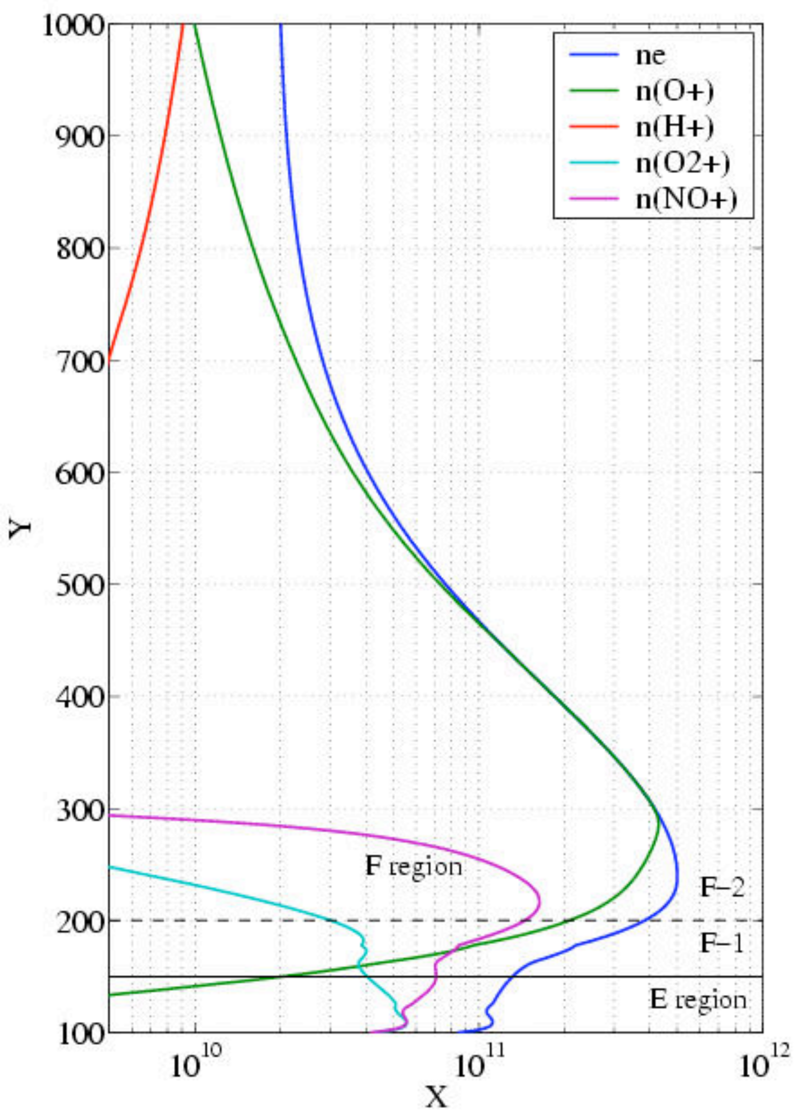
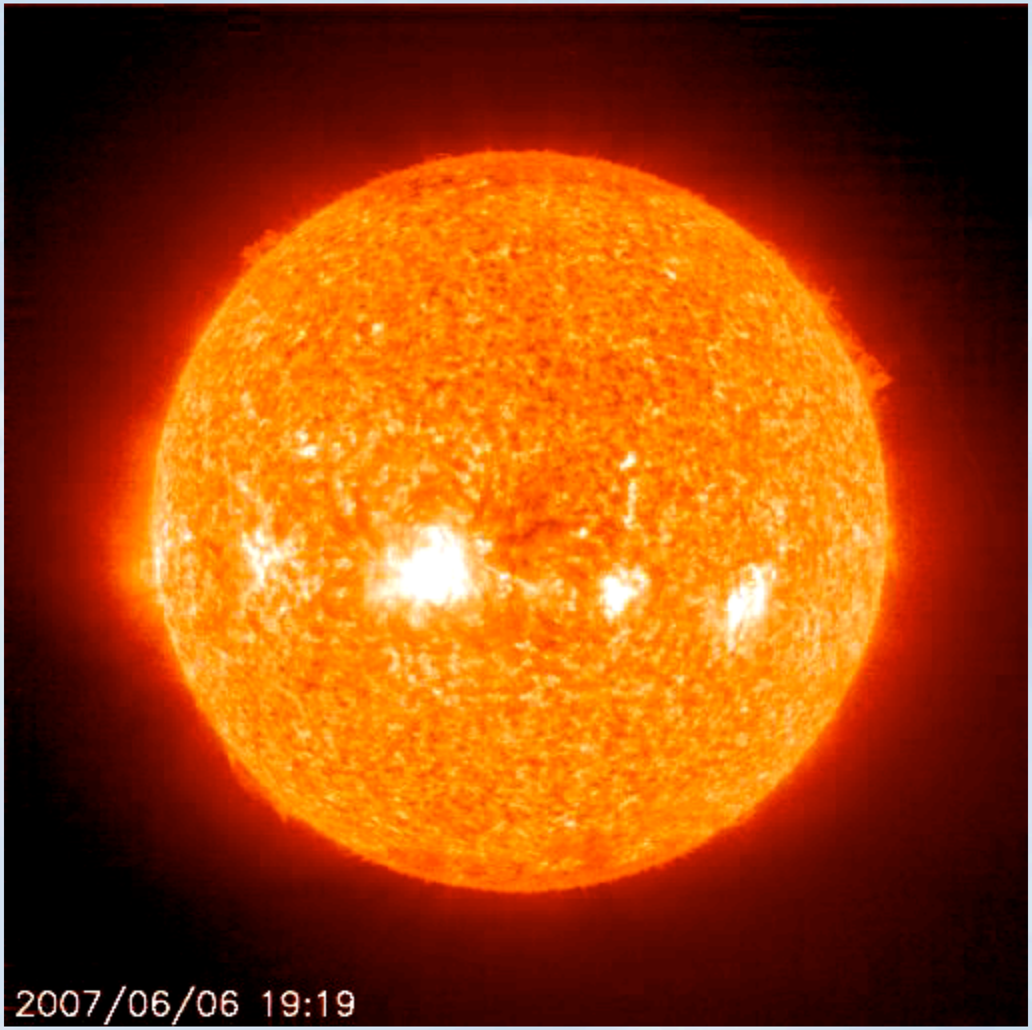
The short introduction to Incoherent Scatter (IS) Theory

Anja Strømme
SRI International

First: We need an Ionsophere…

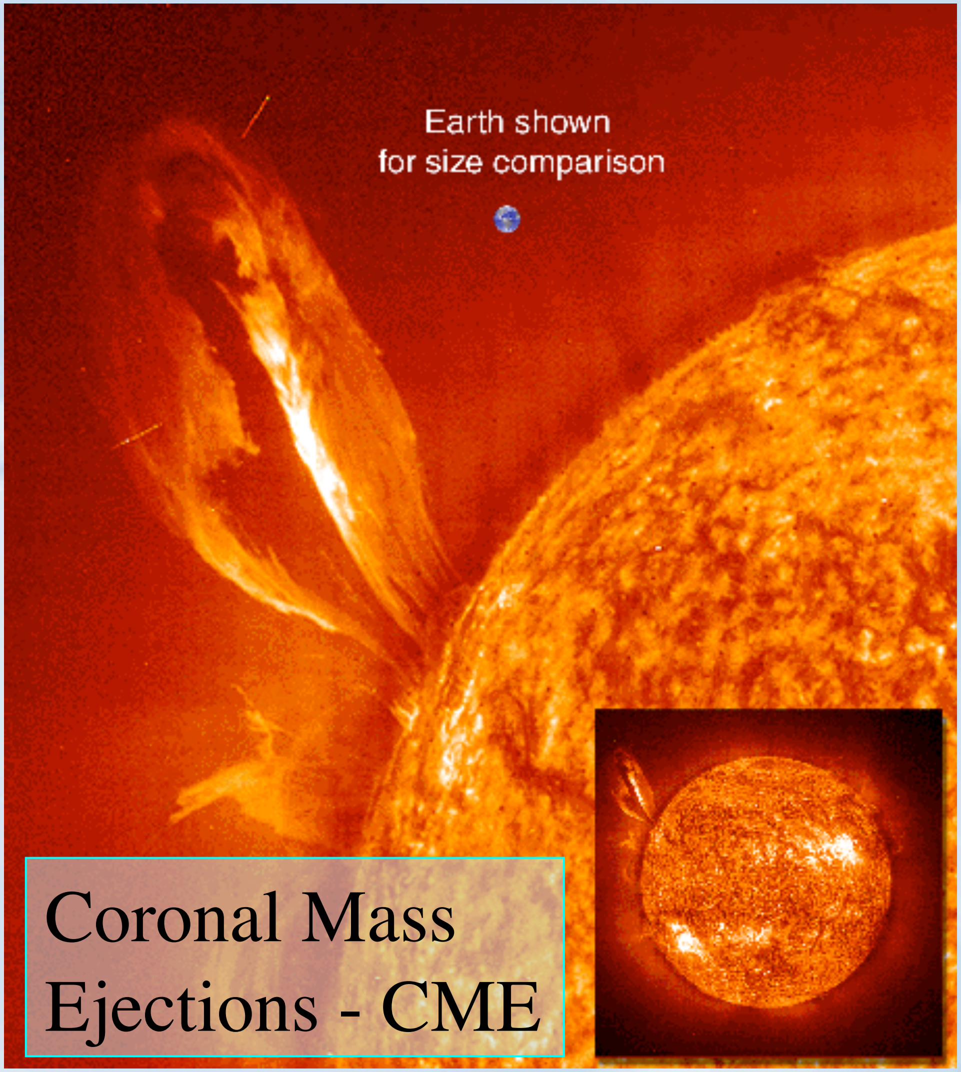
The Earths Ionosphere





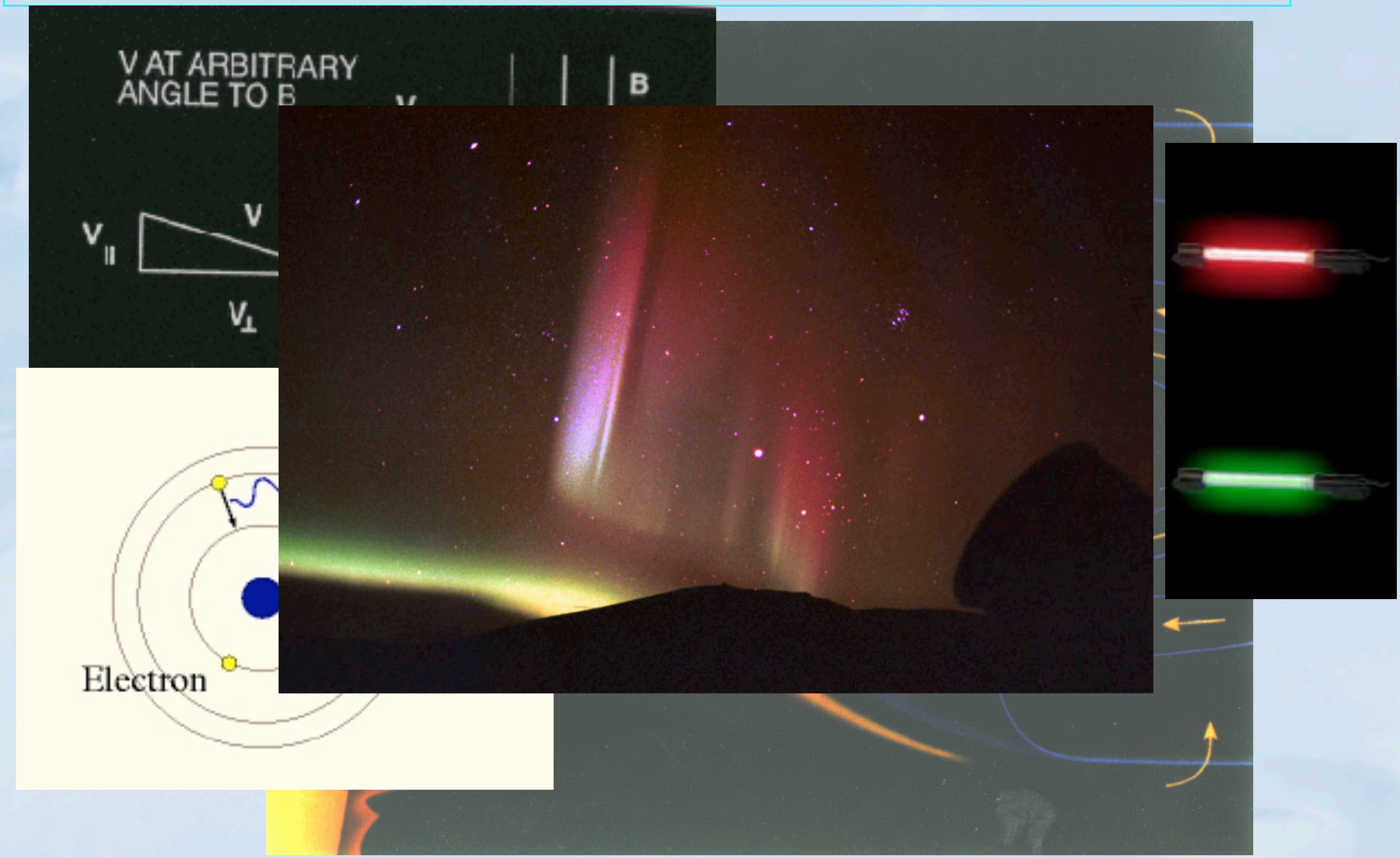
Additional ionization at high latitudes

- The Sun evaporates at supersonic velocities
- The Sun's atmosphere is very hot and ionises the escaping gas
- The expanding 'Solar Wind' carries the surface magnetic fields with it
- The Solar Wind is frequently distorted by huge eruptions which generate vast shock waves



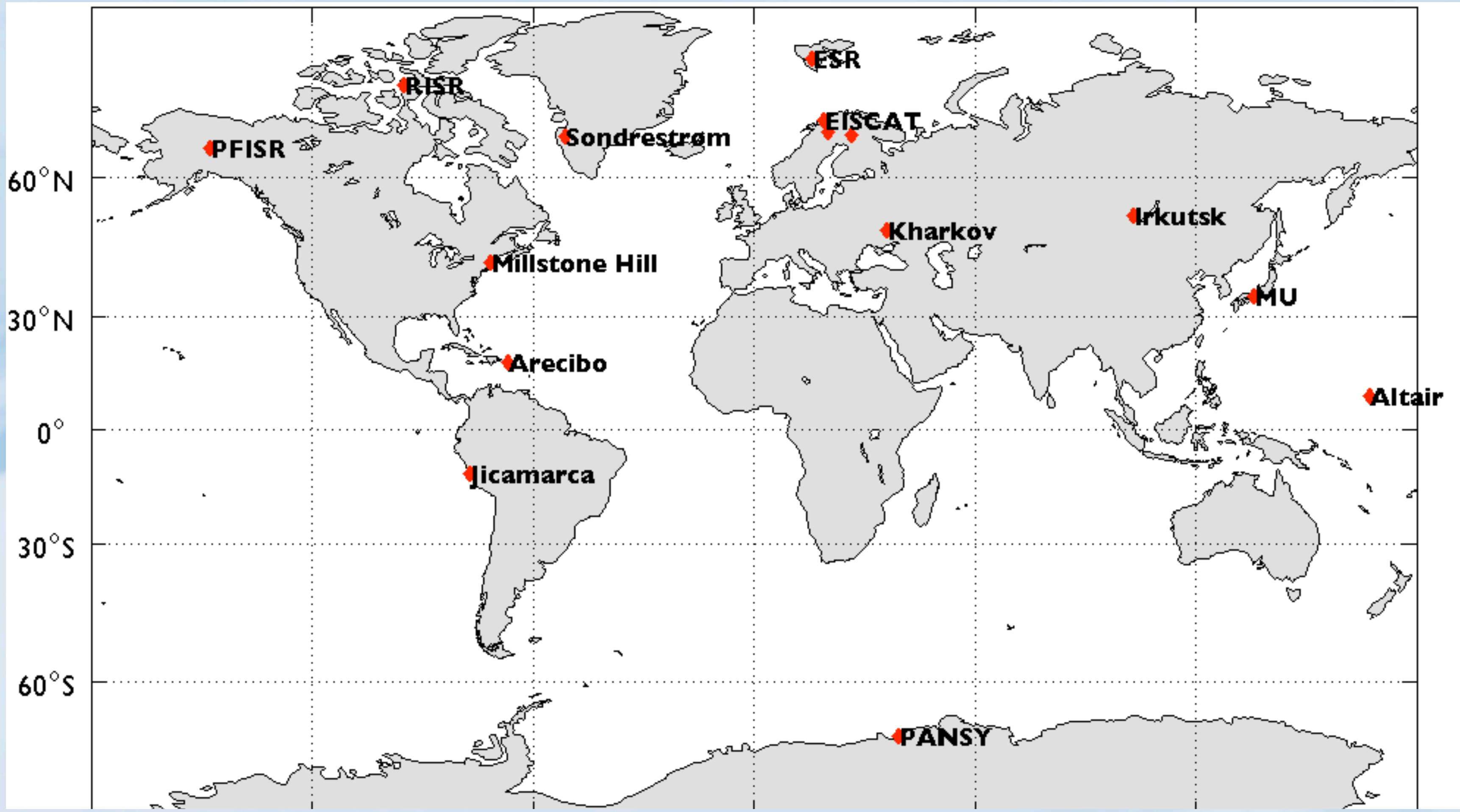
Coronal Mass Ejections - CME

At high latitudes electron (and proton) with solar wind origin creates additional ionization

