Dependencies



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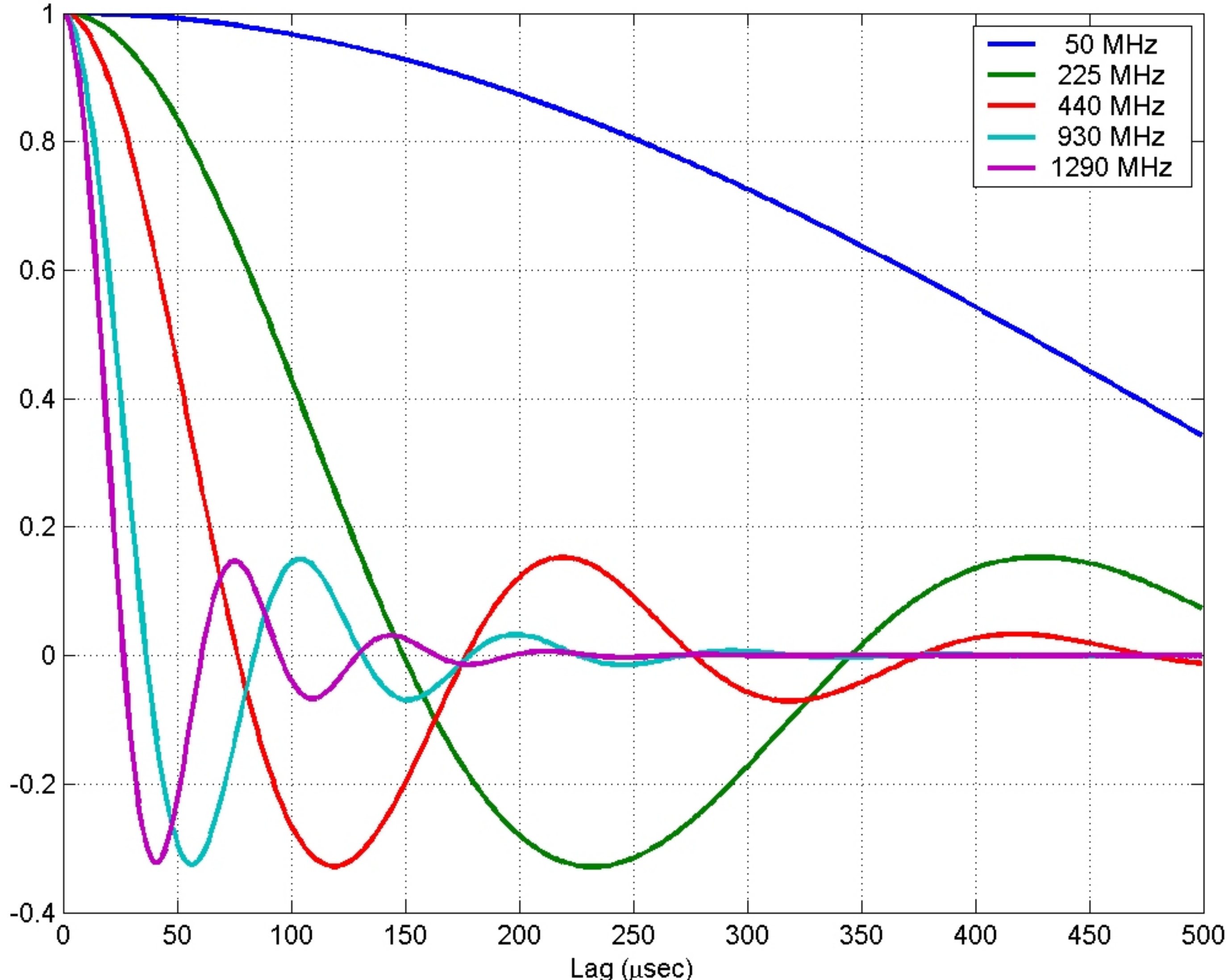
Parameters
Ti: 1000 K
Te: 2000 K



