Incoherent scatter - An invaluable tool in the field of space and plasma physics

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for the ISSI Working Group

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ISSI Working Group Objective:

- ‘To create the **first definitive textbook** which covers all aspects of incoherent scatter radar (ISR) techniques, theory and applications with **particular relevance** to the fields of space and atmospheric physics’
- (To put together the text book we wish we had when we teach the subject / have new students and researchers coming onboard / host ISR summer schools)


EISCAT Svalbard Radar, Norway

SYISR, China

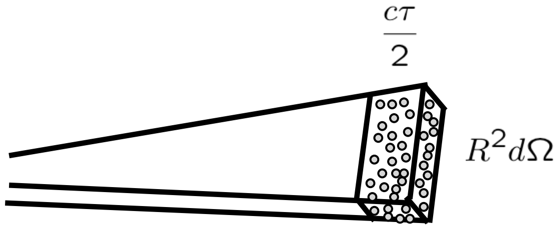

RISR-N and RISR-C, Canada


PFISR, USA

Incoherent scatter radar: The experimental (radar) view

Suppose we transmit a wave towards a plasma and measure the scattered wave:

$$P_{rec} = (P_{inc})A_{scat}(\frac{A_{rec}}{4\pi R^2})$$



$$A_{scat} = \sigma_{radar} V_s$$ (ionosphere is a beam filling target)

$$\sigma_{radar} = 4\pi\sigma_{total}$$ (Solid angle)

$$\left(\frac{P_{rec}}{P_{inc}}\right)\left(\frac{4\pi R^2}{A_{rec}}\right)\left(\frac{1}{V_s}\right) = 4\pi r_e^2 \sin^2\delta \left\langle |\Delta N(k)|^2 \right\rangle$$

Measurable experimentally

Physics info is here!

(1 for backscatter)

Radar cross-section of ionospheric plasma

Assume a beam filling plasma at F region altitudes (300 km) with very high electron density (1E12 electrons per m3 - BEST CASE):

Classical electron scattering cross-section $\sigma_e = 10^{-28} m^2 / e^-$

Assume a pulse length of 10 km.
Assume a cross-beam width of 1 km (~ Arecibo).

Total cross section is then (10 km x 1 km x 1 km x 1E12 m^-3 x 1E-28 m^-2/e-):

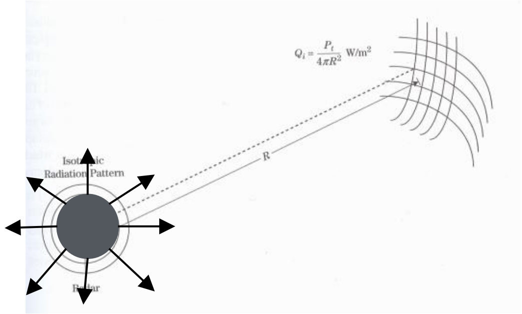
$$\sigma_{tot} \sim 10^{-6} m^2$$

-60 dBsm! Are we going to be able to do this at all?

NB: Born approximation is very valid, since total amount of scattered power in the volume ~ 1E-12. So **we can make full range profiles if we can detect the scatter.**

Detectability of scatter from ionospheric plasma

For fraction of scattered power actually received, assume isotropic scatter and a BIG ~100 m diameter antenna:



$$f_{rec} = \frac{A_{rec}}{4\pi R^2} \sim \frac{10^4\ m^2}{4(300 \times 10^3\ m)^2}$$

About -80 dB (1E-8): not much. So:

$$\frac{P_{rec}}{P_{tx}} \sim 10^{-20}$$

Arecibo, PR
Decommissioned

So an Arecibo-size radar, with 1 MW transmitted signal, receives **10 femtowatts** of incoherently scattered power from free electrons in the ionosphere.

REALLY not very much.

Detectability of scatter from ionospheric plasma

What matters, though, is the signal to noise ratio:

$$P_{noise} = (k_B T_{eff})\,(BW)$$

Typical effective noise temperatures ~100 to 200 K at UHF frequencies (430 MHz, say).