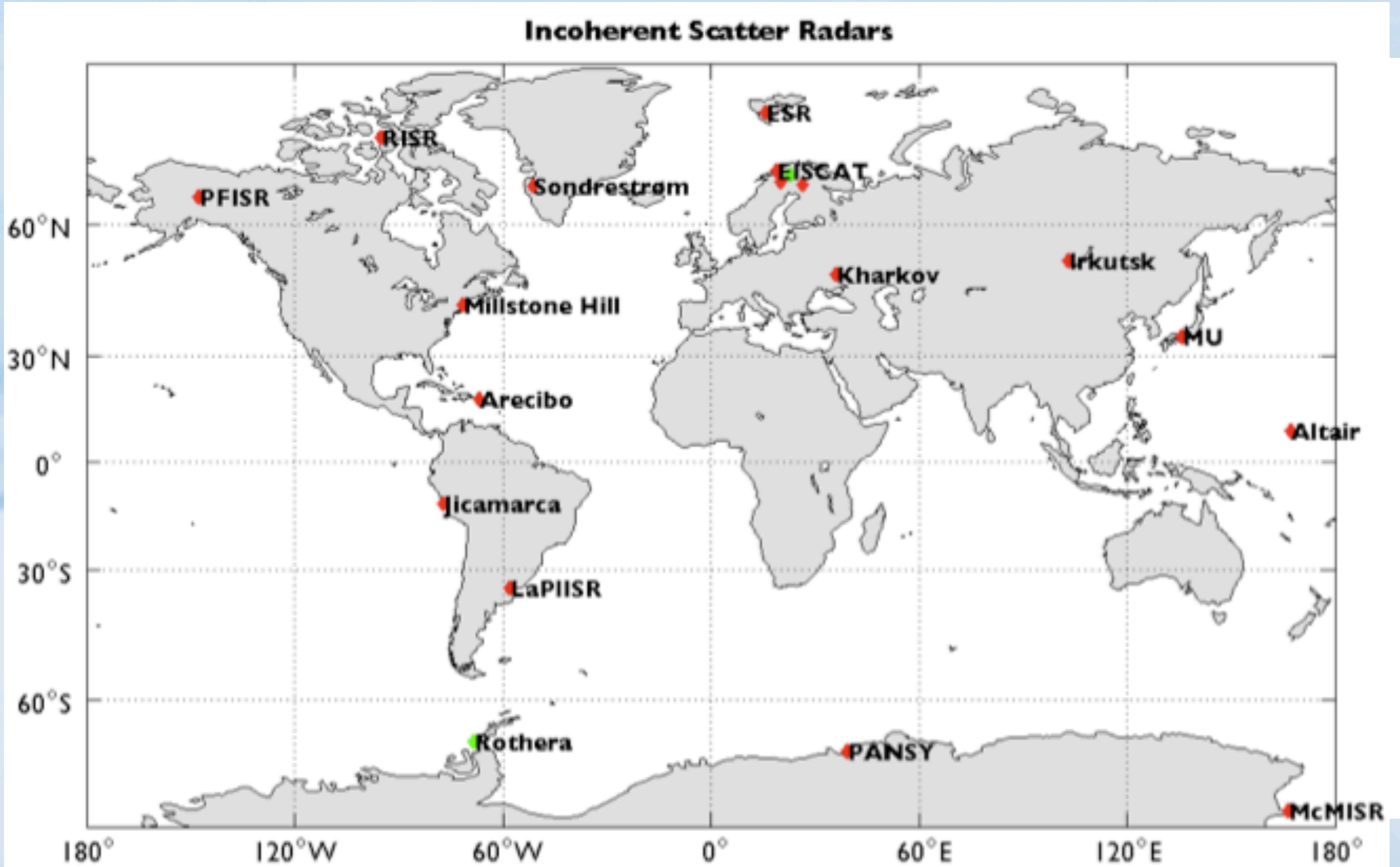


Now we have an ionosphere - let’s add the Incoherent Scatter Radar (ISR) to probe it!

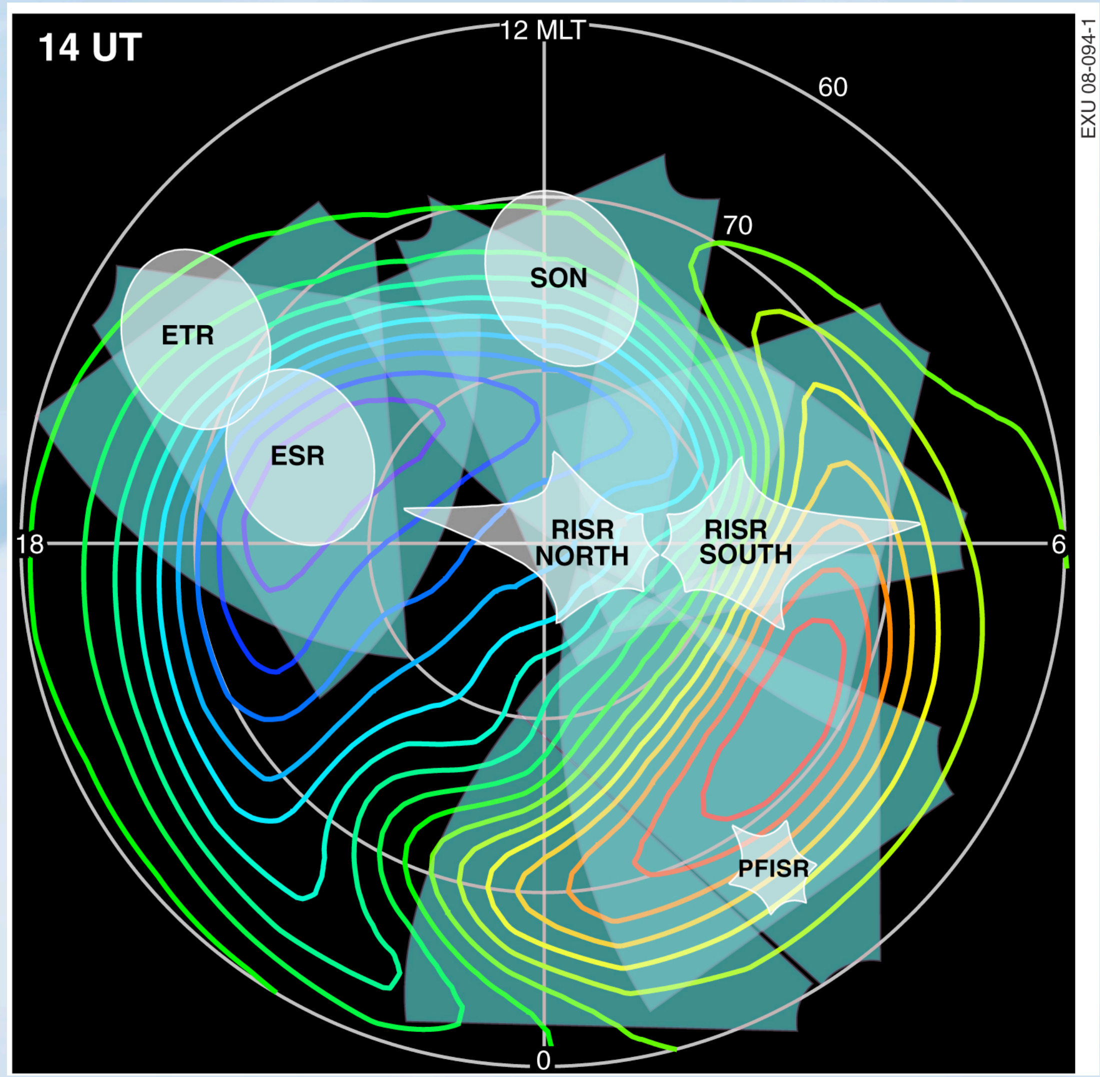
Incoherent Scatter Radars of the World



Incoherent Scatter Radars of the World



Map of the north…

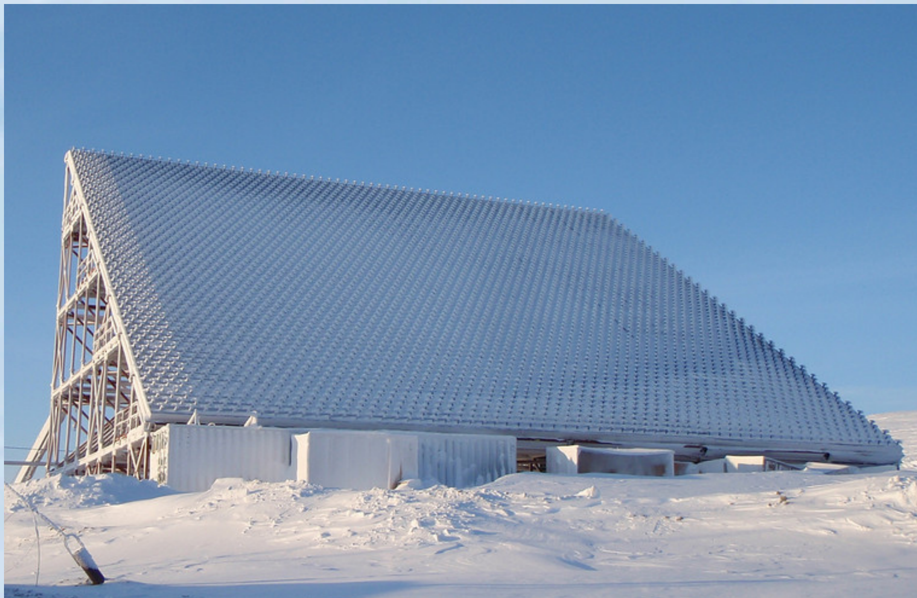


High latitude Incoherent Scatter Radars….

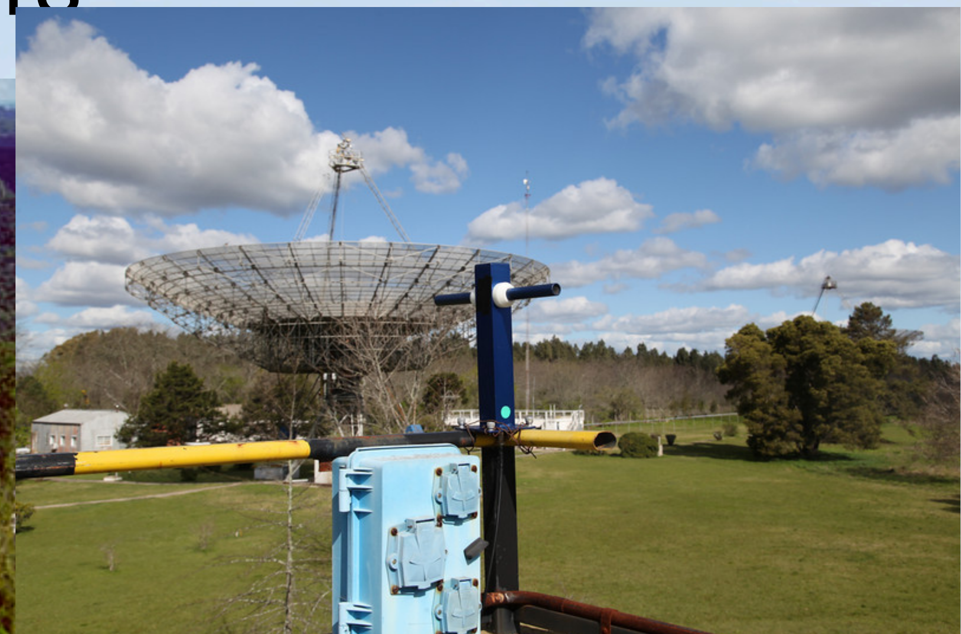
PFISR (Poker Flat Incoherent Sc

(Resolute Bay Incoherent Sc

AMISRs currently at



Mid-Latitude Incoherent Scatter Radars

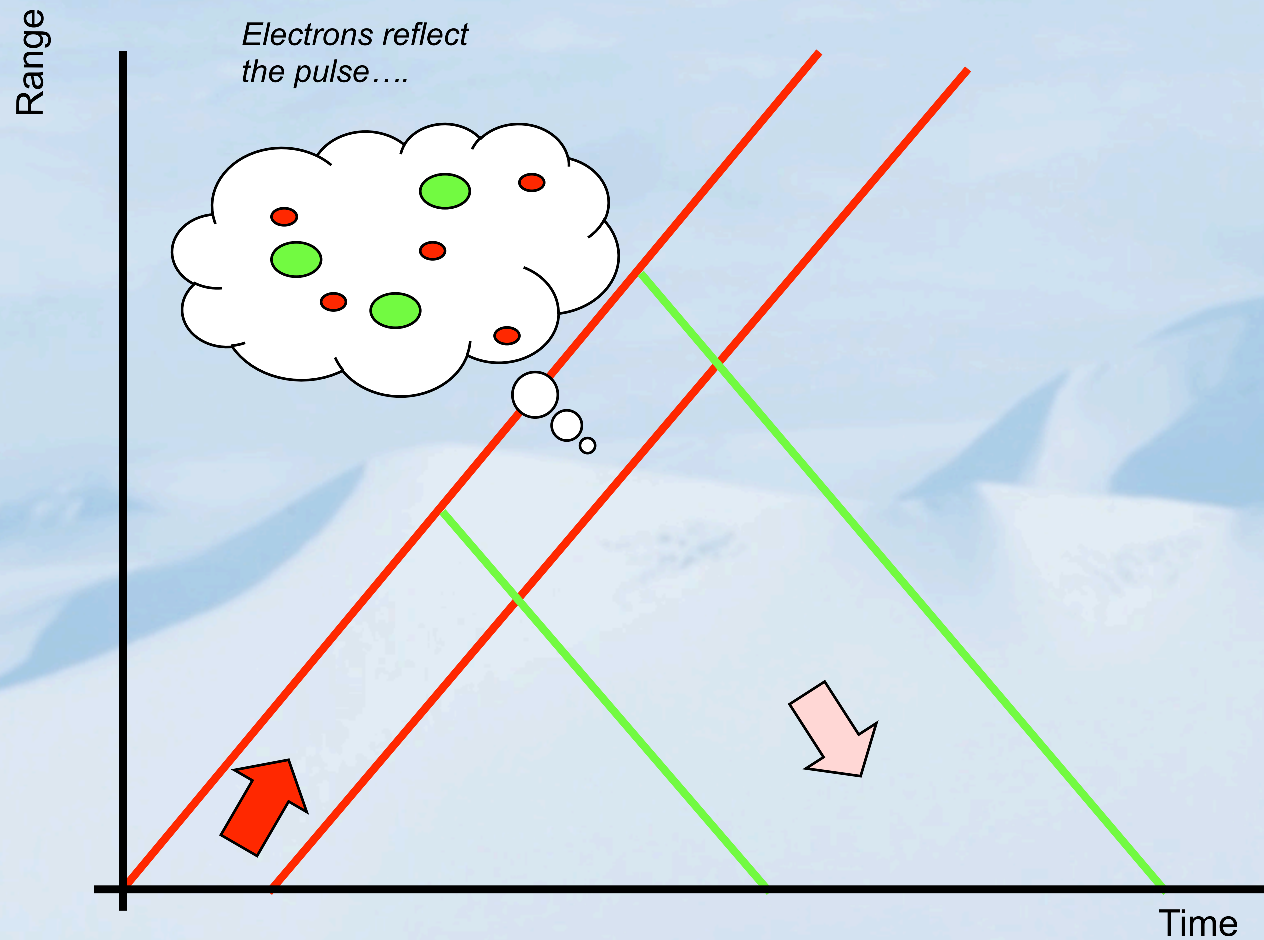


Low-Latitude Incoherent Scatter Radars

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?

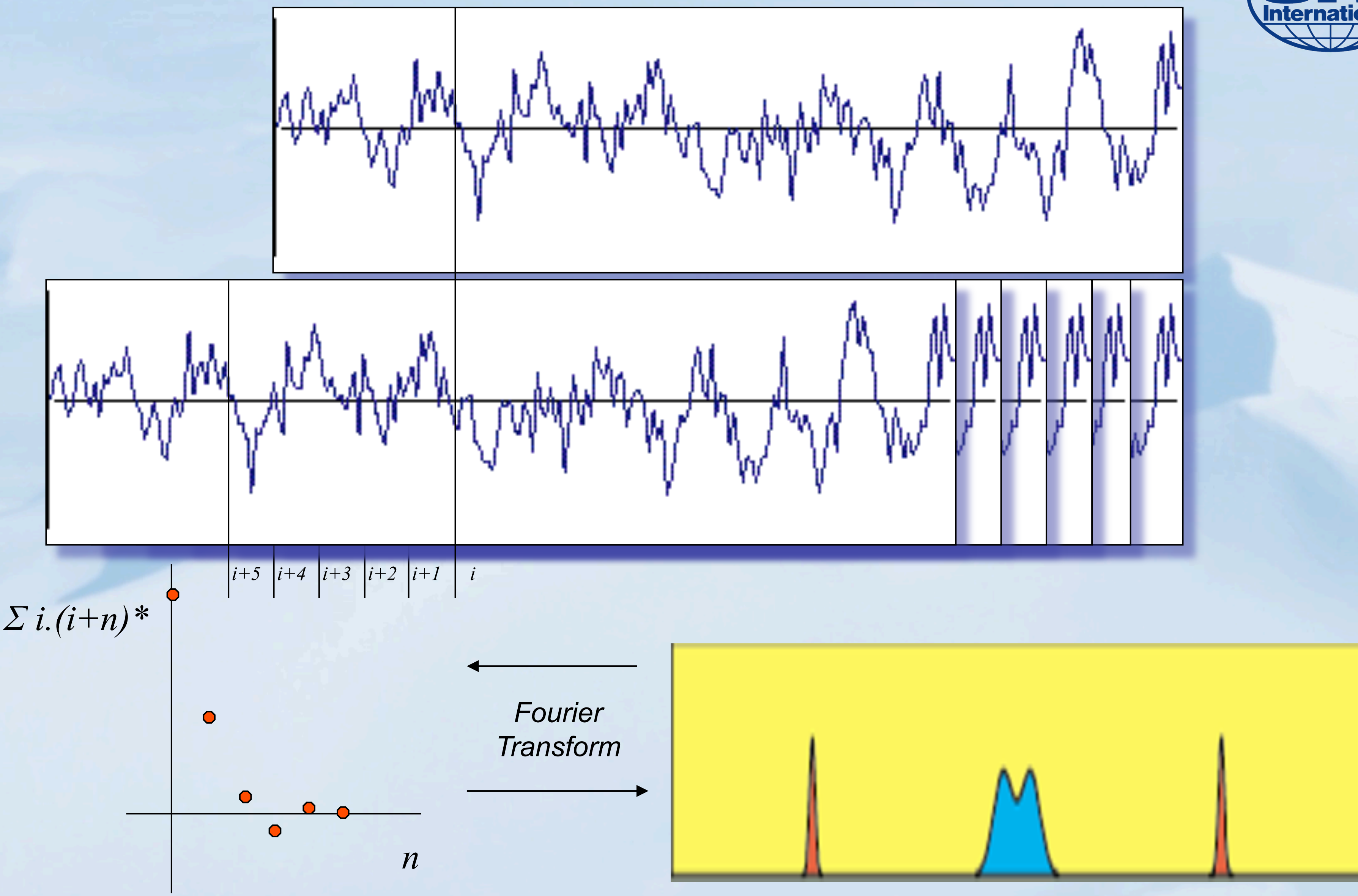
How ISRs work...