Parameters

Ne: 10^{12} m^{-3}

Ti: 1000 K

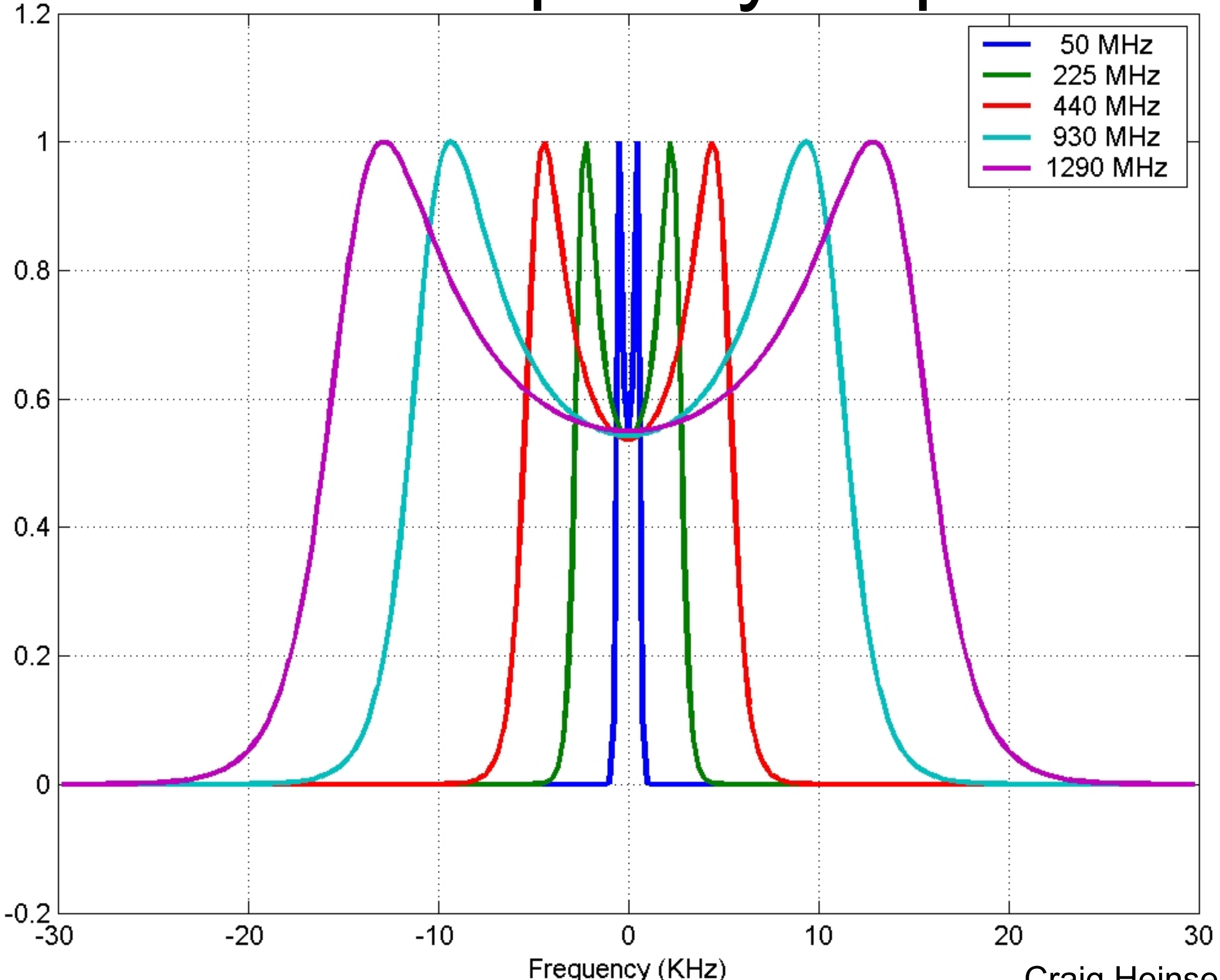
Te: 2000 K

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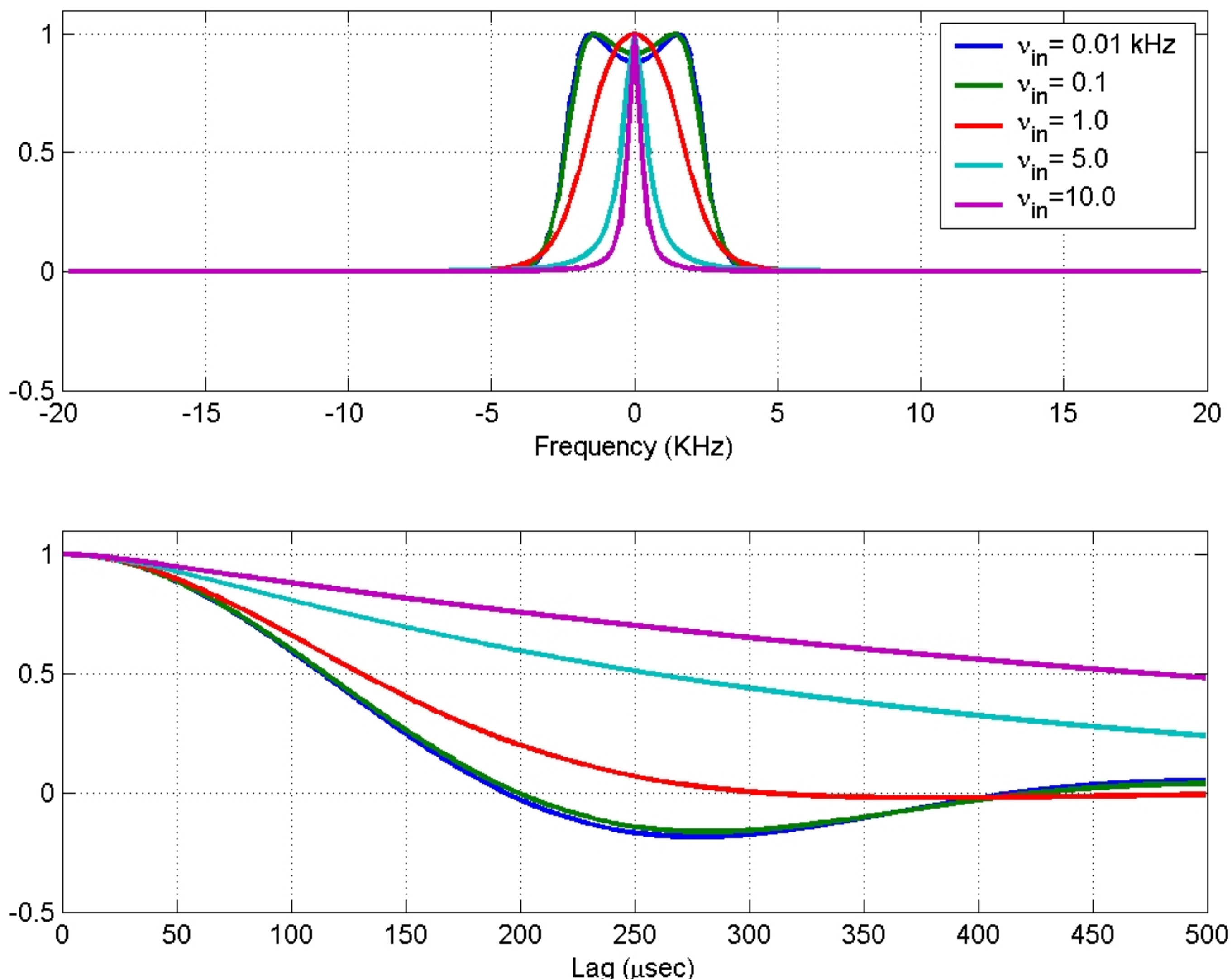
With the frequency of the radar chosen (which is a one time thing!), how does the spectra depend on geophysical parameters?