Assume the bandwidth is set by thermal electron motions in a Boltzmann sense:

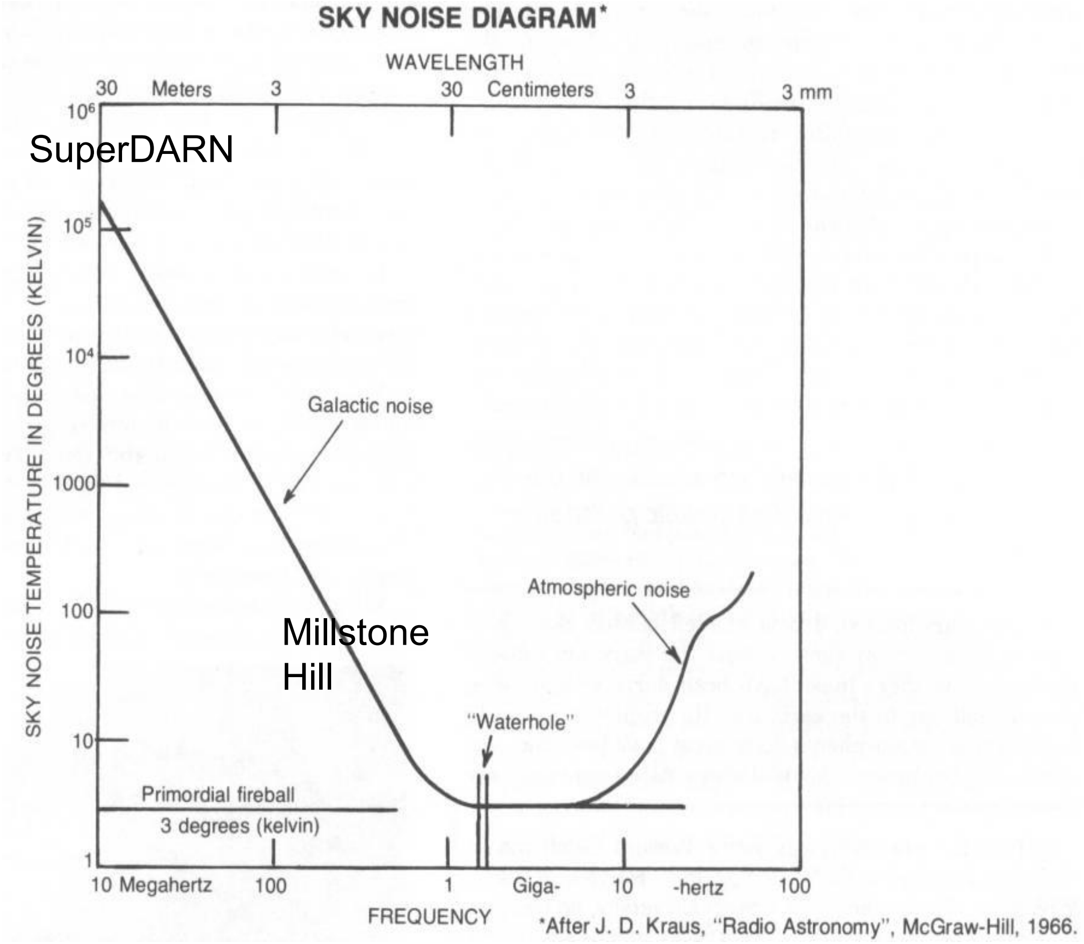
$$3k_B T_e \sim m_e v_{e,th}^2$$

$$v_{e,th} \sim \sqrt{\frac{3k_B T_e}{m_e}} \sim 2 \times 10^5 m/s$$

$$BW \sim (v_{e,th})\,(2)(2)(\frac{f_{tx}}{c}) \sim 10^6 Hz$$

(2s are for up/down, backscatter)

The Universe is our RFI



Detectability of scatter from ionospheric plasma

Finally,

$$P_{noise} \sim 2 \times 10^{-15} W$$

$$S/N \sim 5$$

Workable!