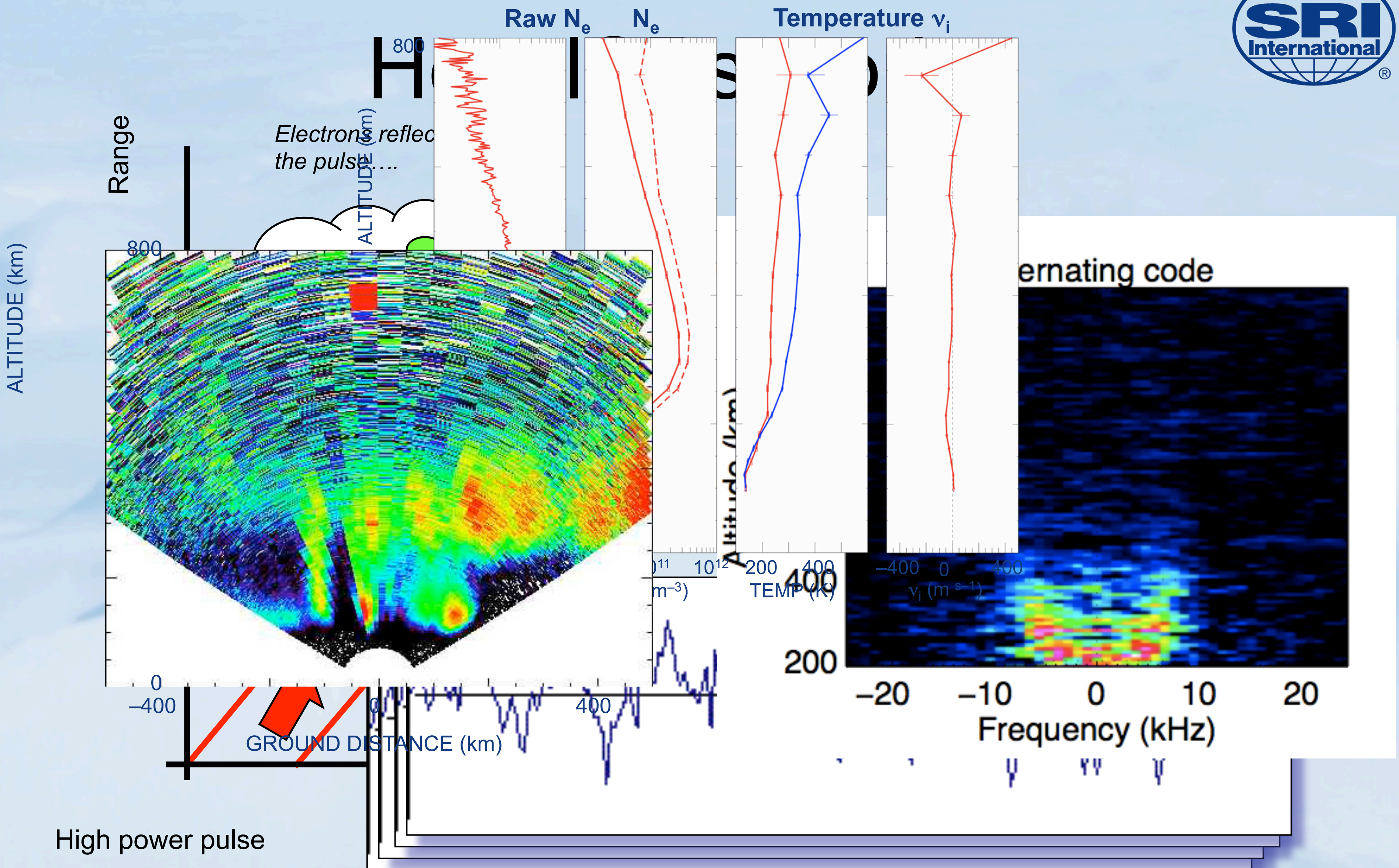


High power pulse

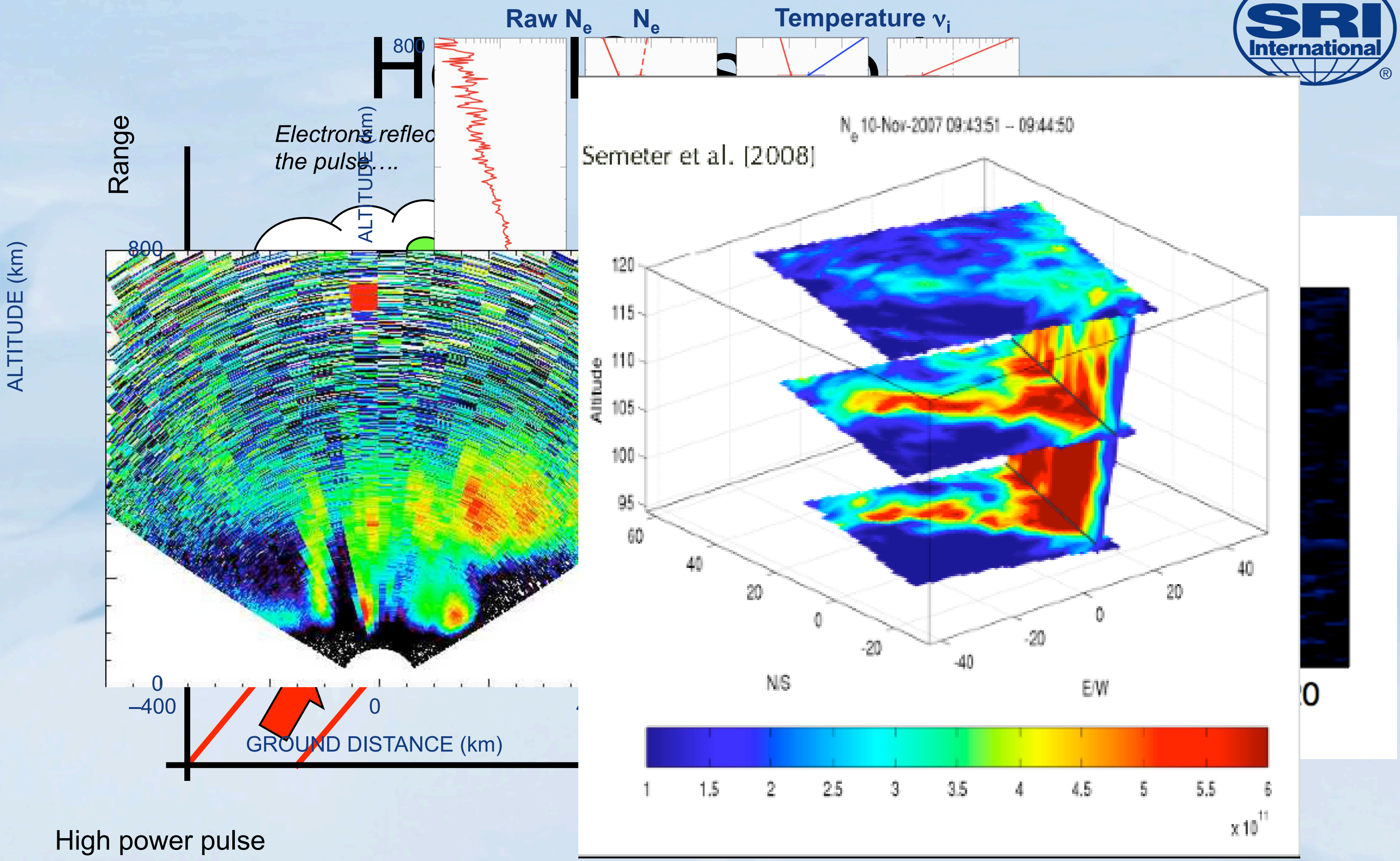
Very sensitive receiver

Only ~0.0000000000000000001% of the transmitted power is returned!


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

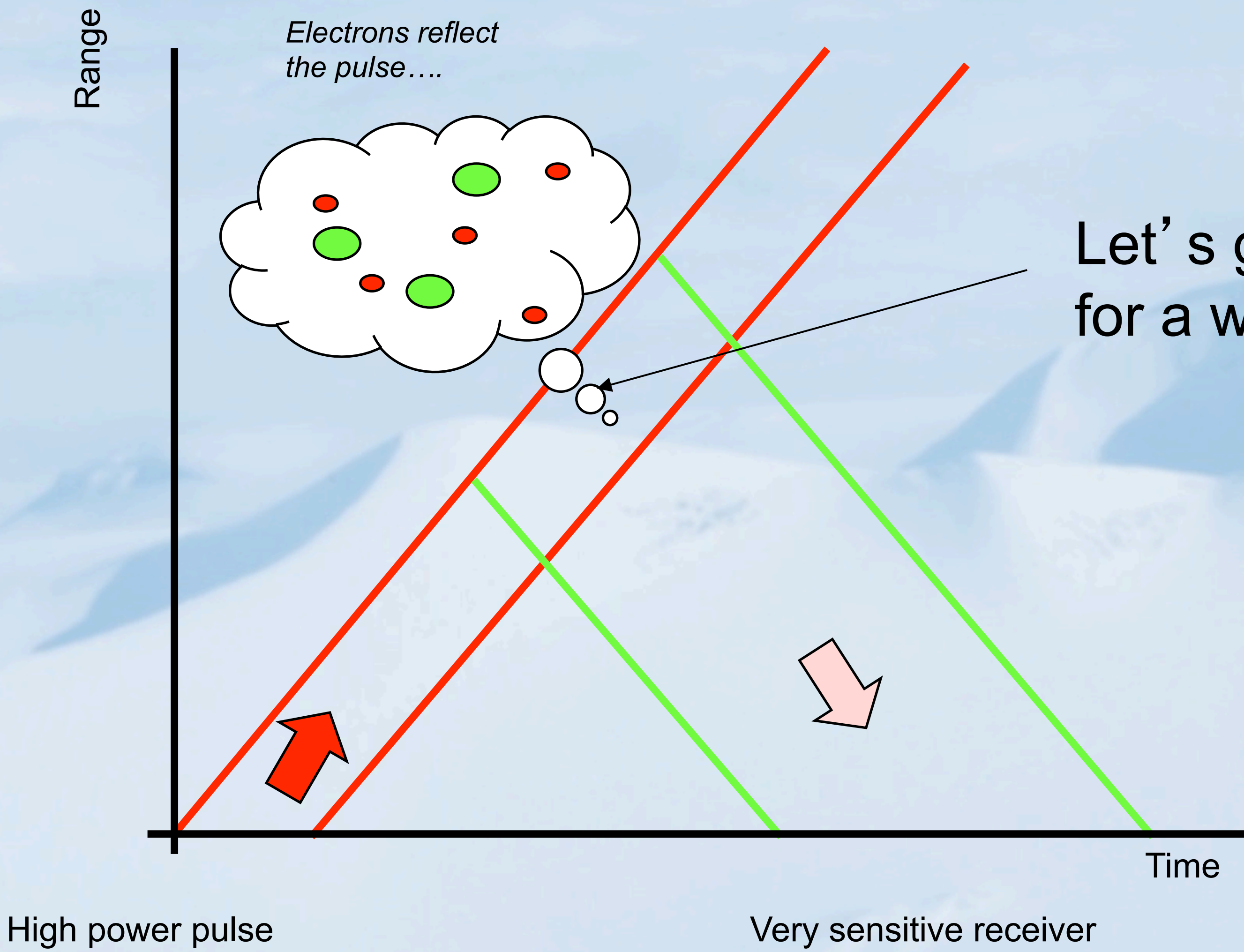


Only ~0.0000000000000000001% of the transmitted power is returned!

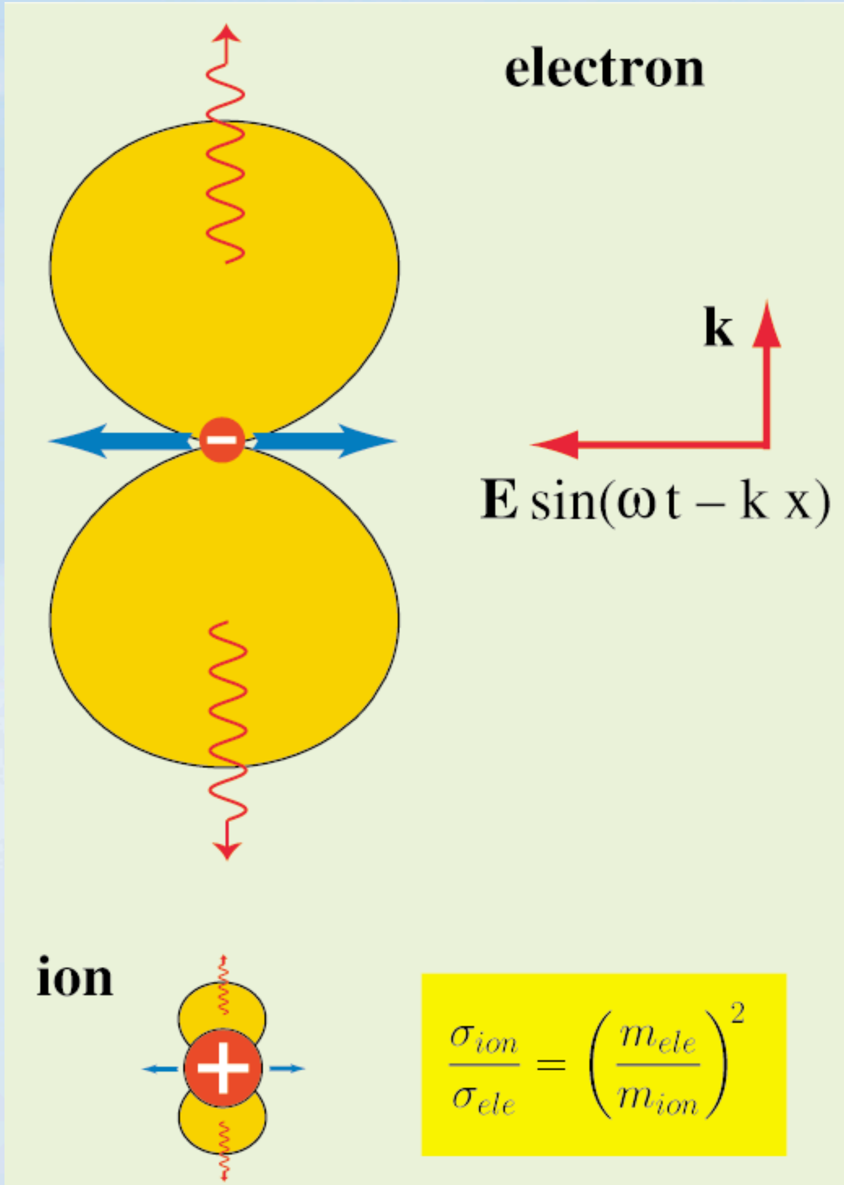


Only ~0.0000000000000000001% of the transmitted power is returned!

How ISRs work...