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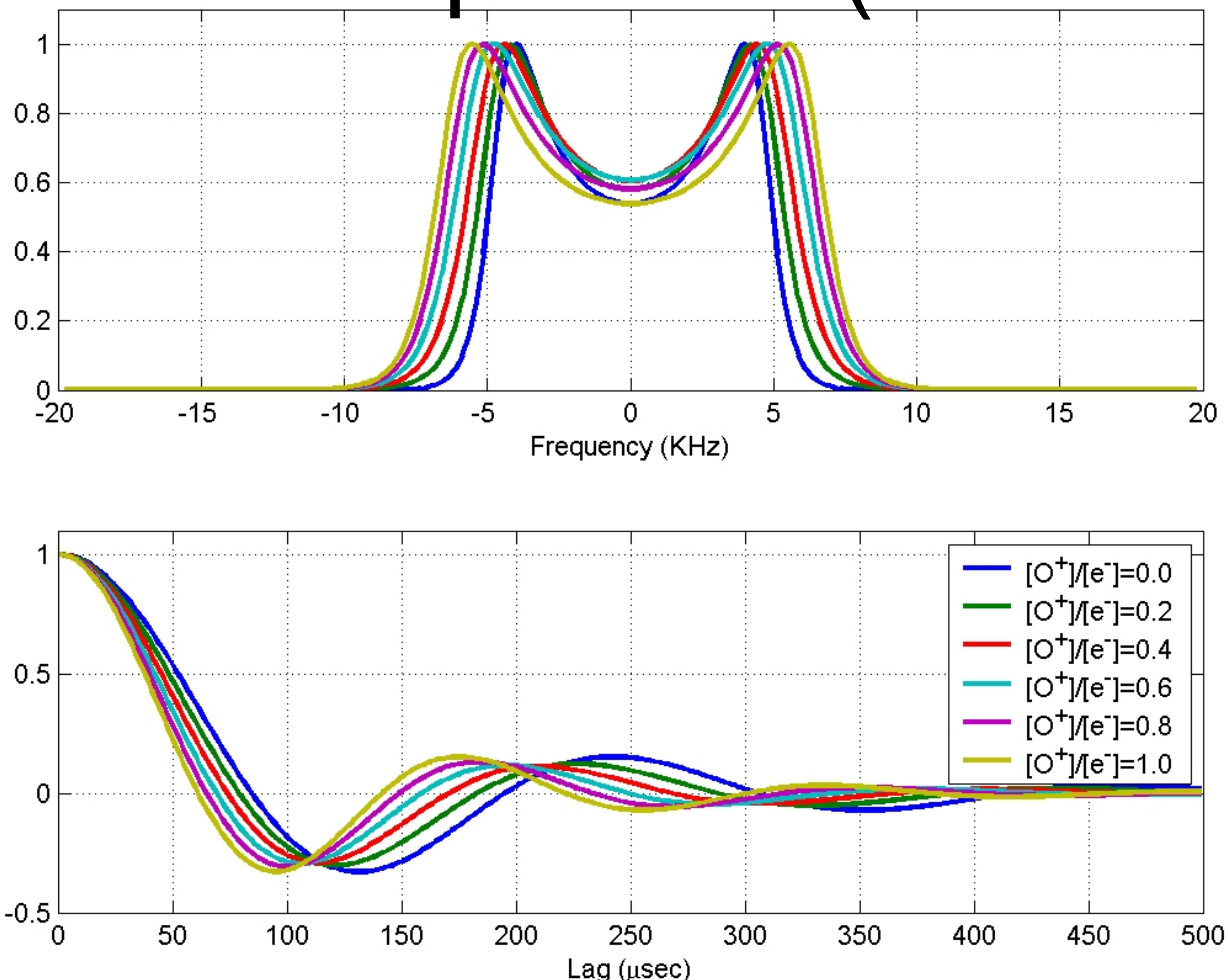
Ion Composition (O^+ vs. NO^+)



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

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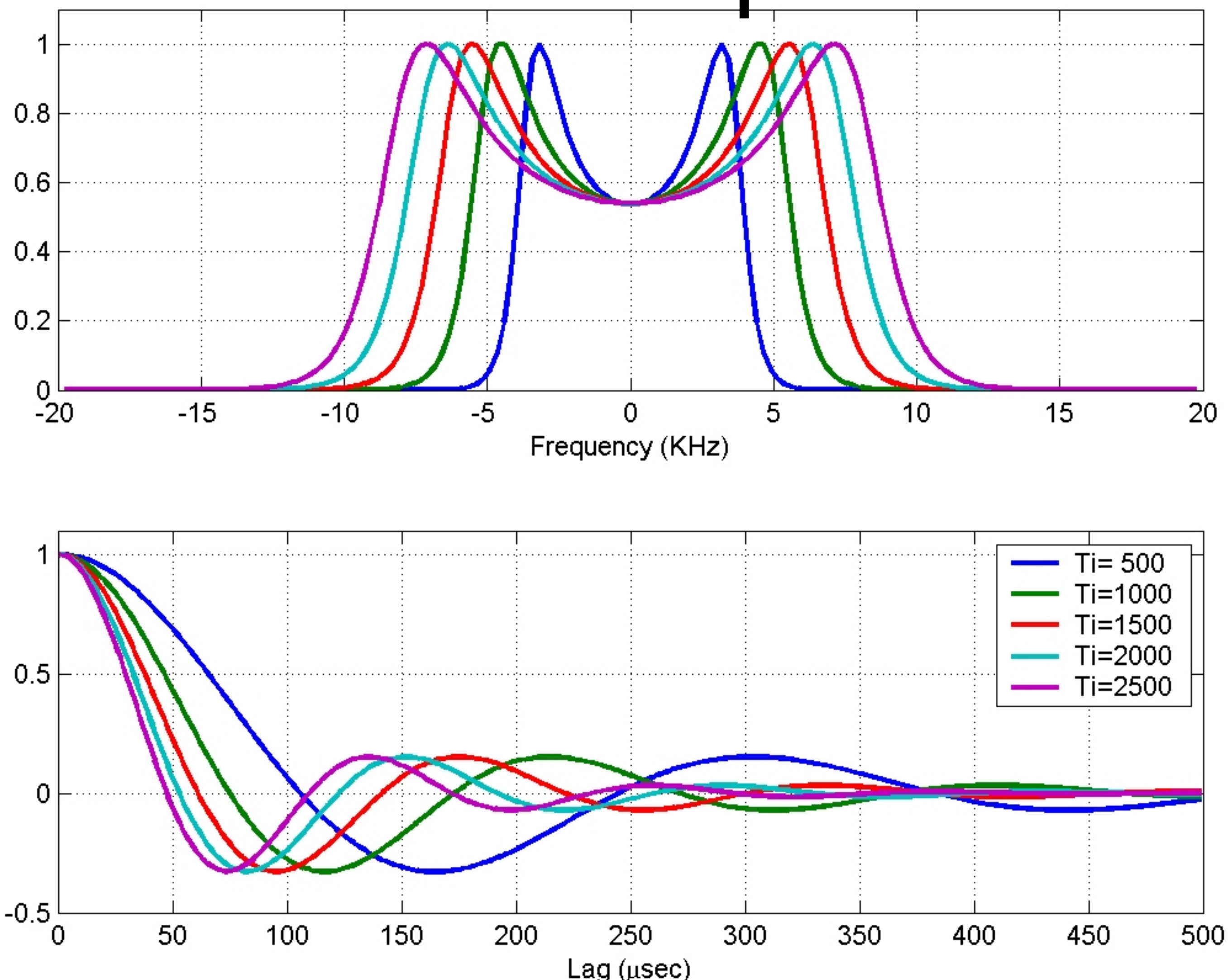
Ion Temperature