But you need a megawatt class transmitter and a huge (Arecibo size!) antenna.

1950s: technology makes this possible (radio astronomy + construction = large antennas, military needs = high power transmitters)

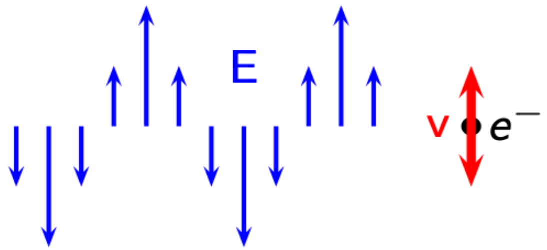
Happy accident: this calculation is WRONG – signal is >40X stronger because thermal motion of electrons is set by ION MOTION (bandwidth is ~40X smaller)

Arecibo, PR
Decommissioned

Millstone Hill
MA, USA

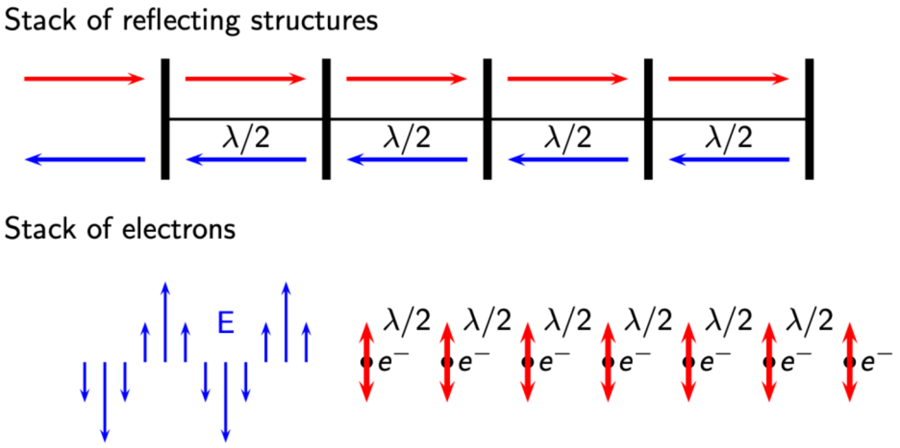
The Ionosphere = A Box Of Thermal Electrons ("Soft Target")

- Scatter from targets spaced by the Bragg wavelength ($\lambda/2$) add constructively
- Scatter from a large number of electrons samples the Fourier transform of the electron density distribution at the Bragg wavenumber
- Thermal plasmas are naturally full of a whole spectrum of waves
- ISR is Bragg scatter from those thermal waves that match the Bragg wavenumber