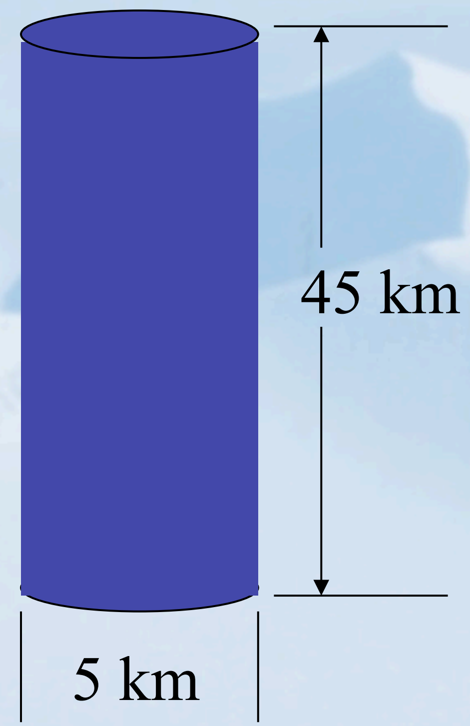


Let’s go back here for a while…


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

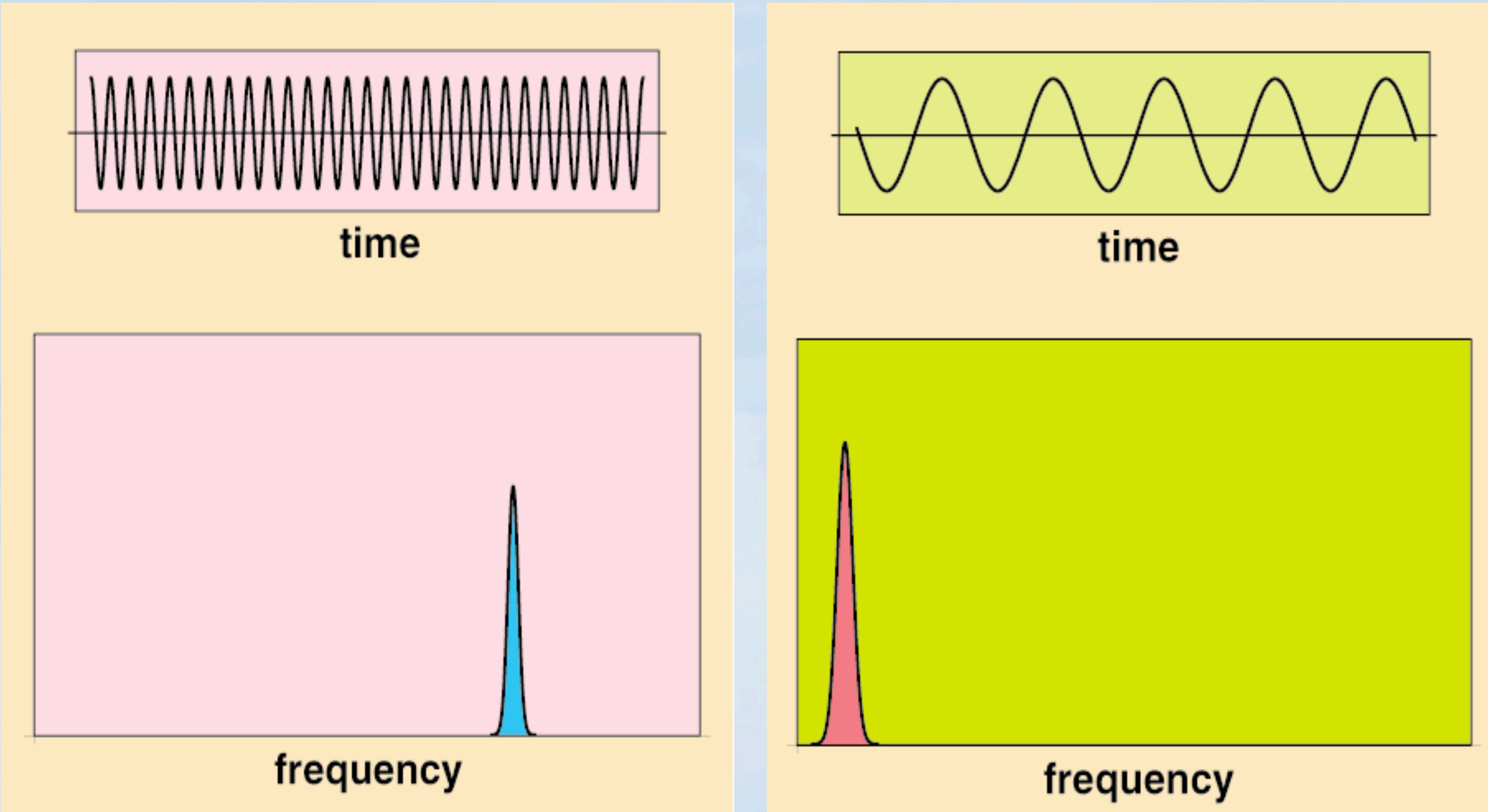
Total Cross-Section Estimate

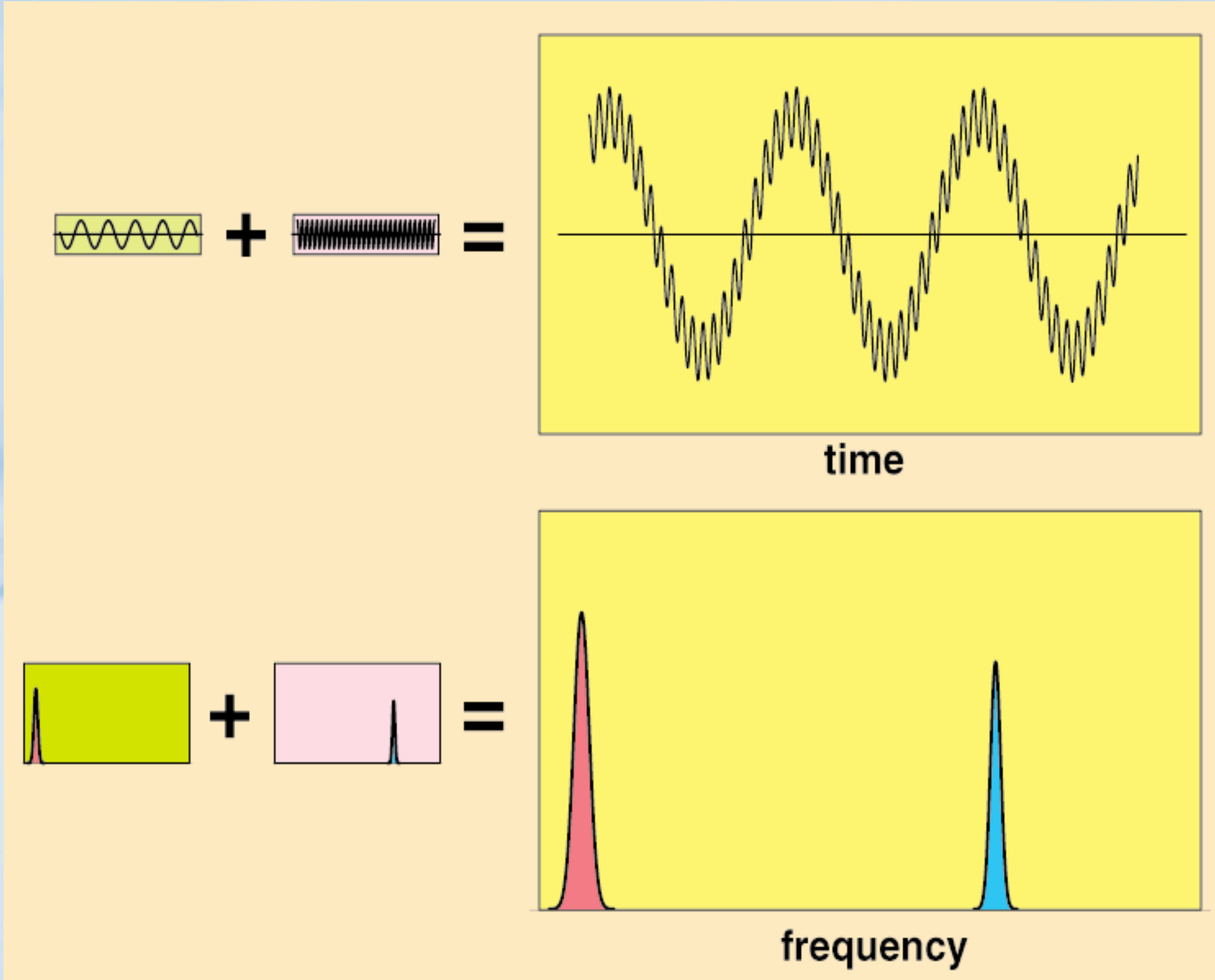
Consider an antenna with a 1-degree beam measuring the ionospheric plasma at 300 km range and using a 300 microsecond pulse.
If the electron density is 10^{12} m^{-3}, the total number of electrons scattering into a given measurement is ~$8.8x10^{23}$. This yields a total cross-section of 88 mm^2 – we need a big radar!



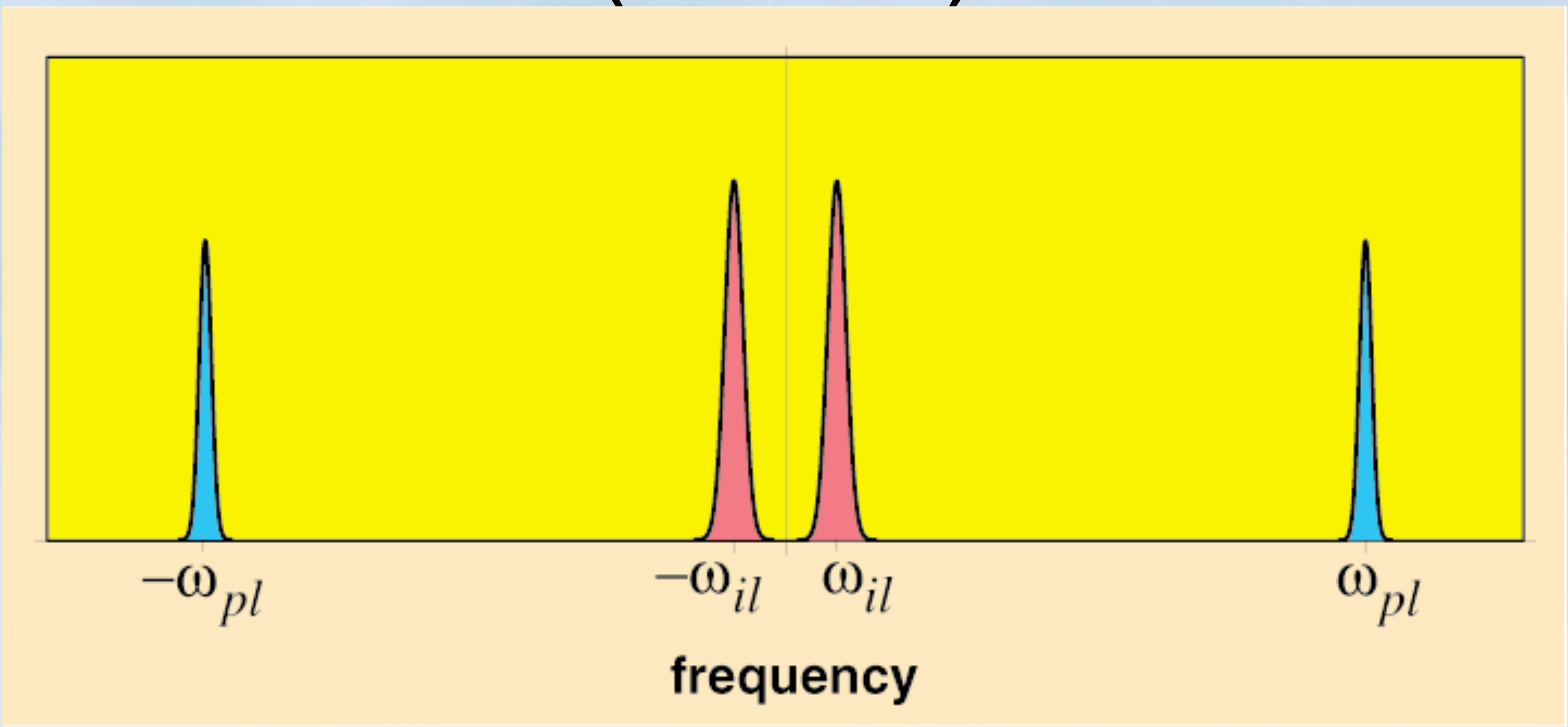
Incoheret scattering - the short story

Incoherent scattering - the short story

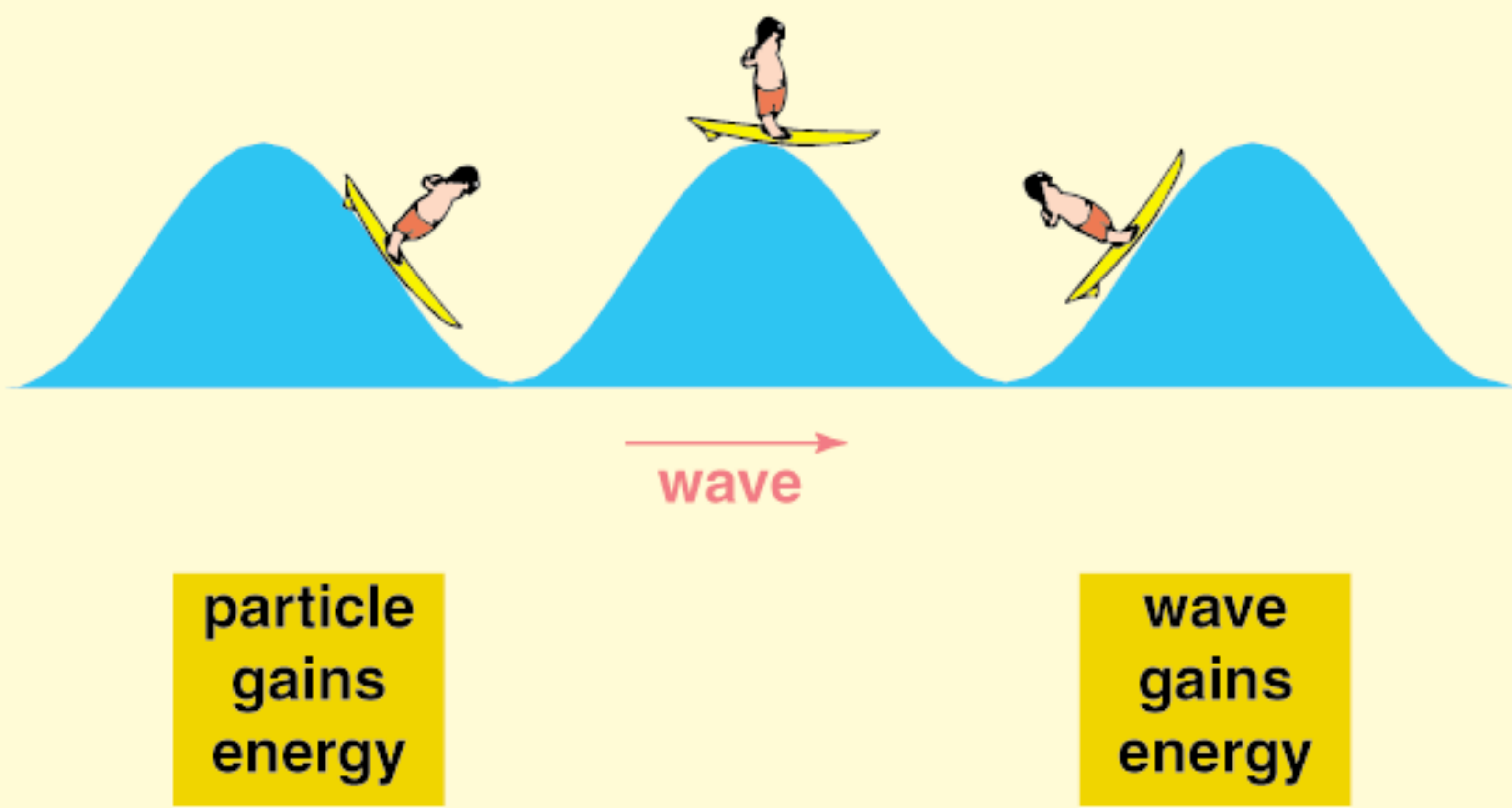

time
frequency
time
frequency


+
=
time
+
=
frequency

Plasma Wave Approach (cont’d)