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

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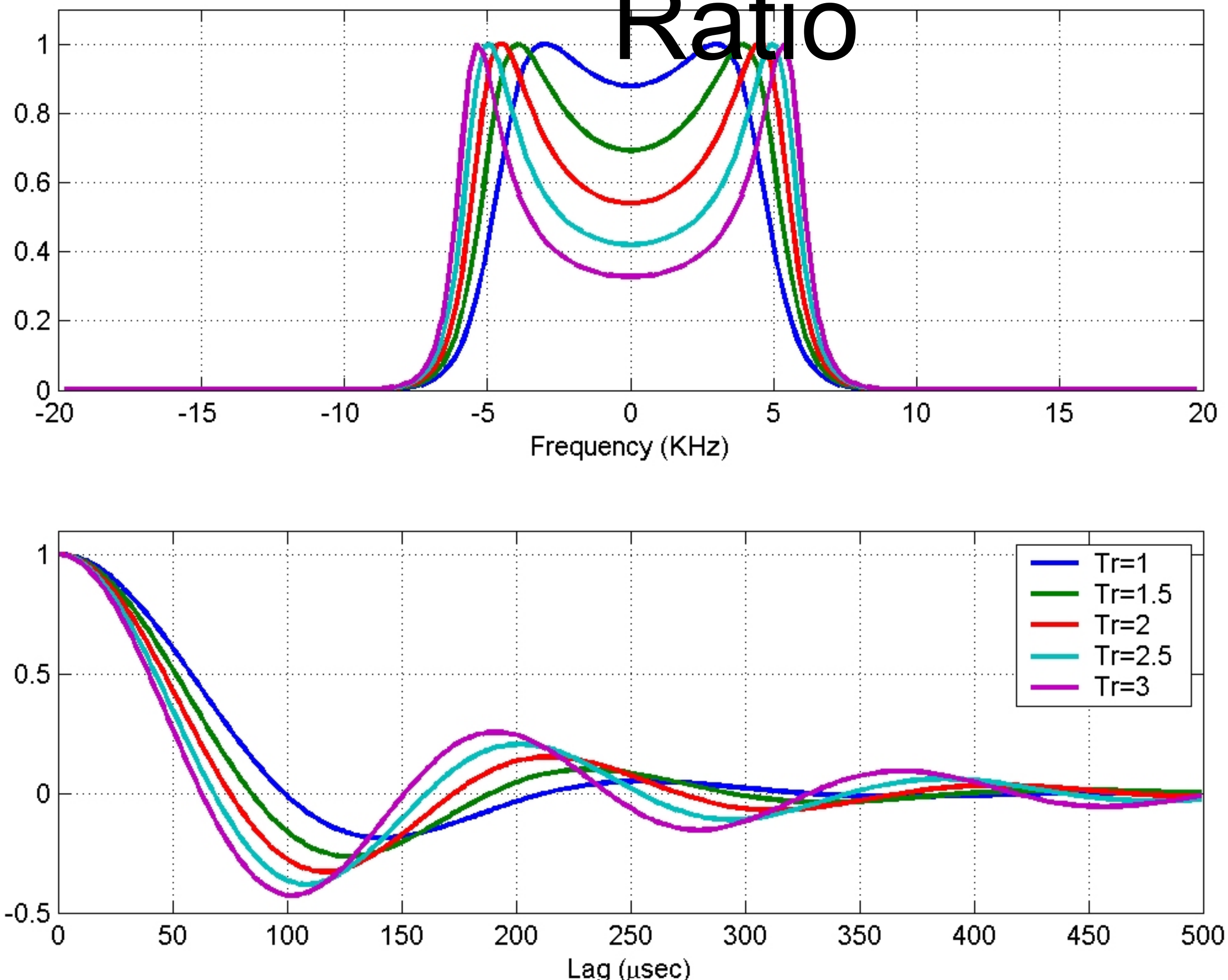
Electron/Ion Temperature Ratio