Closeup:
Scatter from
one electron

$$\sigma_e = 10^{-28} m^2/e^-$$



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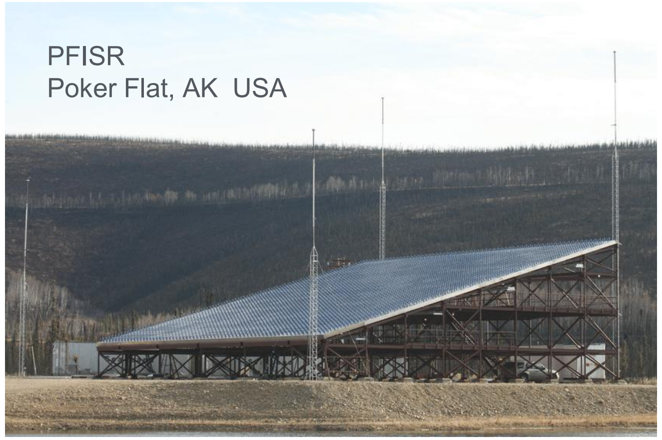
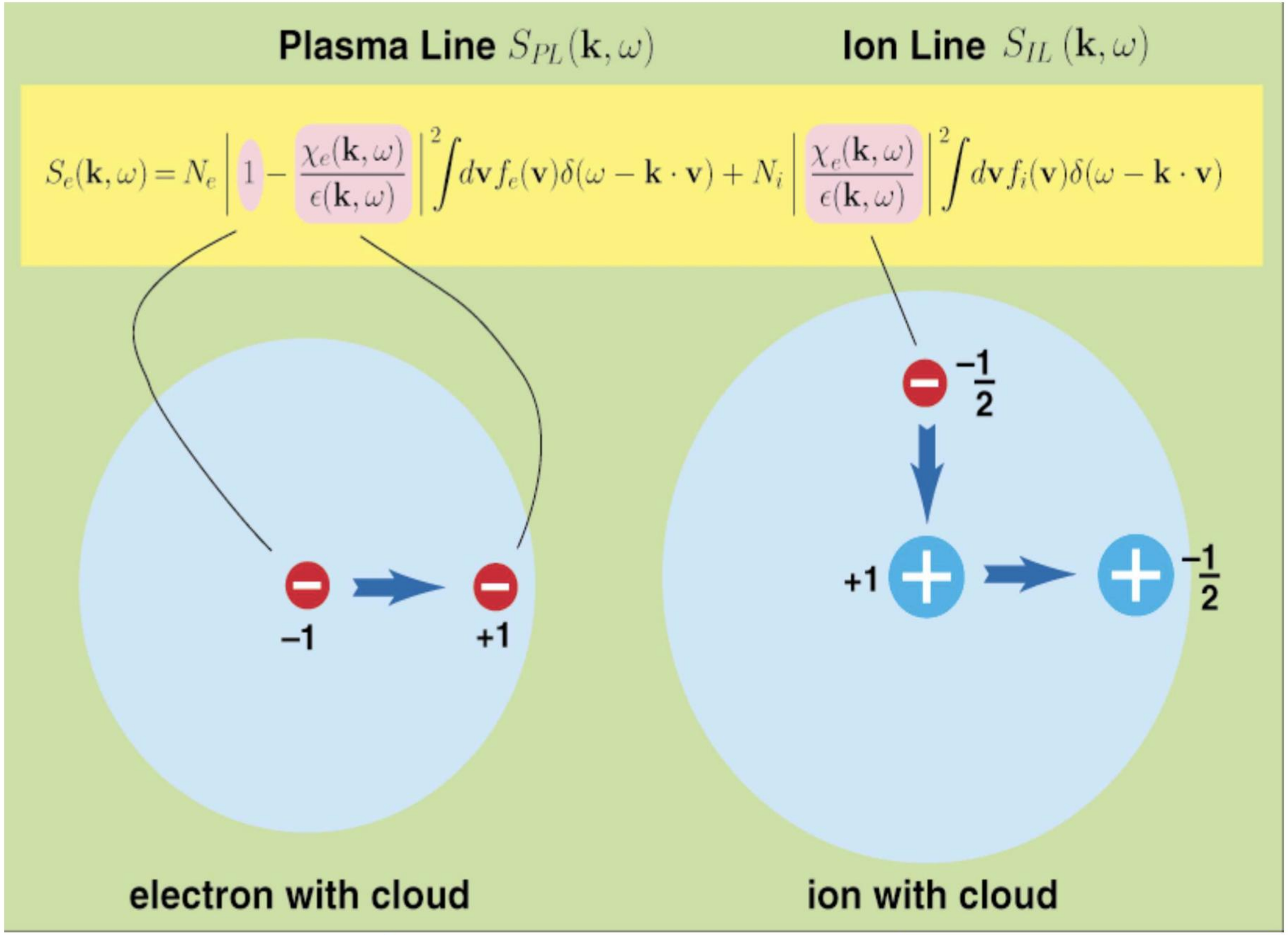