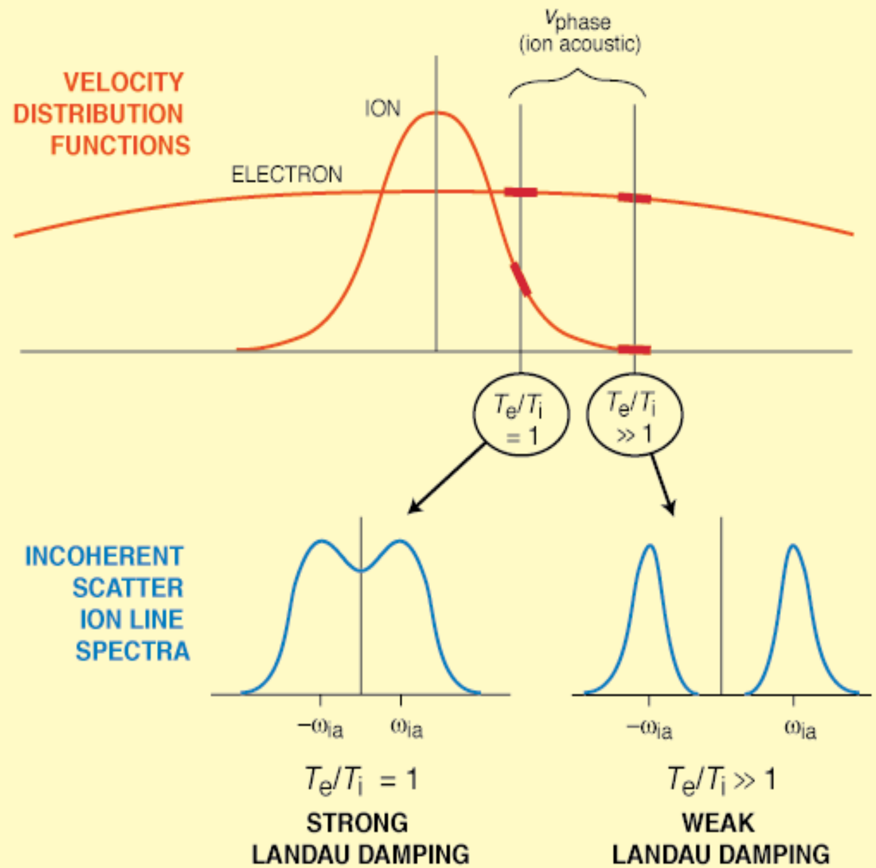
Landau wave-particle interactions

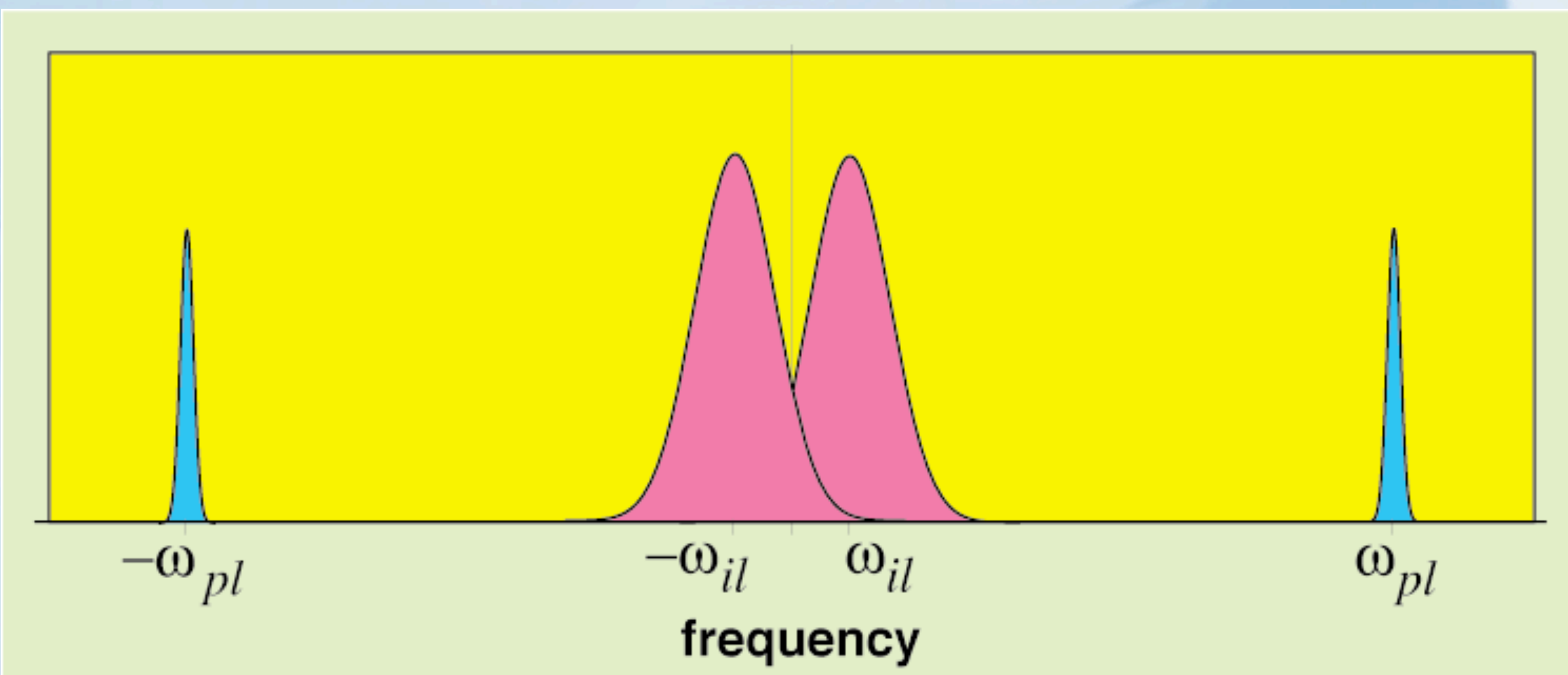


THE EFFECT OF LANDAU DAMPING ON THE INCOHERENT SCATTER ION LINE SPECTRUM

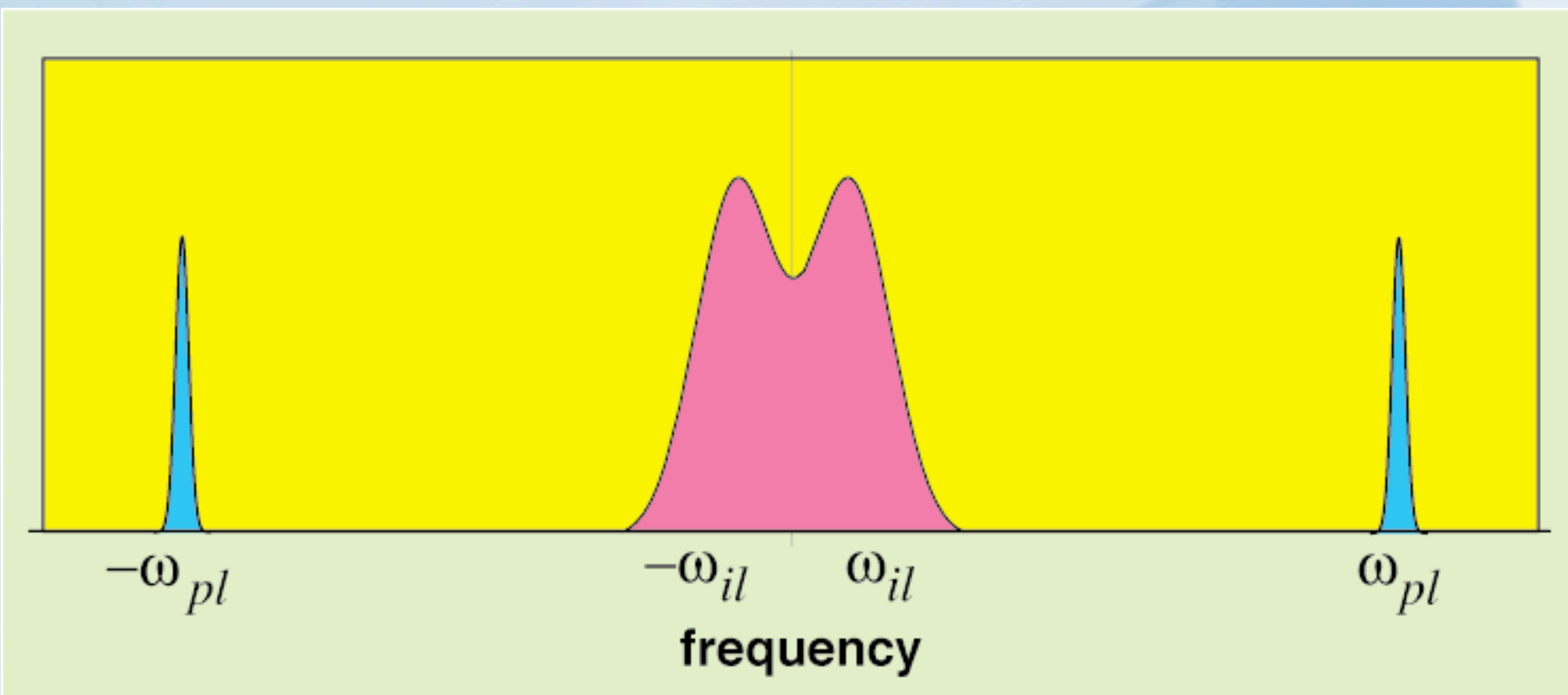
ION-ACOUSTIC DISPERSION EQUATION

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





−ωpl
−ωil
ωil
ωpl
frequency



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

Incoherent Scattering Spectrum

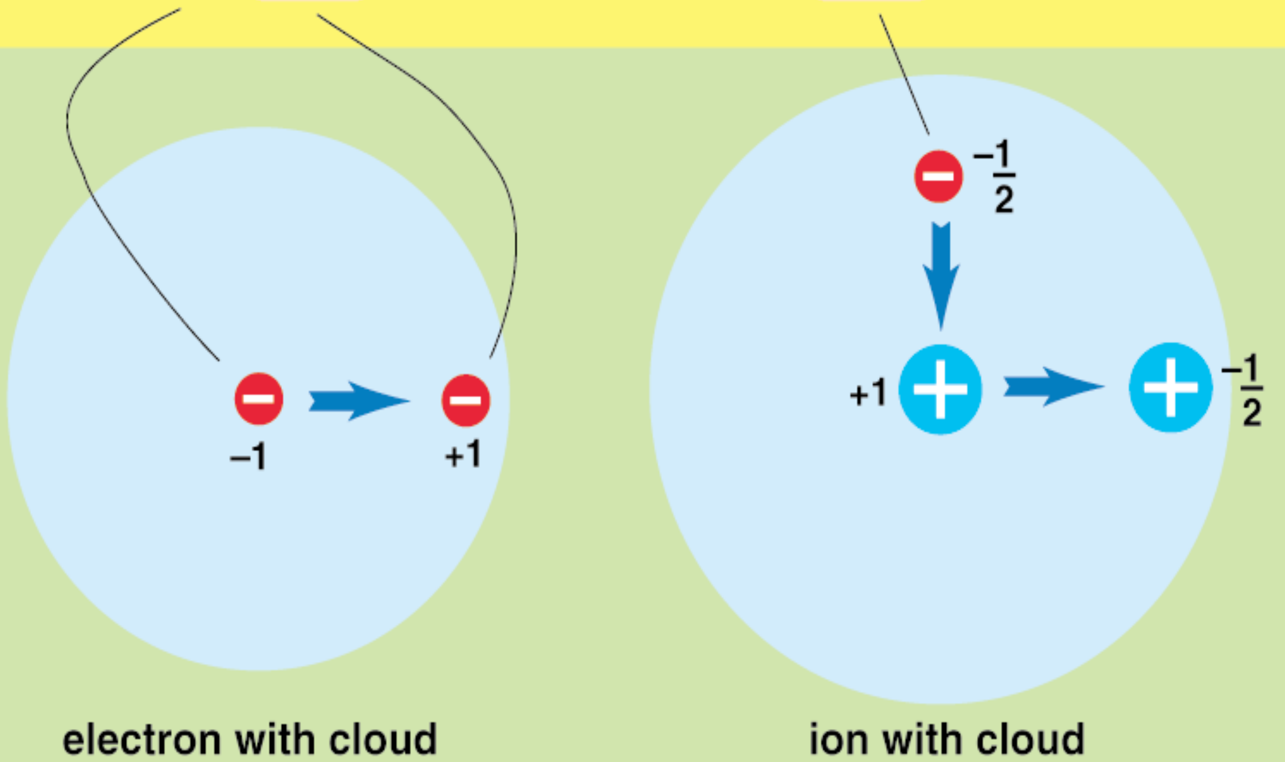
$$S_e(\mathbf{k},\omega) = N_e \left|1 - \frac{\chi_e(\mathbf{k},\omega)}{\epsilon(\mathbf{k},\omega)}\right|^2 \int d\mathbf{v}\, f_e(\mathbf{v})\,\delta(\omega - \mathbf{k}\cdot\mathbf{v}) + N_i \left|\frac{\chi_e(\mathbf{k},\omega)}{\epsilon(\mathbf{k},\omega)}\right|^2 \int d\mathbf{v}\, f_i(\mathbf{v})\,\delta(\omega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

Plasma line　　　　Ion line

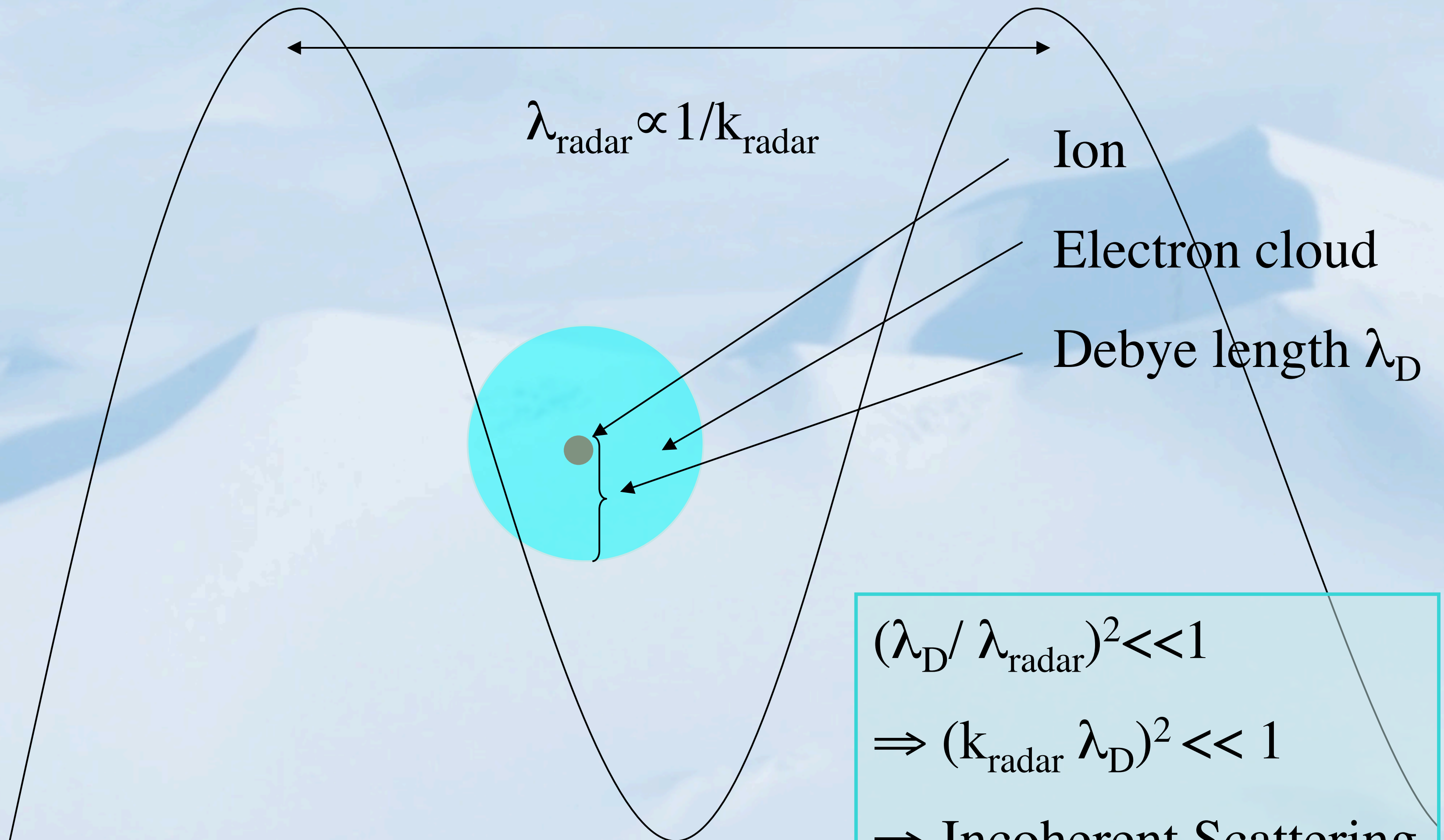
electric susceptibility	$\chi_{e,i}(\mathbf{k},\omega)$
dielectric constant function	$\epsilon(\mathbf{k},\omega)$
velocity distribution function	$f_{e,i}(\mathbf{v})$

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

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



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

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

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

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

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

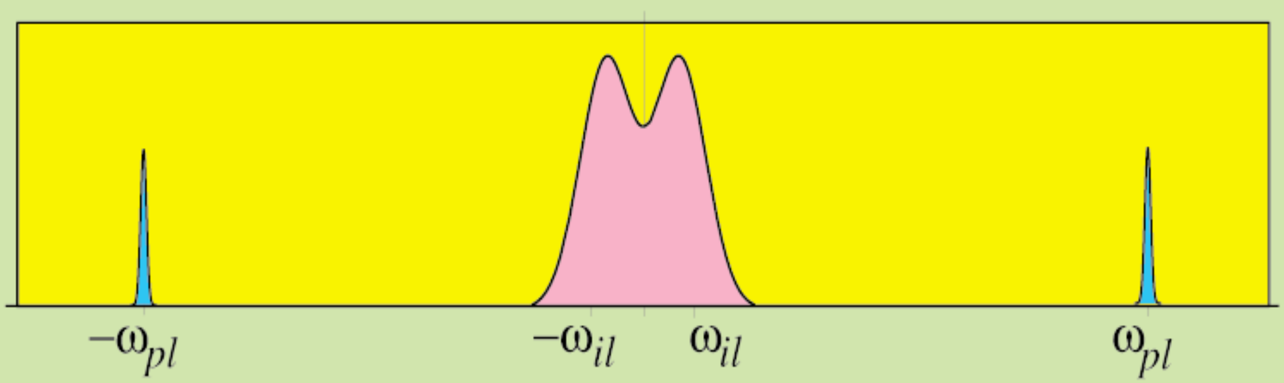
Plasma Line $S_{PL}(\mathbf{k},\omega)$ **Ion Line** $S_{IL}(\mathbf{k},\omega)$

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

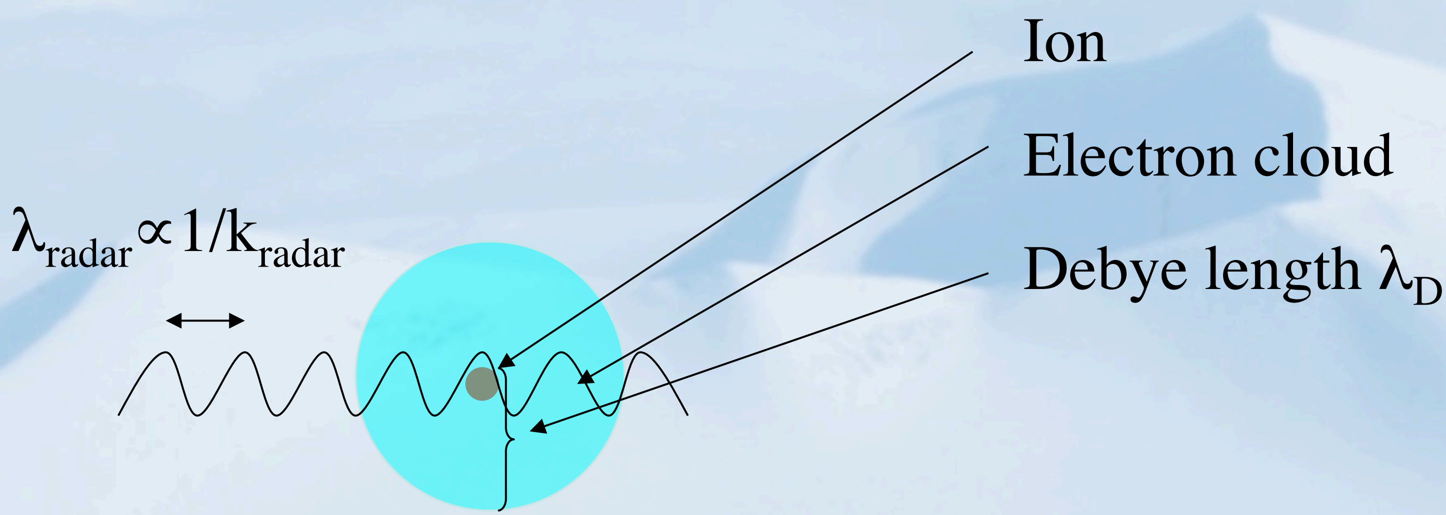
$$\epsilon(\mathbf{k},\omega) = \mathbf{0}$$

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

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



Debye length dependence



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

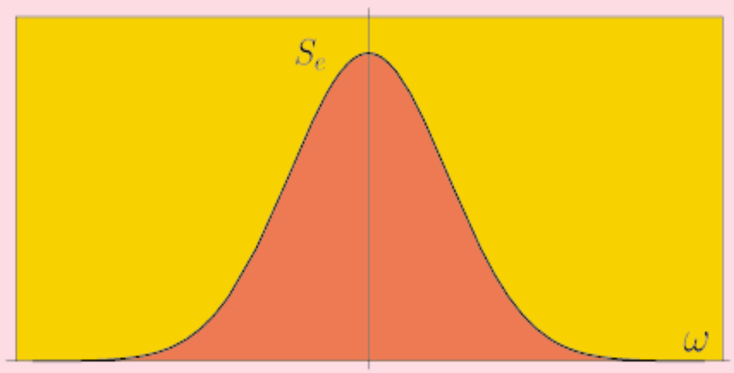
$\Rightarrow (k_{radar}\, \lambda_D)^2 > 1$