<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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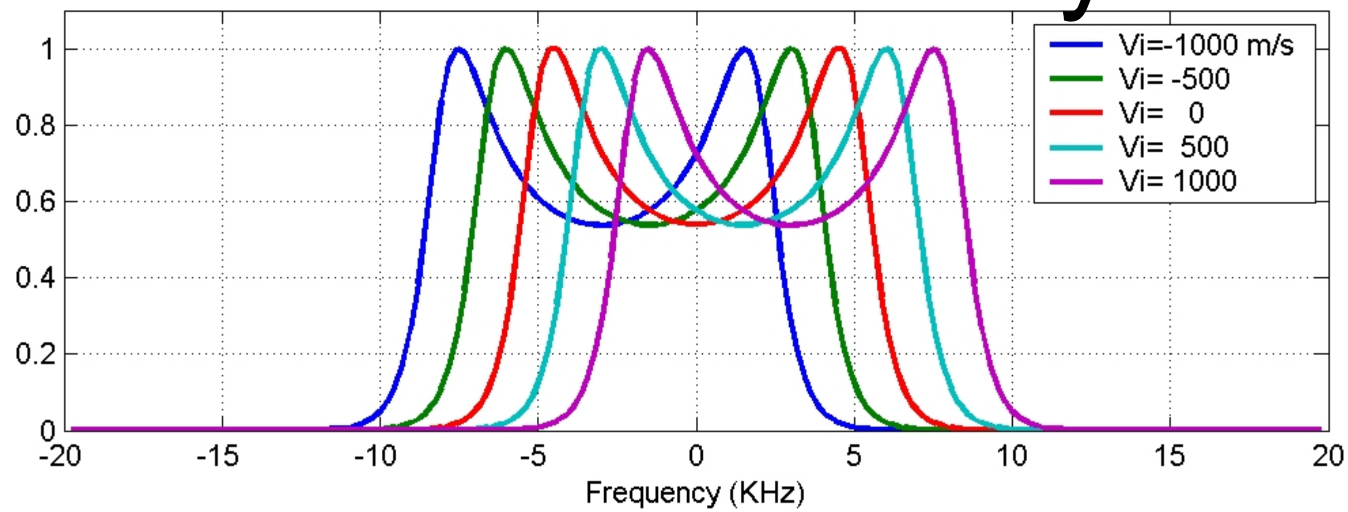
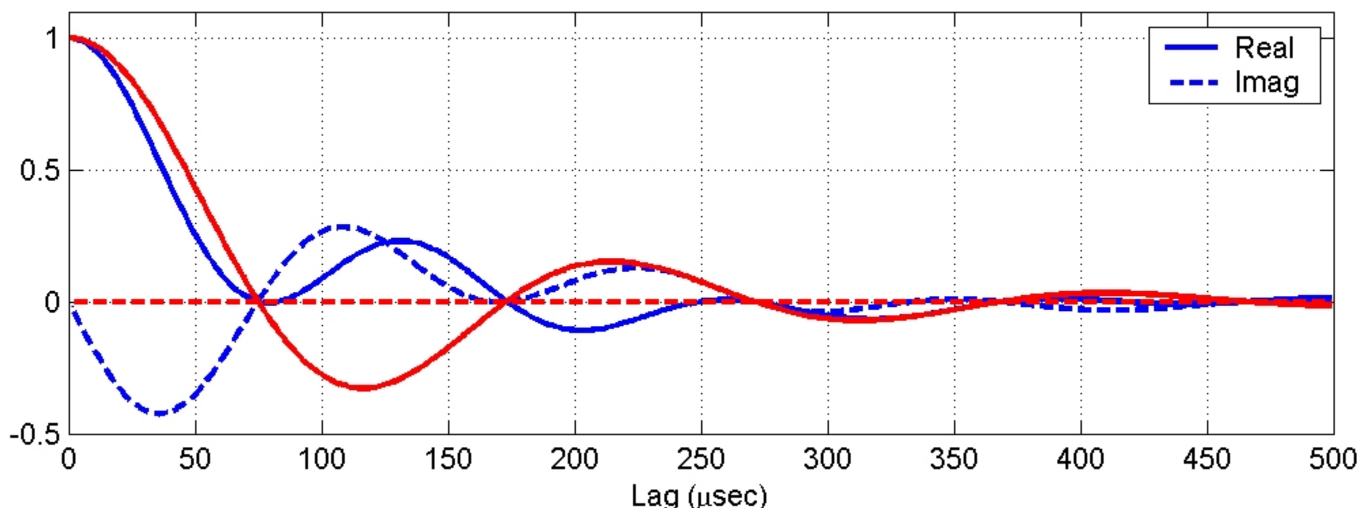
Ion Velocity





Parameters
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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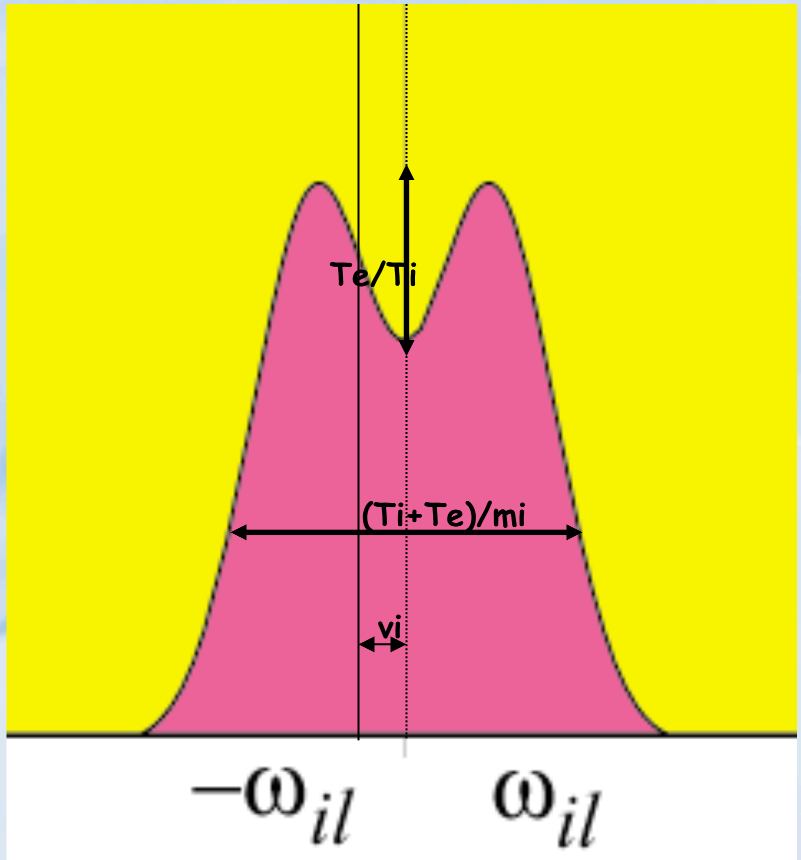
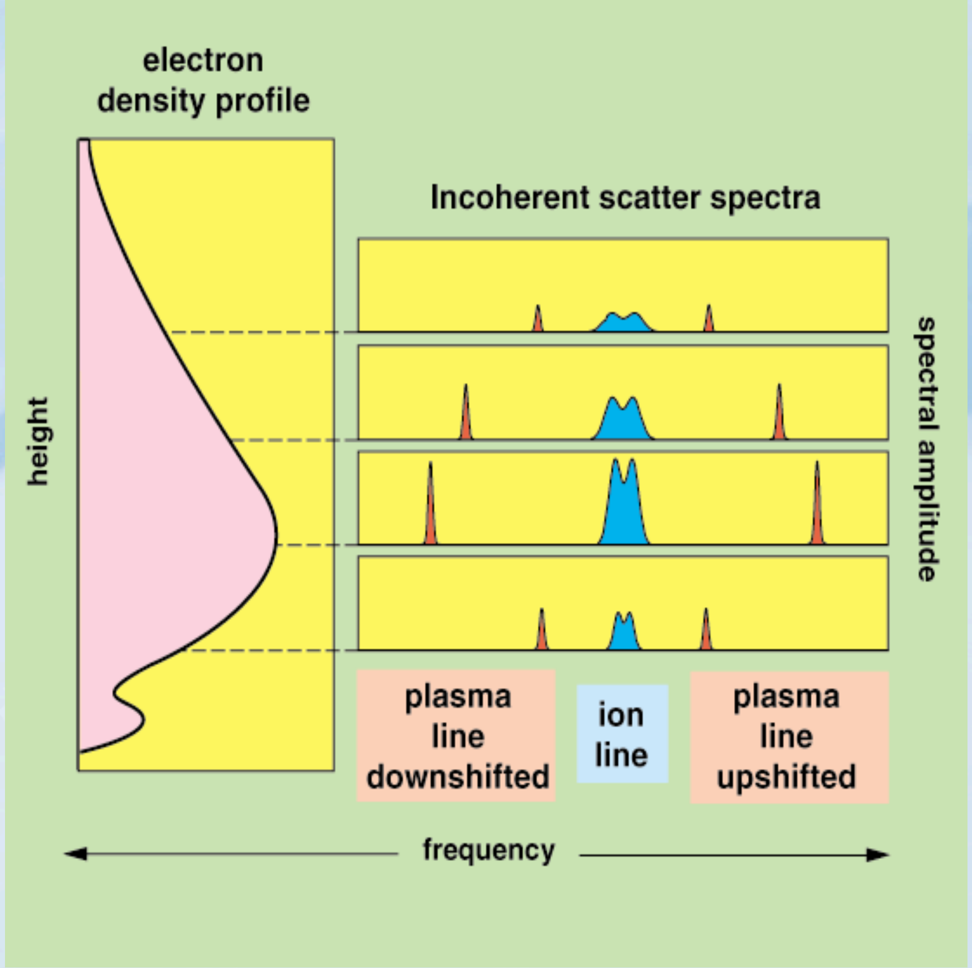
…or to sum up…