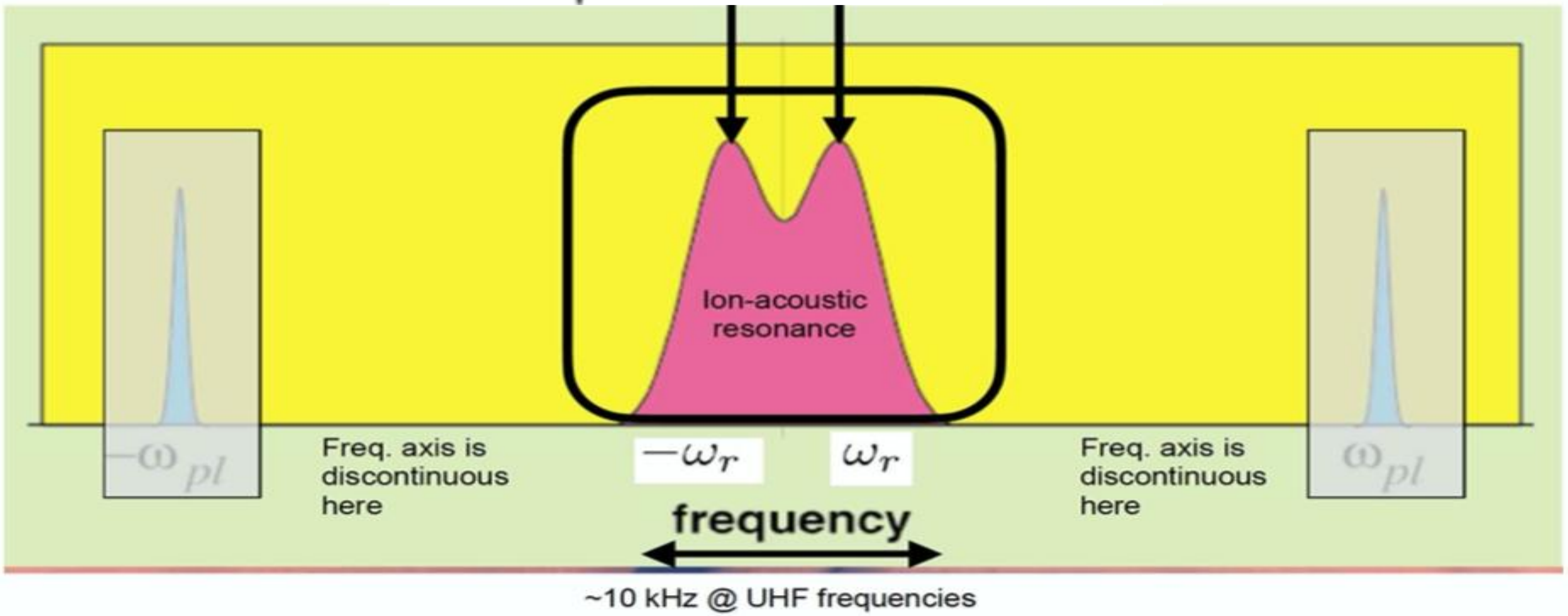
Plasma Theory: Dressed Particles



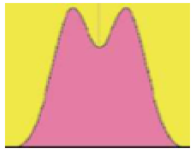
Scattering comes from electrons (light mass), but their fluctuations contain ion information as well!

Ion-Acoustic Mode ("Ion Line"): Electron and Ion Information

$$\omega_r = k\sqrt{\frac{k_B}{m_i}(T_e + \gamma_i T_i)} \qquad \gamma_i \approx 3$$