$\Rightarrow$ No collective interactions

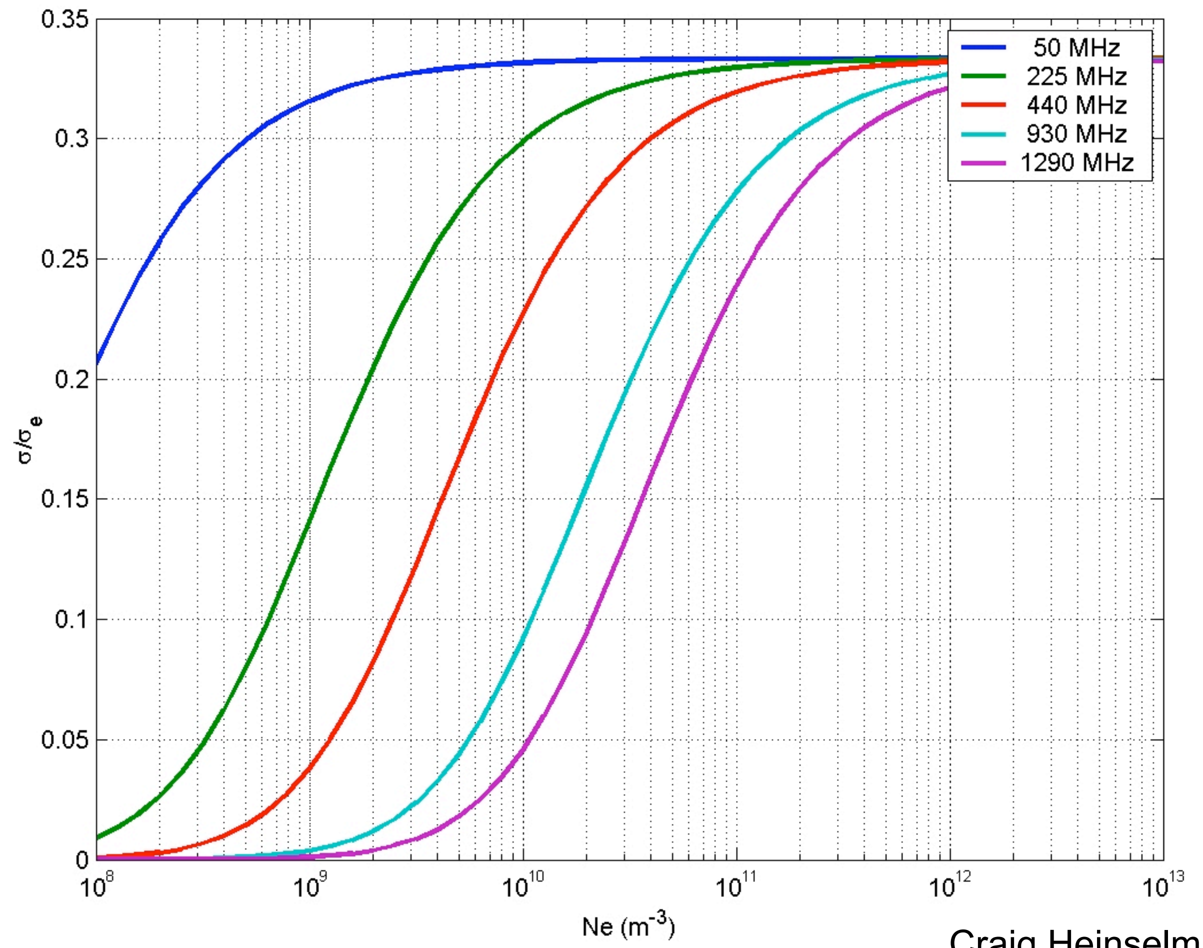
no collective interactions

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

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

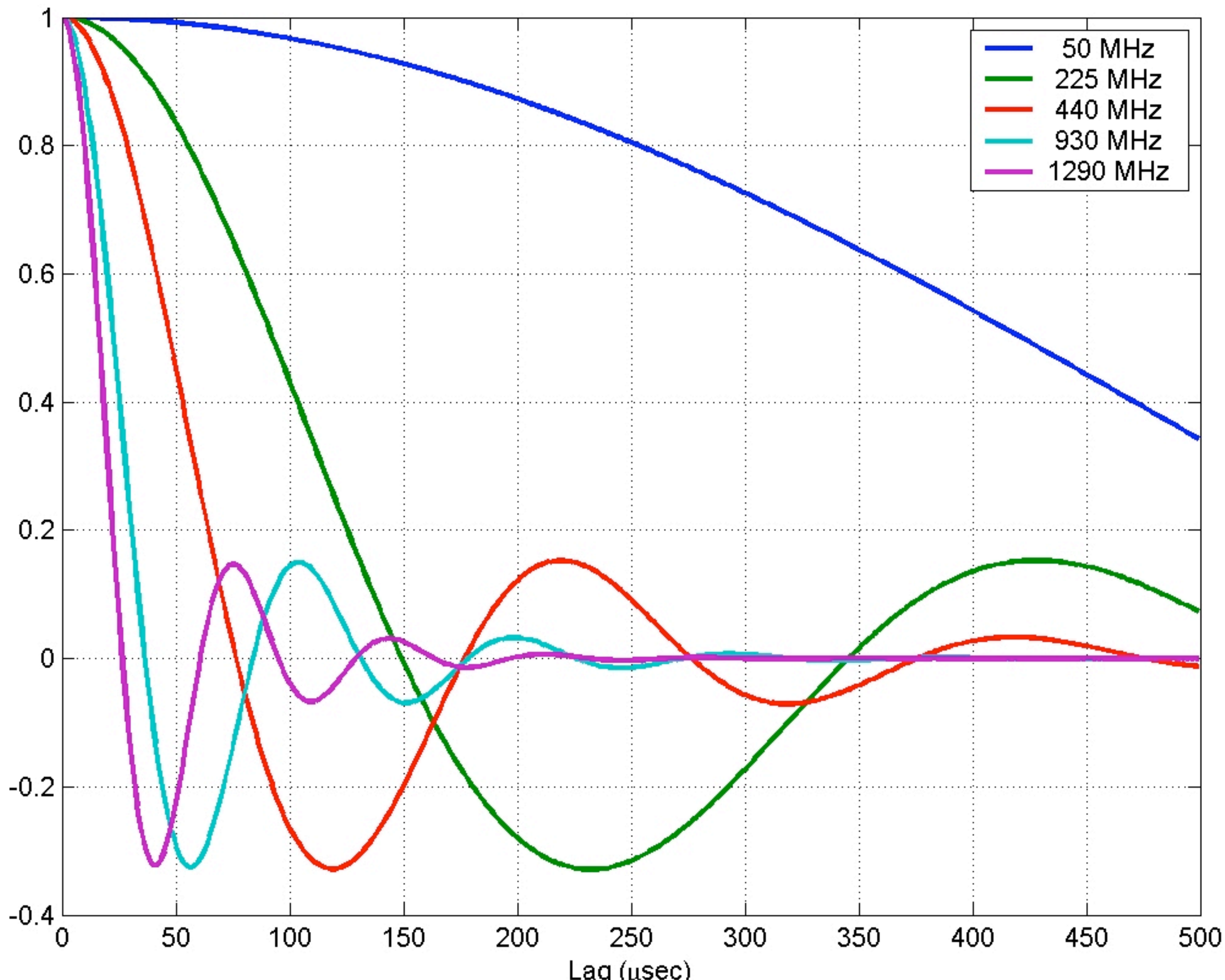


Debye Length Dependencies



Craig Heinselman

Parameters
Ti: 1000 K
Te: 2000 K



Parameters

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

Ti: 1000 K

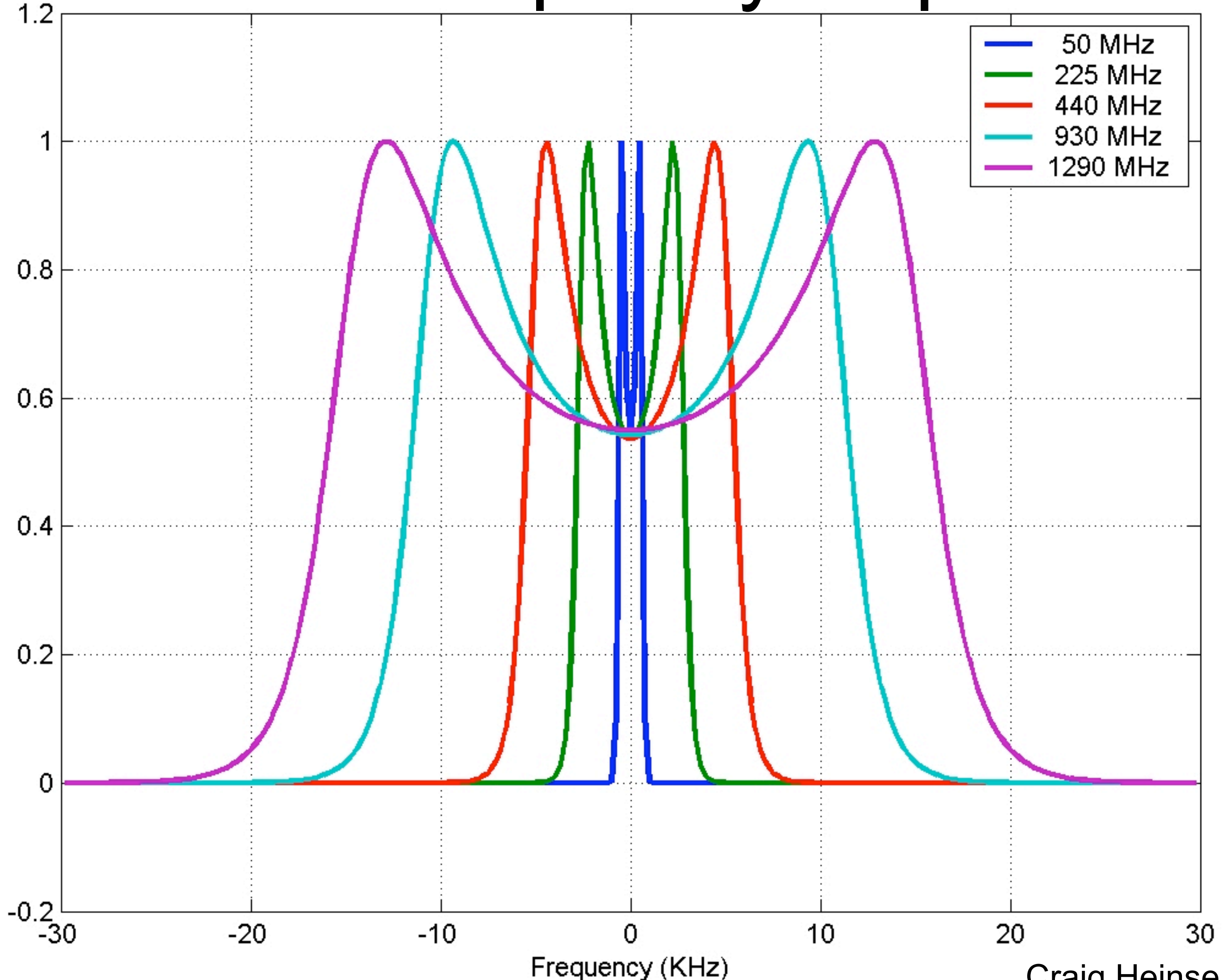
Te: 2000 K

Comp: 100% O^{+}

ν_{in}: 10^{-6} KHz

Craig Heinselman

Radar Frequency Dependencies



<u>Parameters</u>

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

Ti: 1000 K

Te: 2000 K

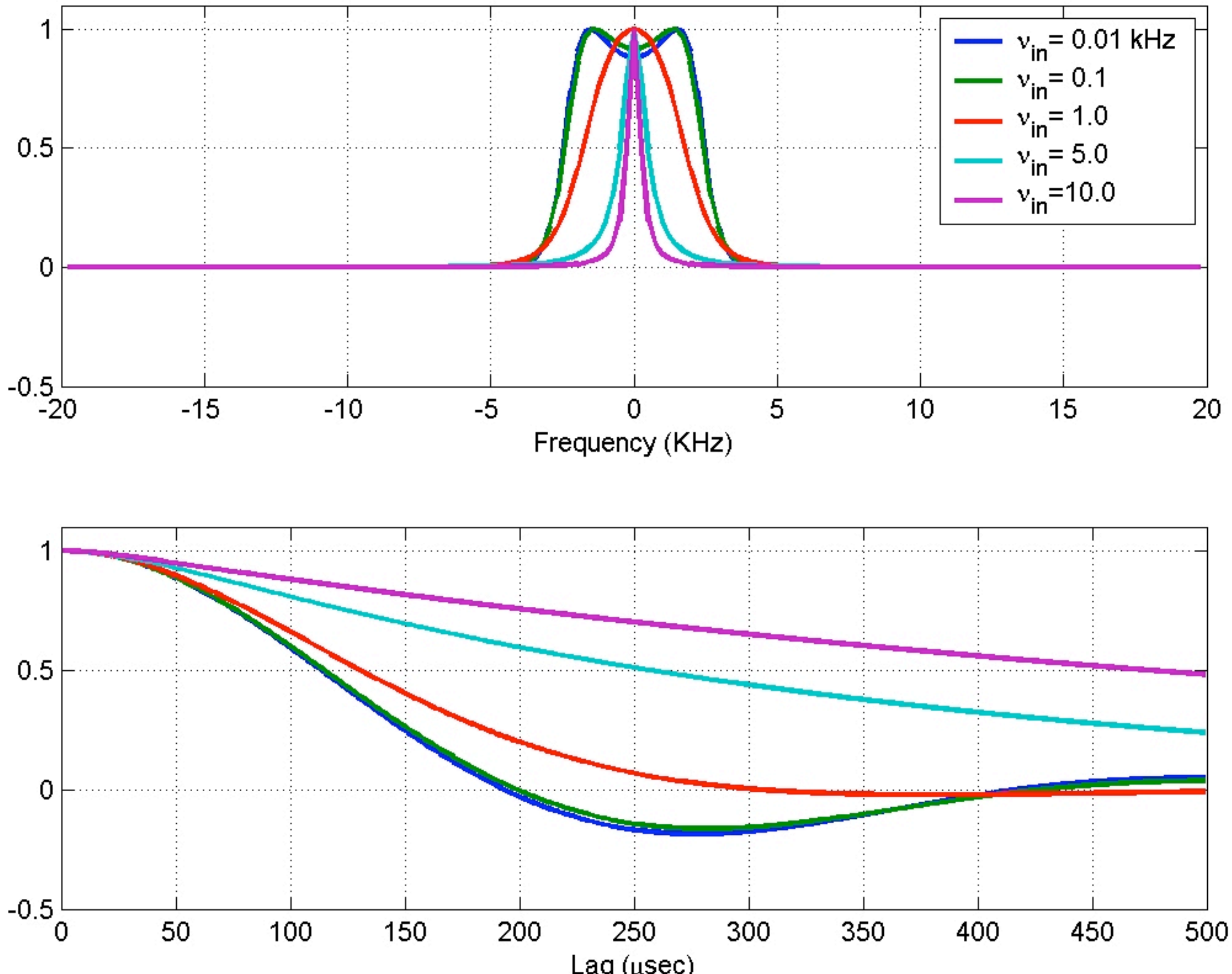
Comp: 100% O^+

ν_{in}: 10^{-6} KHz

Craig Heinselman

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

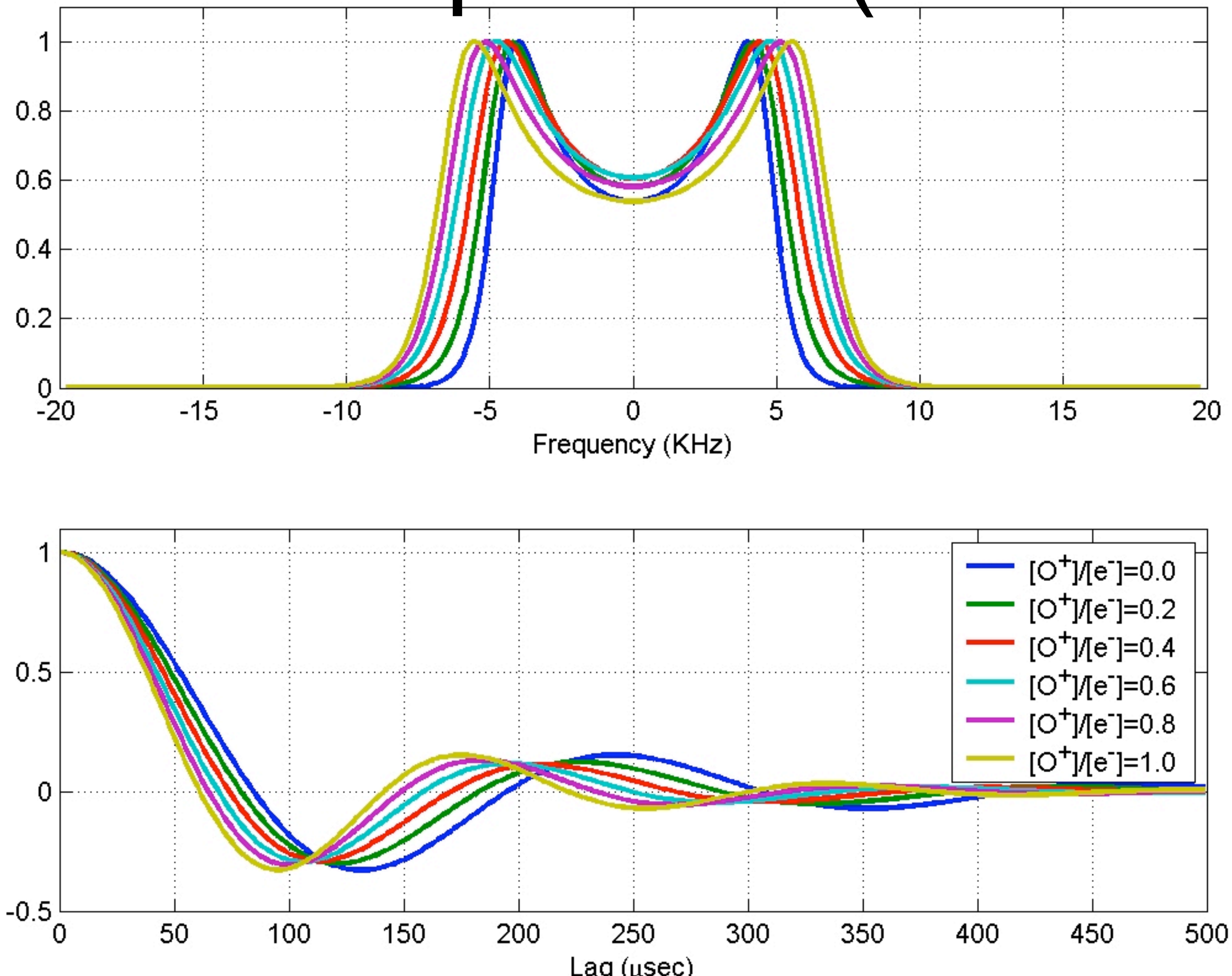