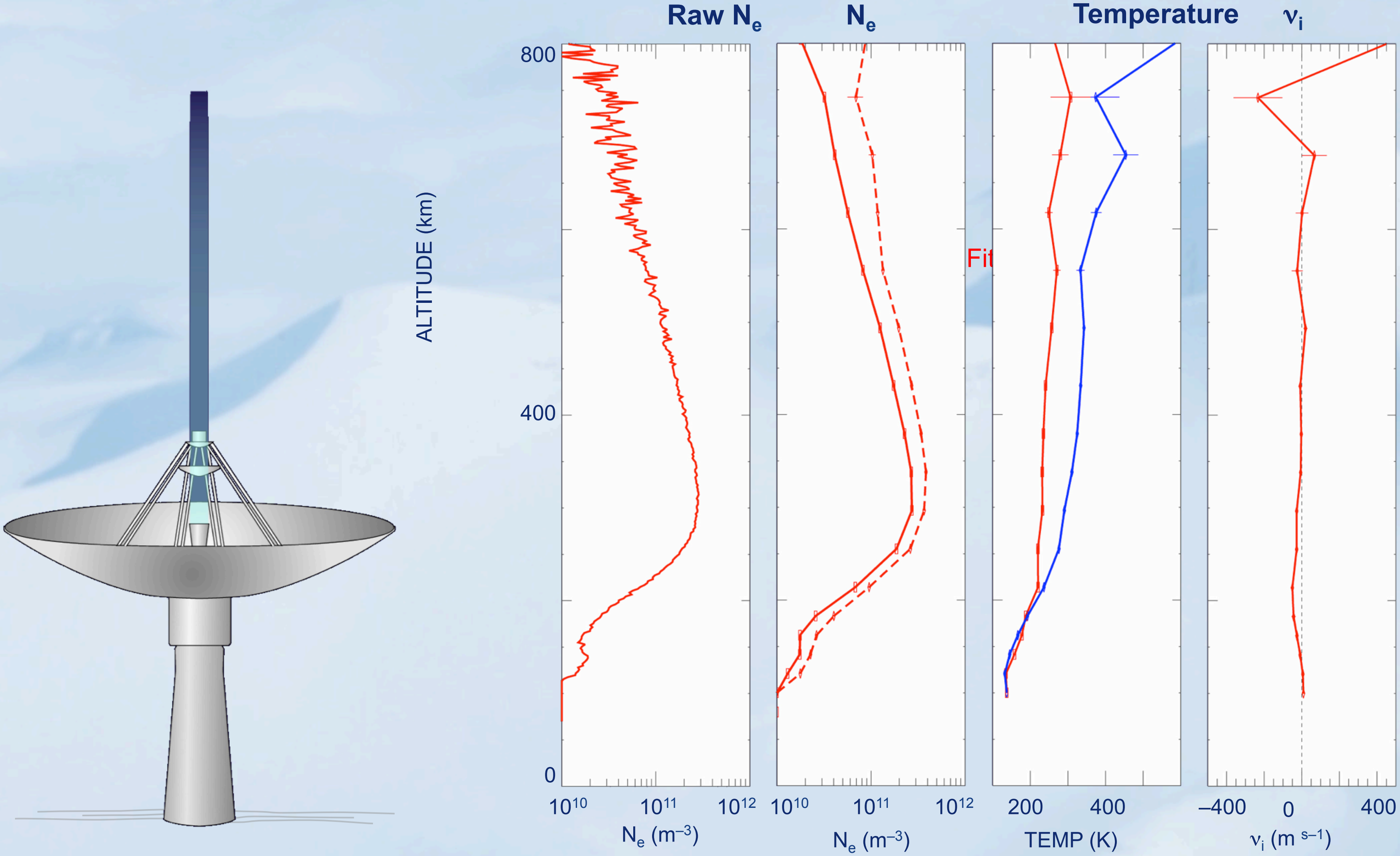


- Ion (and electron) temperature (Ti and Te) to ion mass (mi) ratio from the width of the spectra
- Electron to ion temperature ratio (Te/Ti) from "peak_to_valley" ratio
- Electron (= ion) density from total area (corrected for temperatures)
- Ion velocity (vi) from the Doppler shift