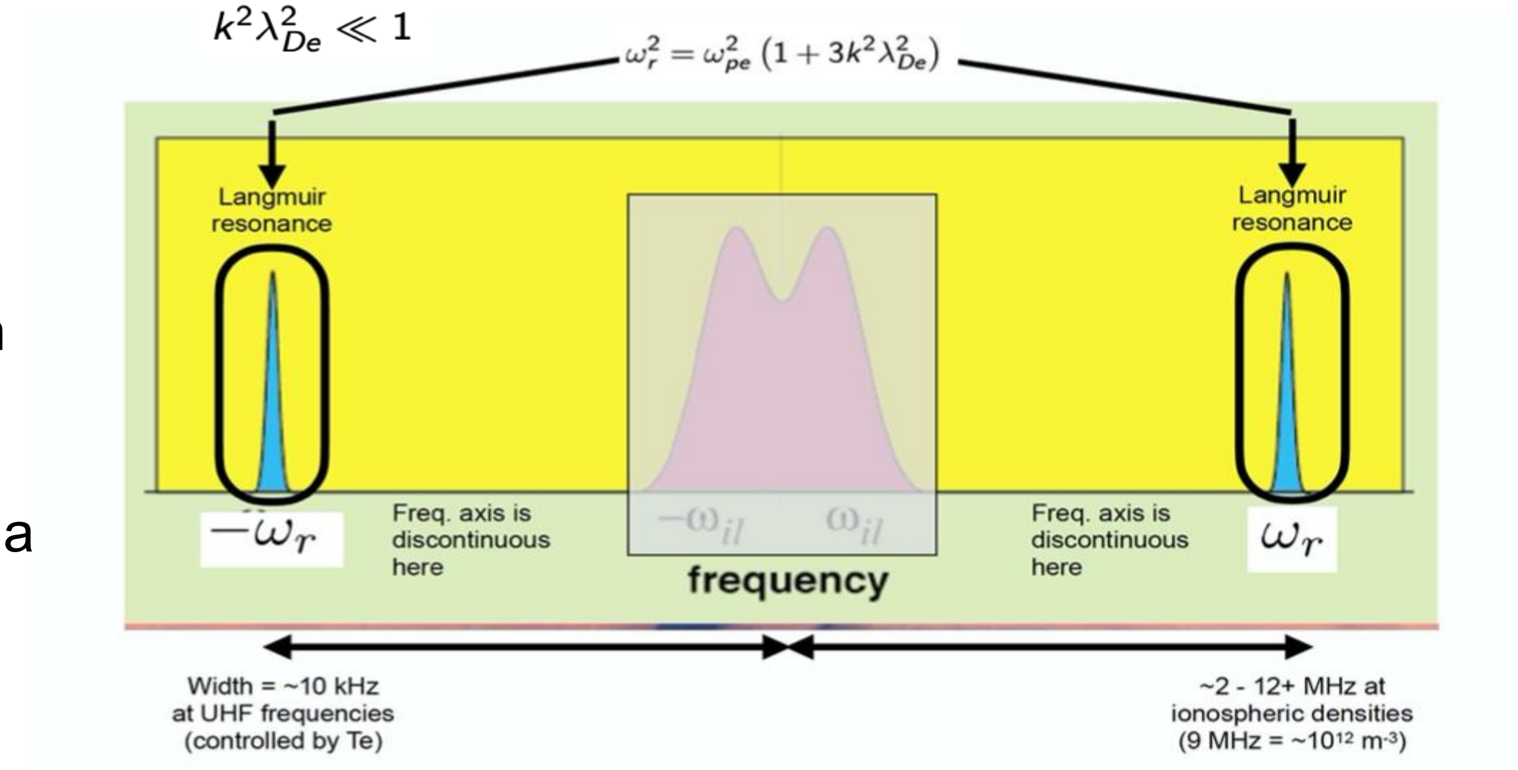
Thermal Motion $\left\langle |n_{ti}(\mathbf{k},\omega)|^2 \right\rangle$ ⟶ Collective Effects $\frac{|\chi_e|^2}{|1+\chi_i+\chi_e|^2}$ ⟶ ISR Spectrum