Ion-Neutral Collision Frequency



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

Craig Heinselman

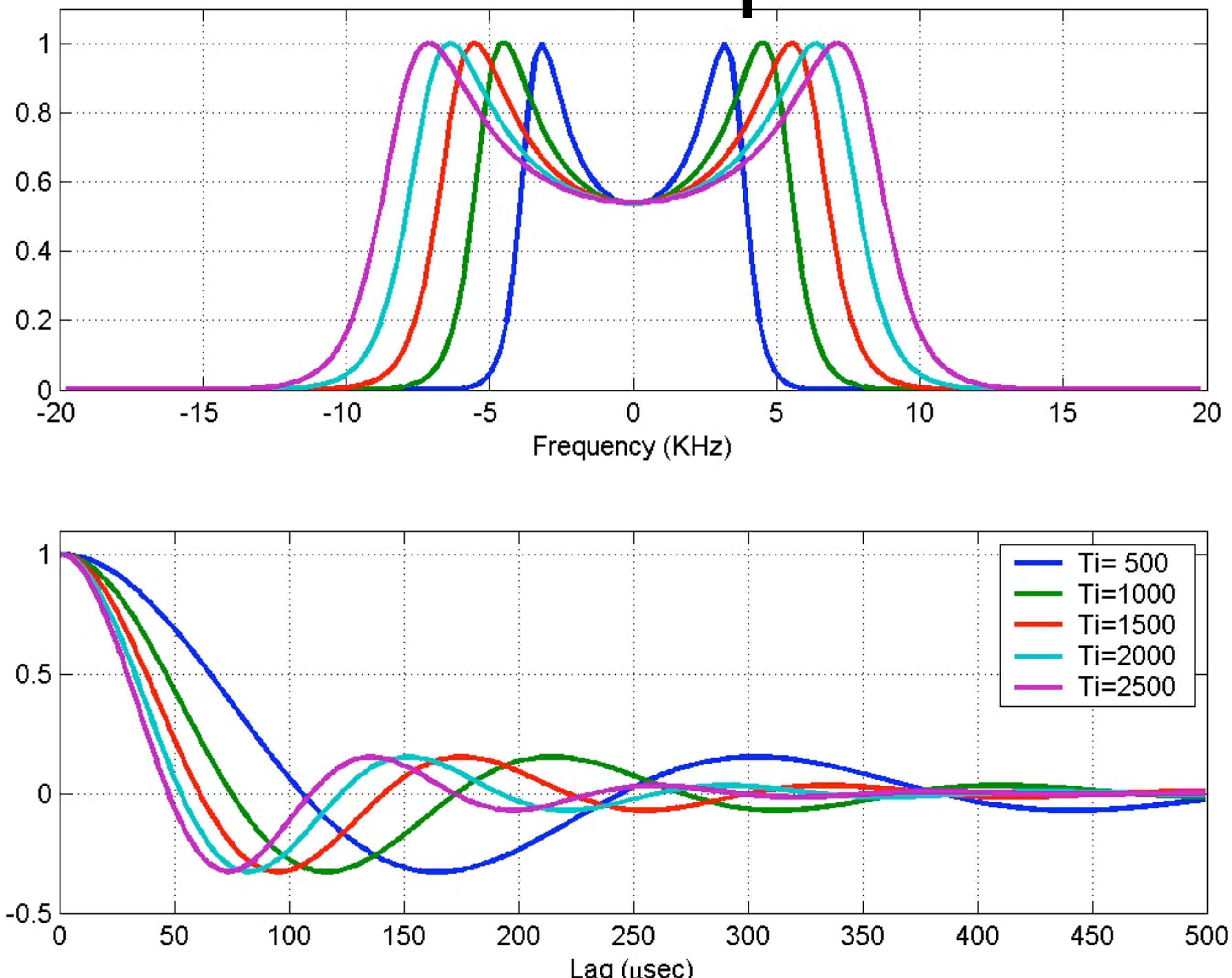
Ion Composition (O^+ vs. NO^+)



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

Craig Heinselman

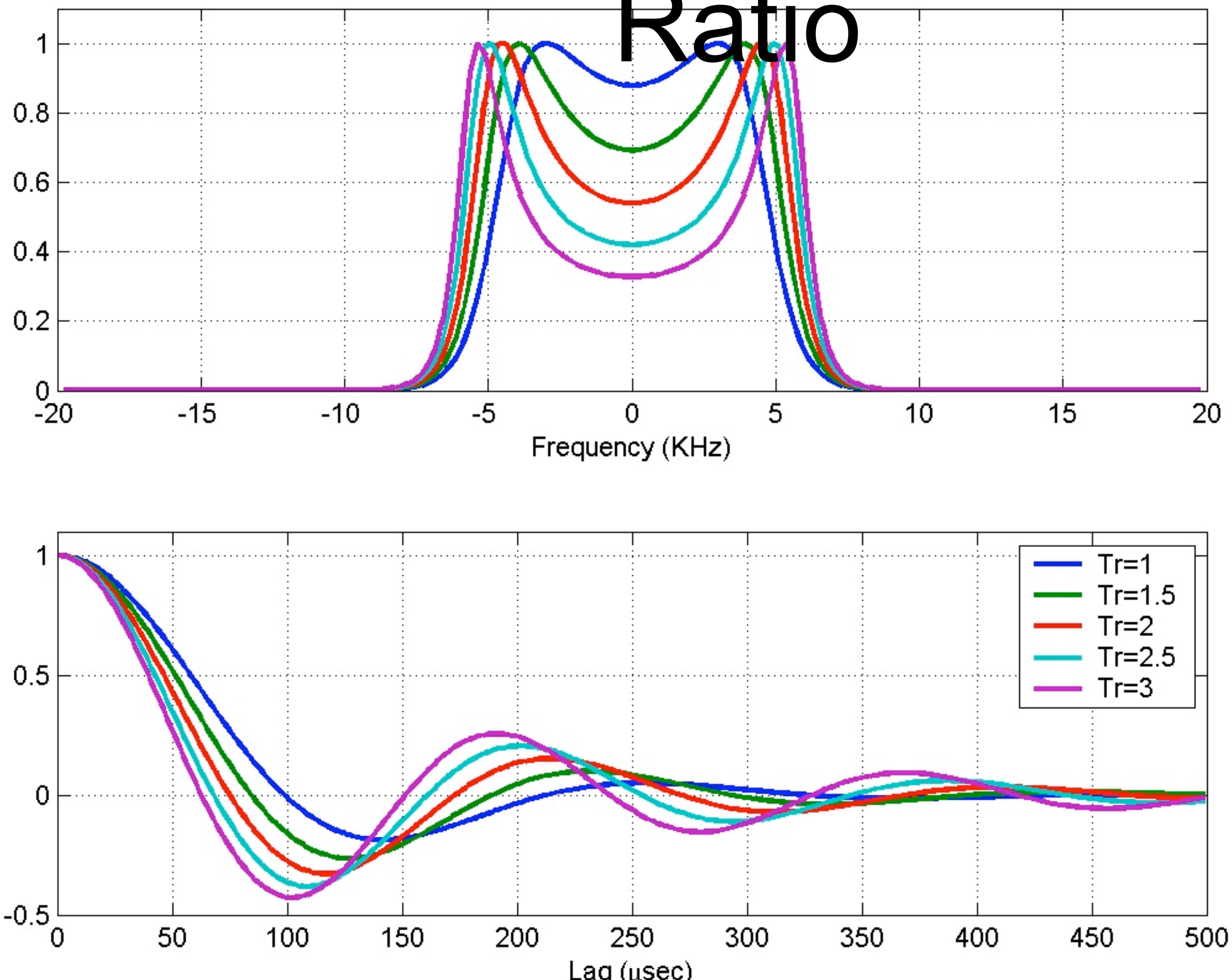
Ion Temperature



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

Craig Heinselman

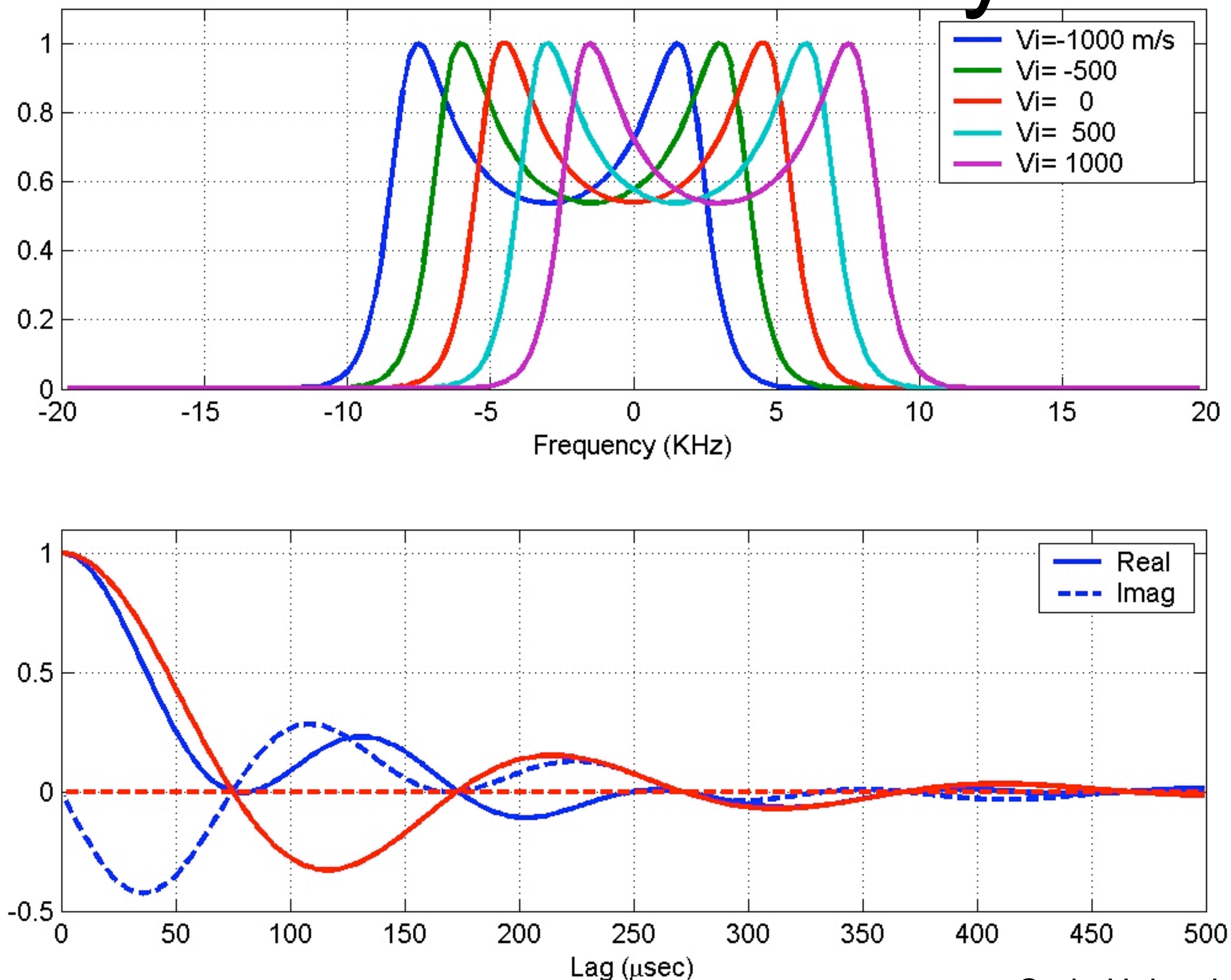
Electron/Ion Temperature Ratio



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

Craig Heinselman

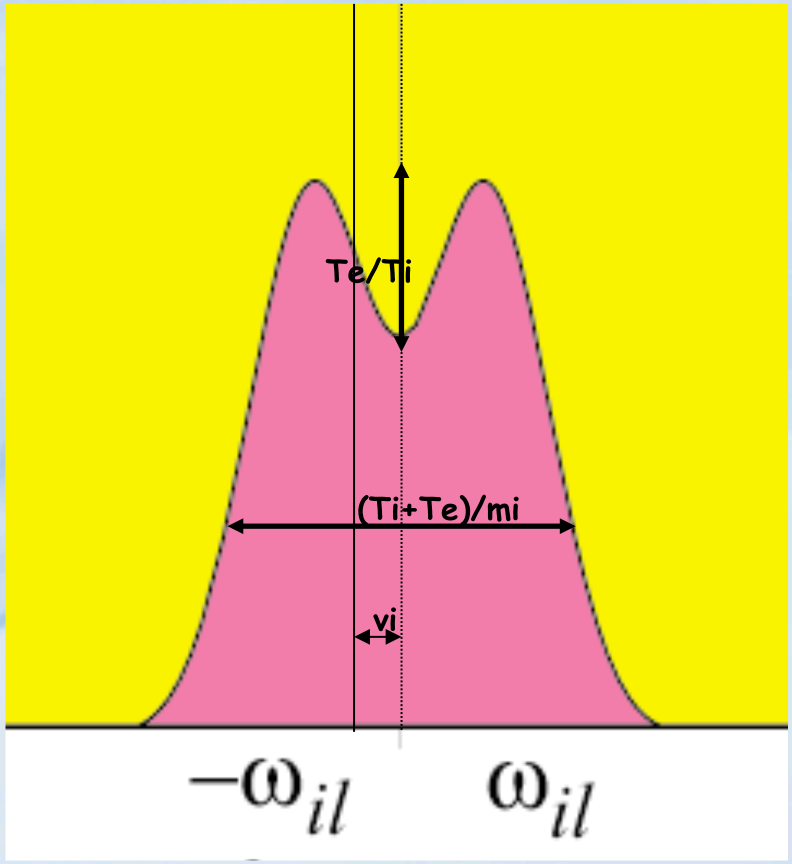
Ion Velocity



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

Craig Heinselman

…or to sum up…



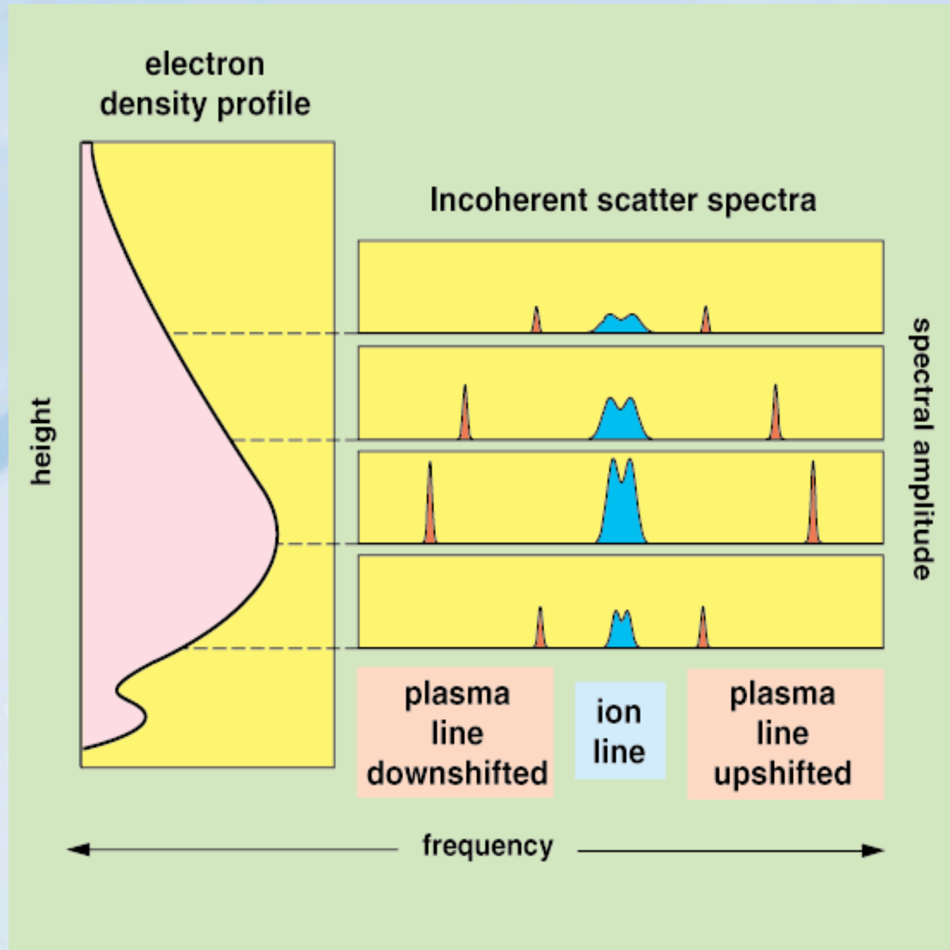
•Ion (and electron) temperature (Ti and Te) to ion mass (mi) ratio from the width of the spectra