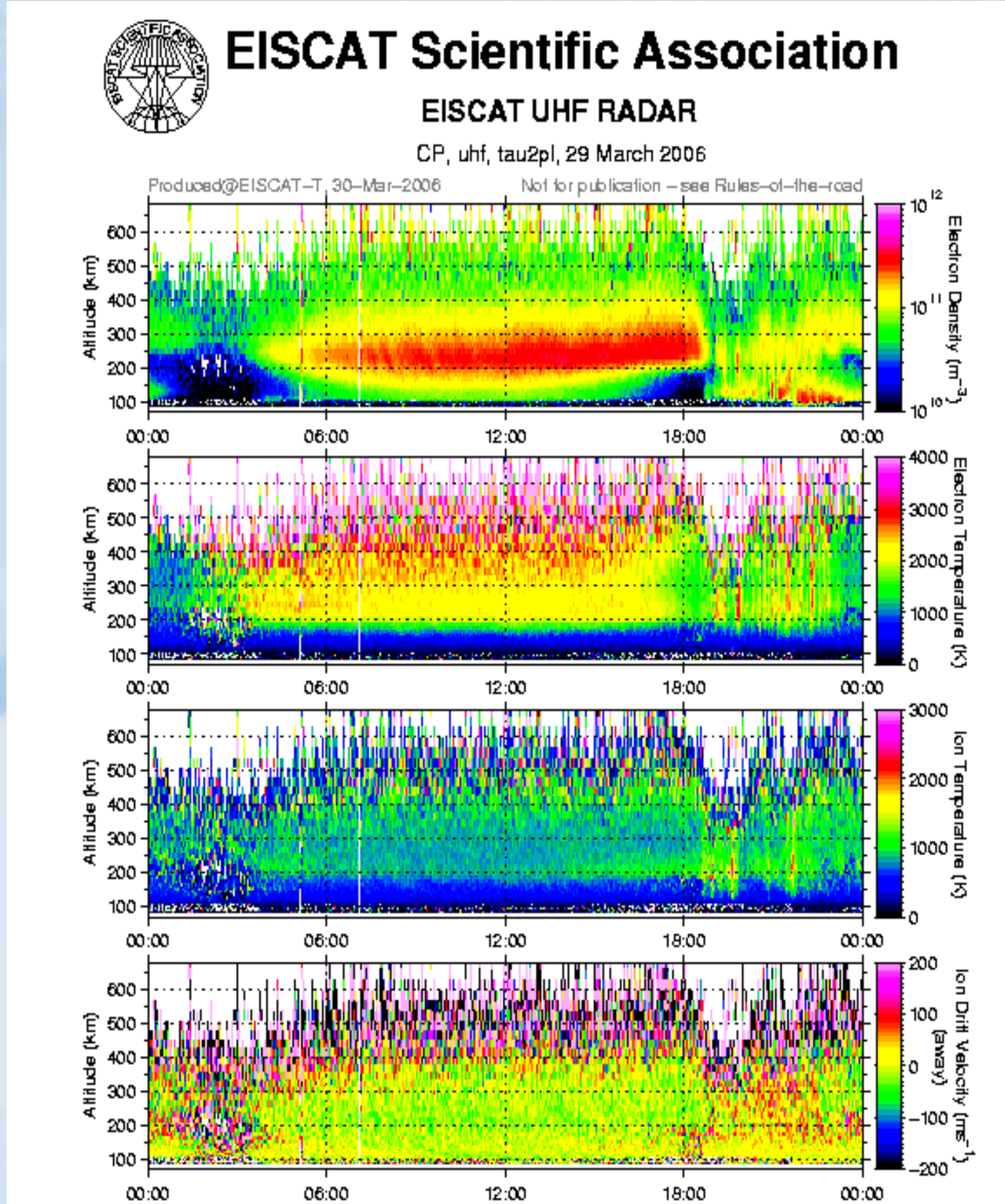
Spectral space as a function of altitude