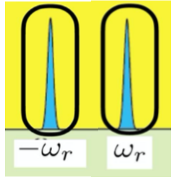
Langmuir Mode ("Plasma Line"): Precise Electron Information, In the Debye Sphere

$$k^2\lambda_{De}^2 \ll 1$$

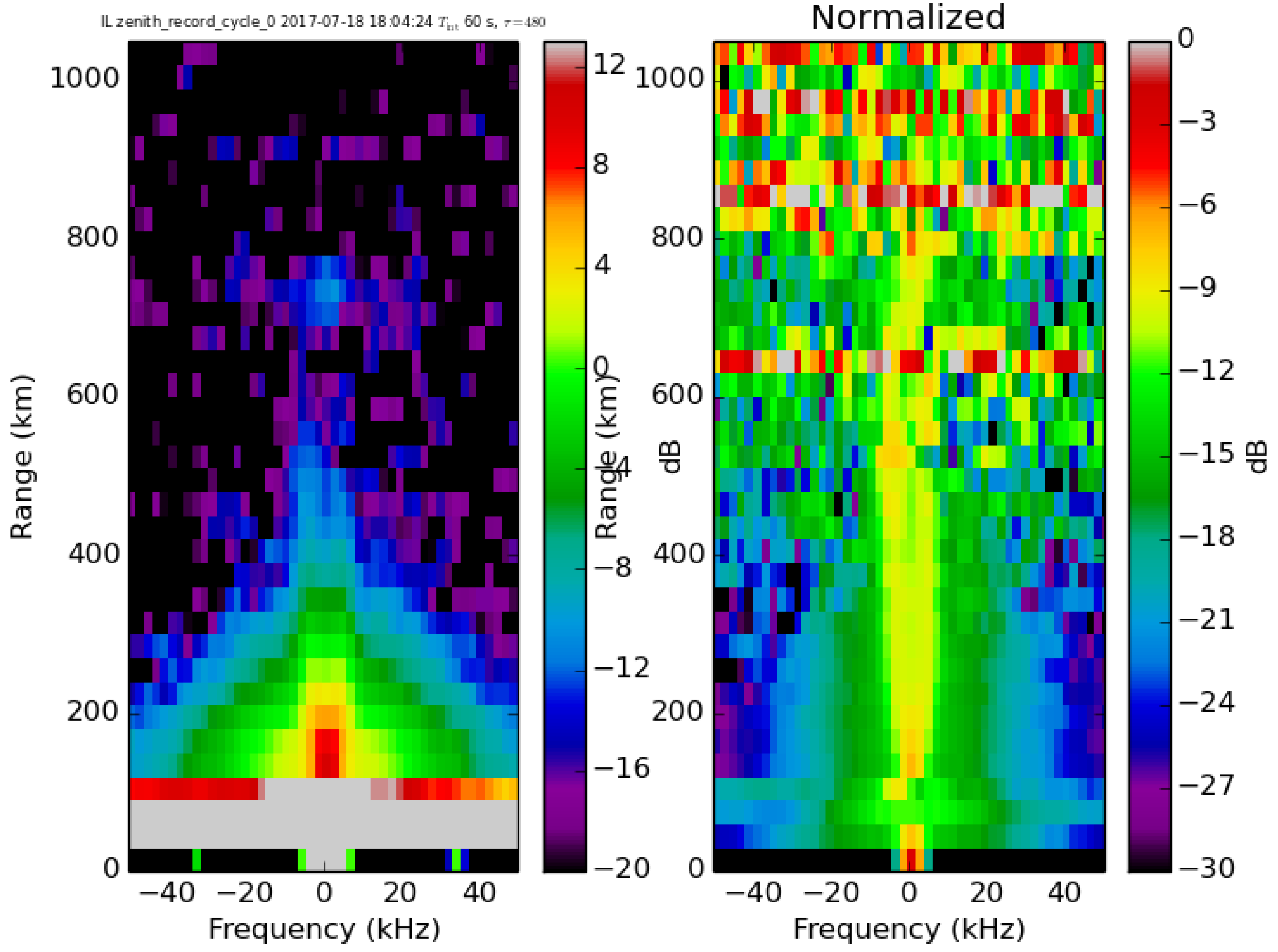
- Weak!
- Typically daytime only (enhanced photoelectron fluxes)
- Precise when visible: primary measurement is a ***frequency***, not an ***area***