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

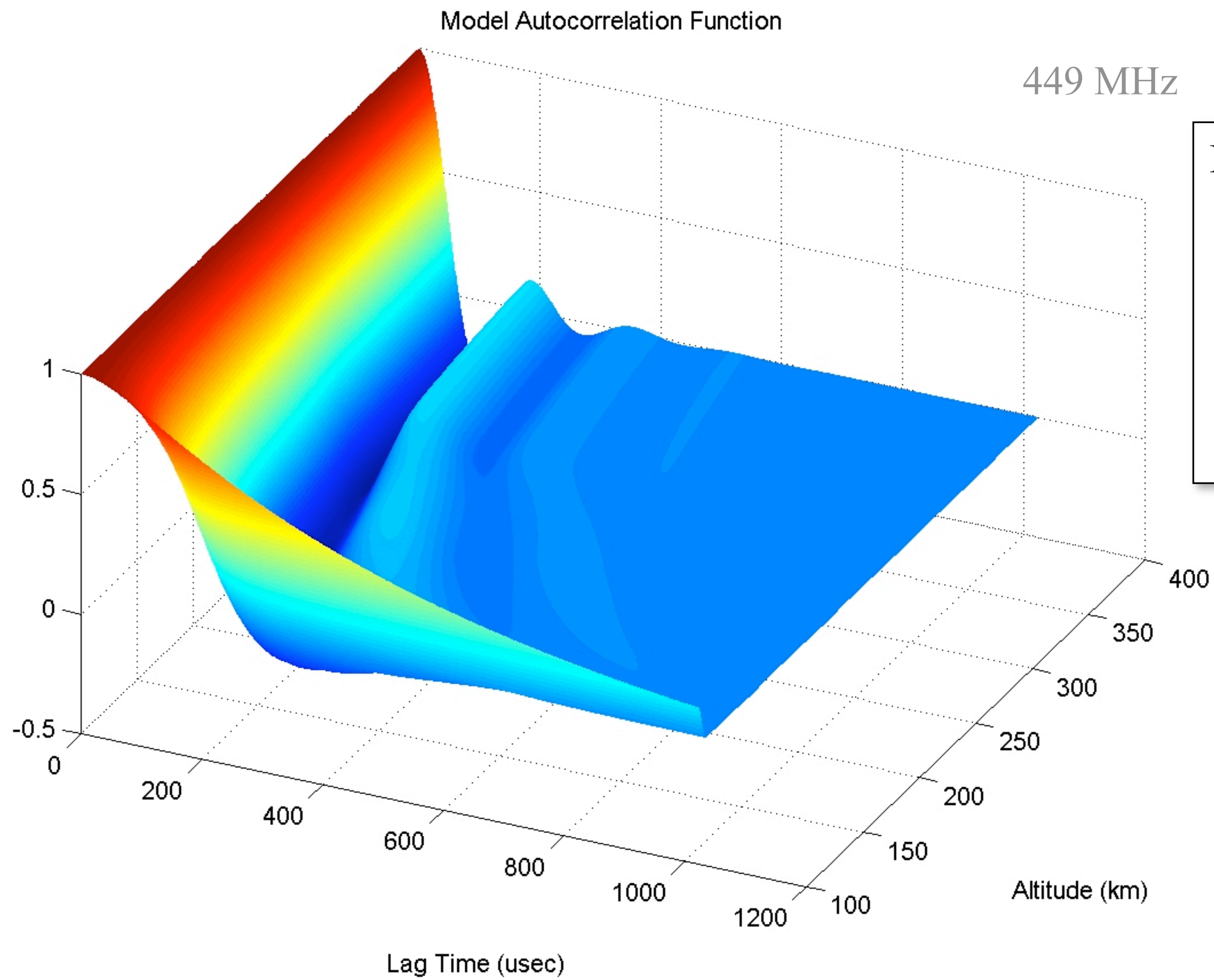
•Electron (= ion) density from total area (corrected for temperatures)

•Ion velocity (vi) from the Doppler shift

Spectral space as a function of altitude



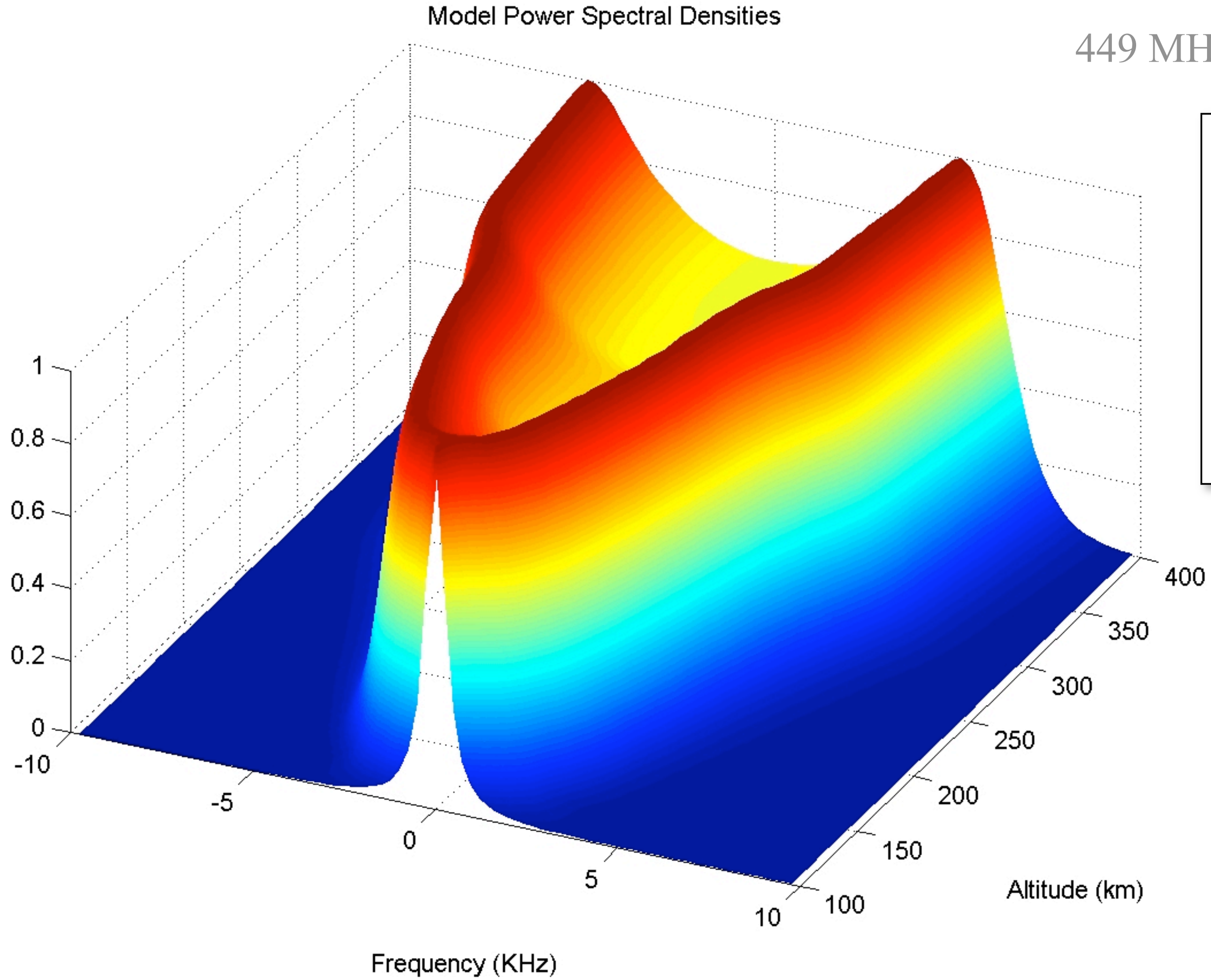
Incoherent Scatter Autocorrelation Functions



Dependencies:

N_e
T_e
T_i
V_i
m_i
ν_{in}

Incoherent Scatter Power Spectra



449 MHz

Dependencies:

N_e

T_e

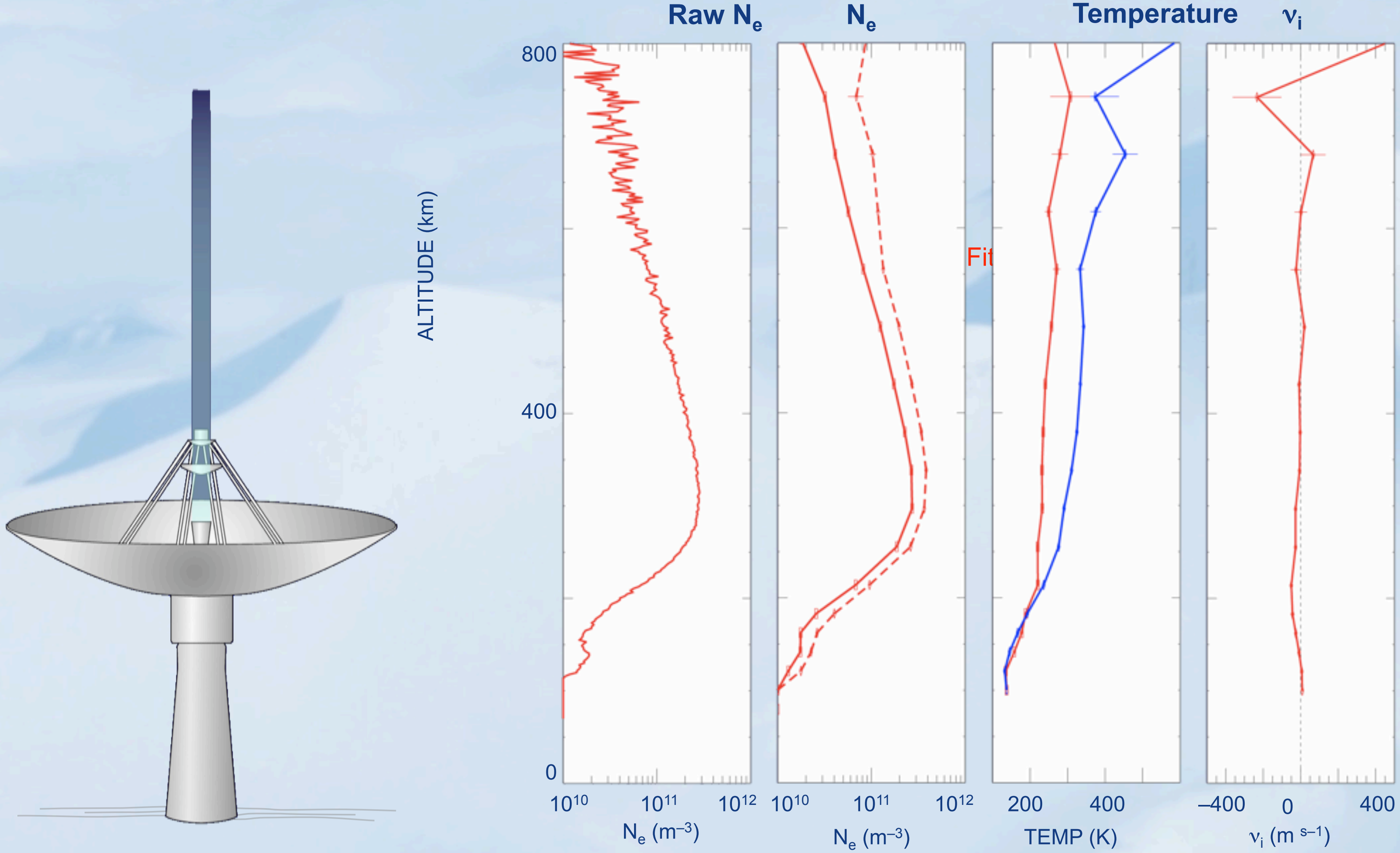
T_i

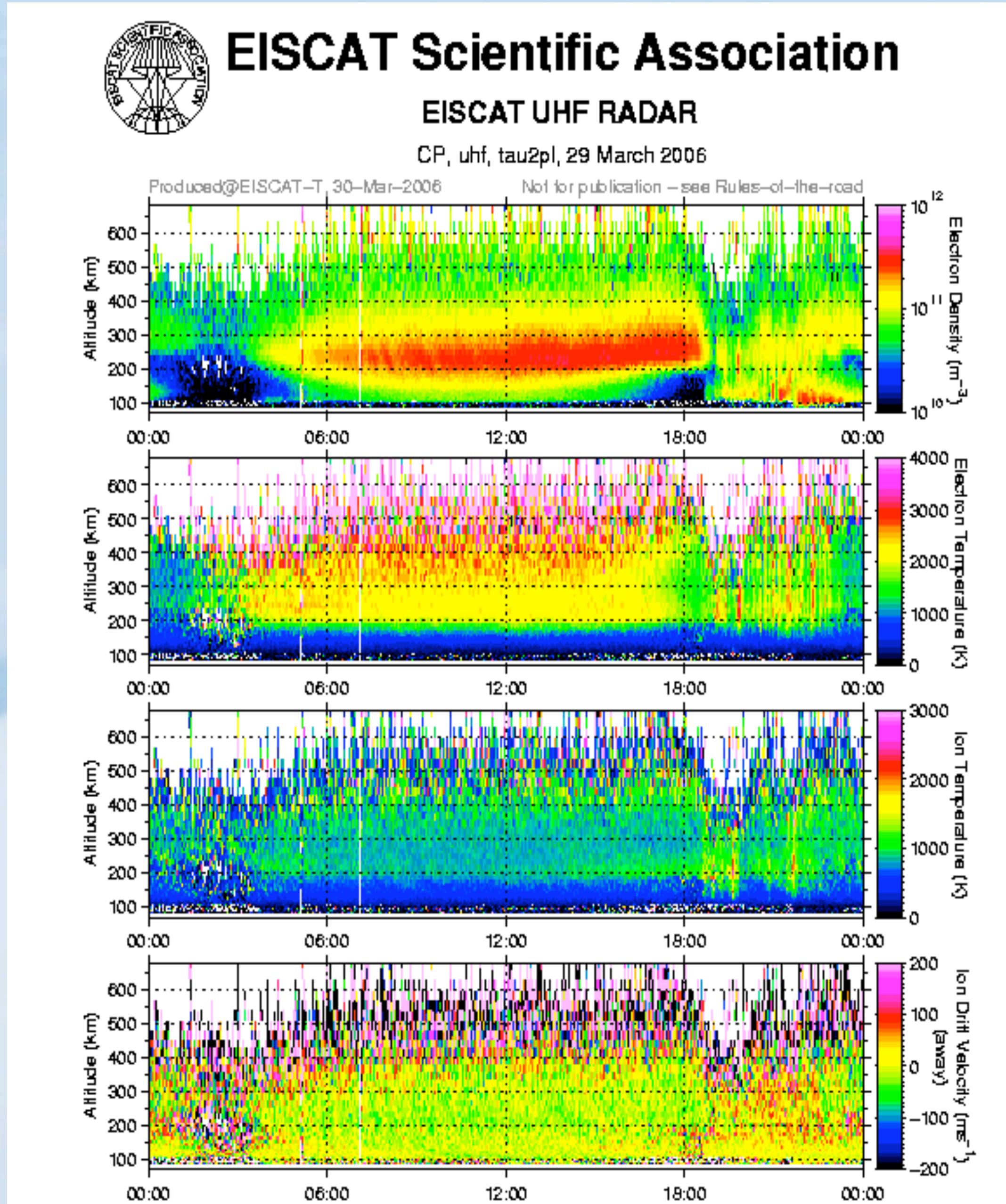
V_i

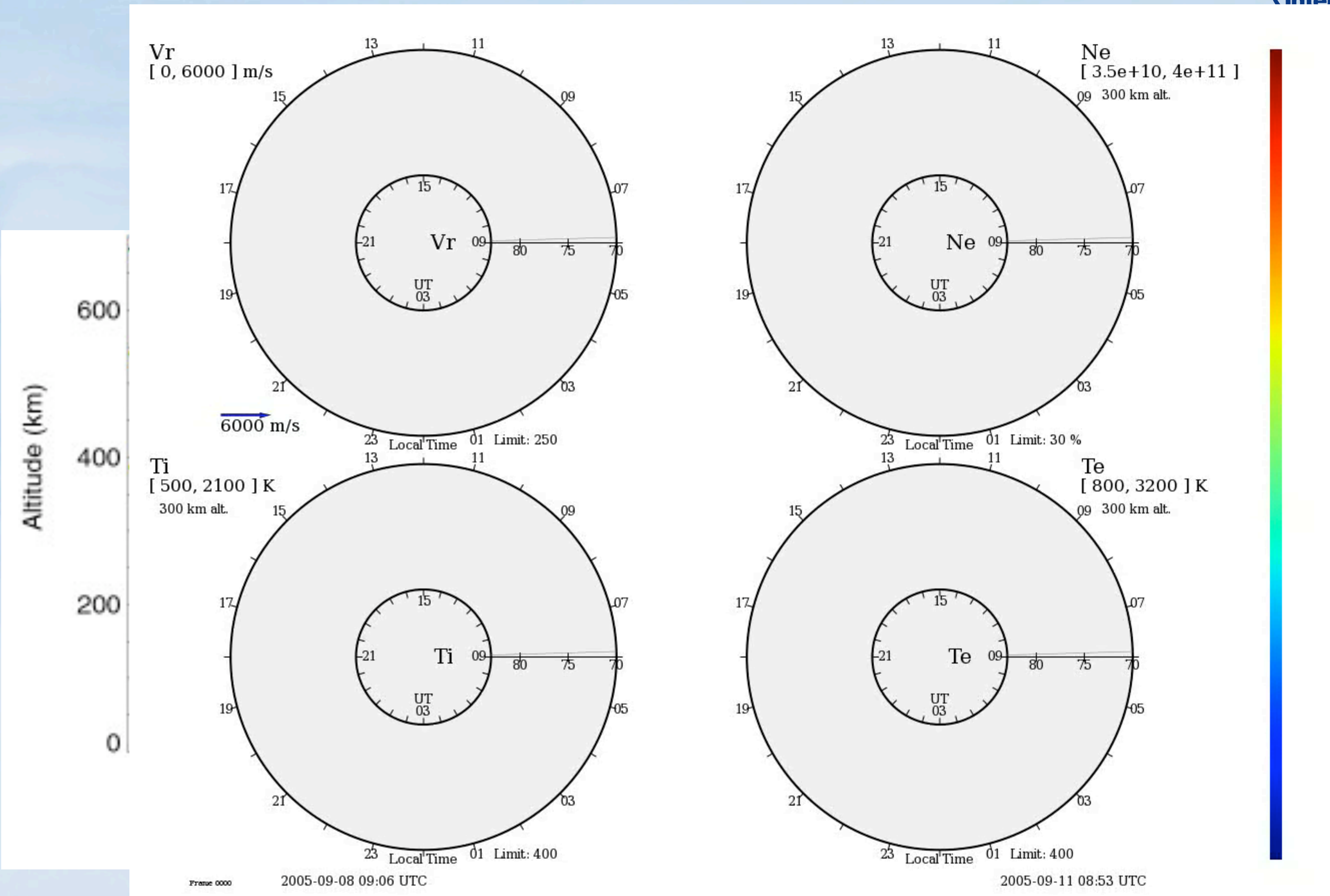
m_i

ν_{in}

Plasma Parameter Profile




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)
100
200
300
400
500
600
00:00
06:00
12:00
18:00
Electron Density (m^-3)
Electron Temperature (K)
Ion Temperature (K)
Ion Drift Velocity (ms^-1) (away)
4000
3000
2000
1000
0
200
100
-100
-200



Vr
[0, 6000] m/s
6000 m/s
Limit: 250
Ne
[3.5e+10, 4e+11]
300 km alt.
Limit: 30 %
Ti
[500, 2100] K
300 km alt.
Limit: 400
Te
[800, 3200] K
300 km alt.
Limit: 400
Local Time
UT
Altitude (km)
600
400
200
0
2005-09-08 09:06 UTC
2005-09-11 08:53 UTC

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