Plasma Parameter Profile

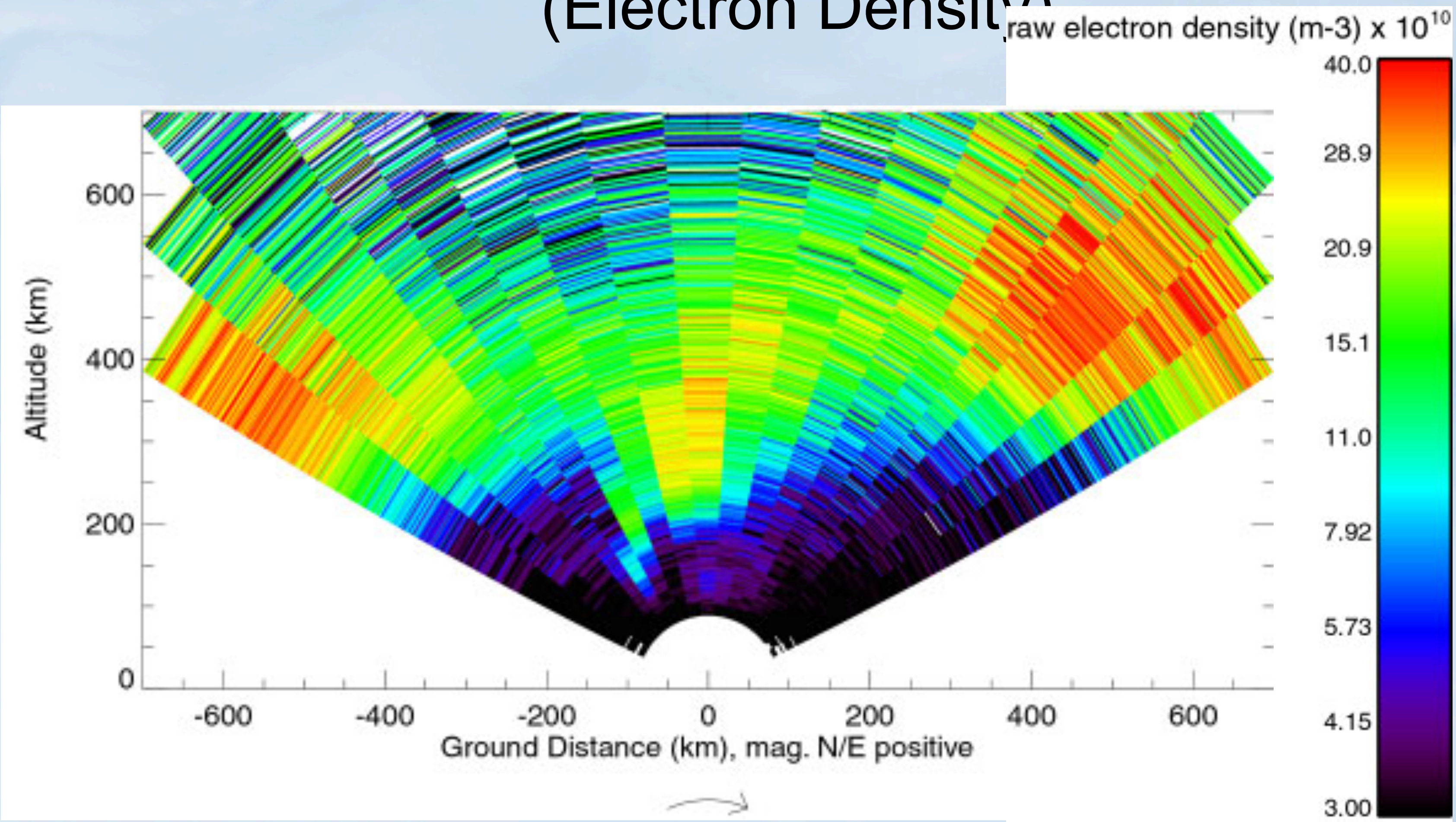


v6

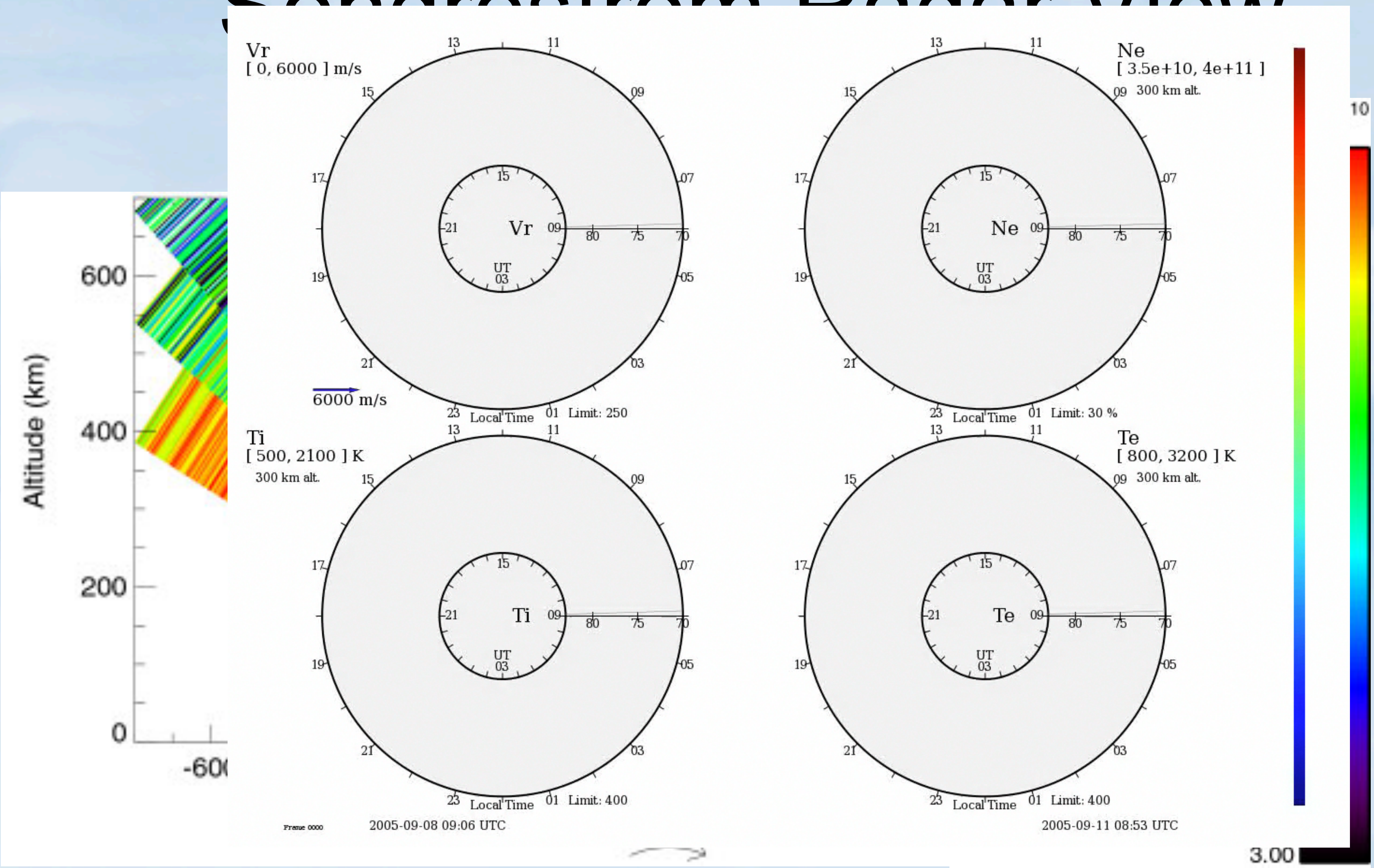

EISCAT Scientific Association
EISCAT UHF RADAR
CP, uhf, tau2pl, 29 March 2006
Produced@EISCAT-T, 30-Mar-2006
Not for publication – see Rules-of-the-road
Altitude (km)
Electron Density (m^-3)
Electron Temperature (K)
Ion Temperature (K)
Ion Drift Velocity (ms^-1) (away)
00:00
06:00
12:00
18:00
00:00

Sondrestrom Radar View

(Electron Density)



Sondrestrom Radar View



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