Thermal Motion $\left\langle |n_{ti}(k,\omega)|^2 \right\rangle$ → Collective Effects $\dfrac{|\chi_e|^2}{|1+\chi_i+\chi_e|^2}$ → ISR Spectrum

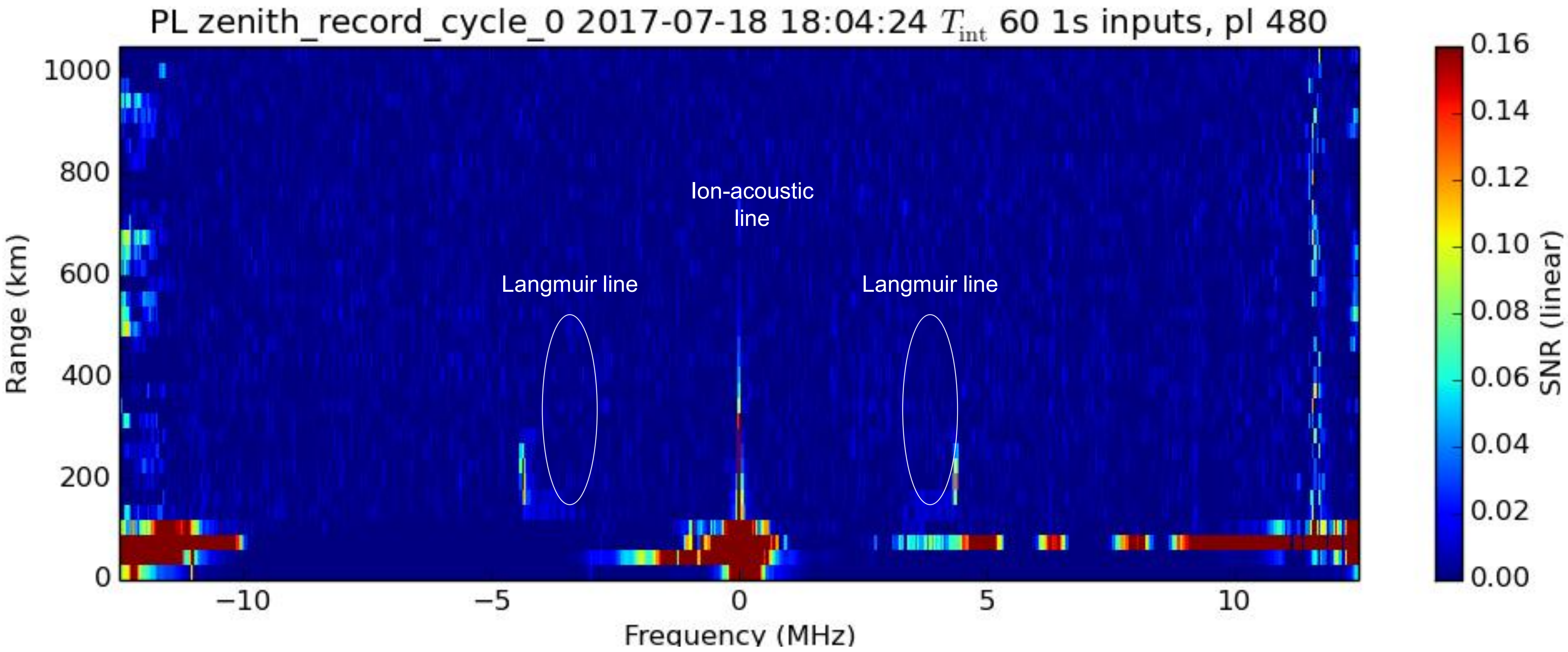


Ion Line Spectra: Millstone Hill (60 sec integrations)



Millstone Hill
MA, USA

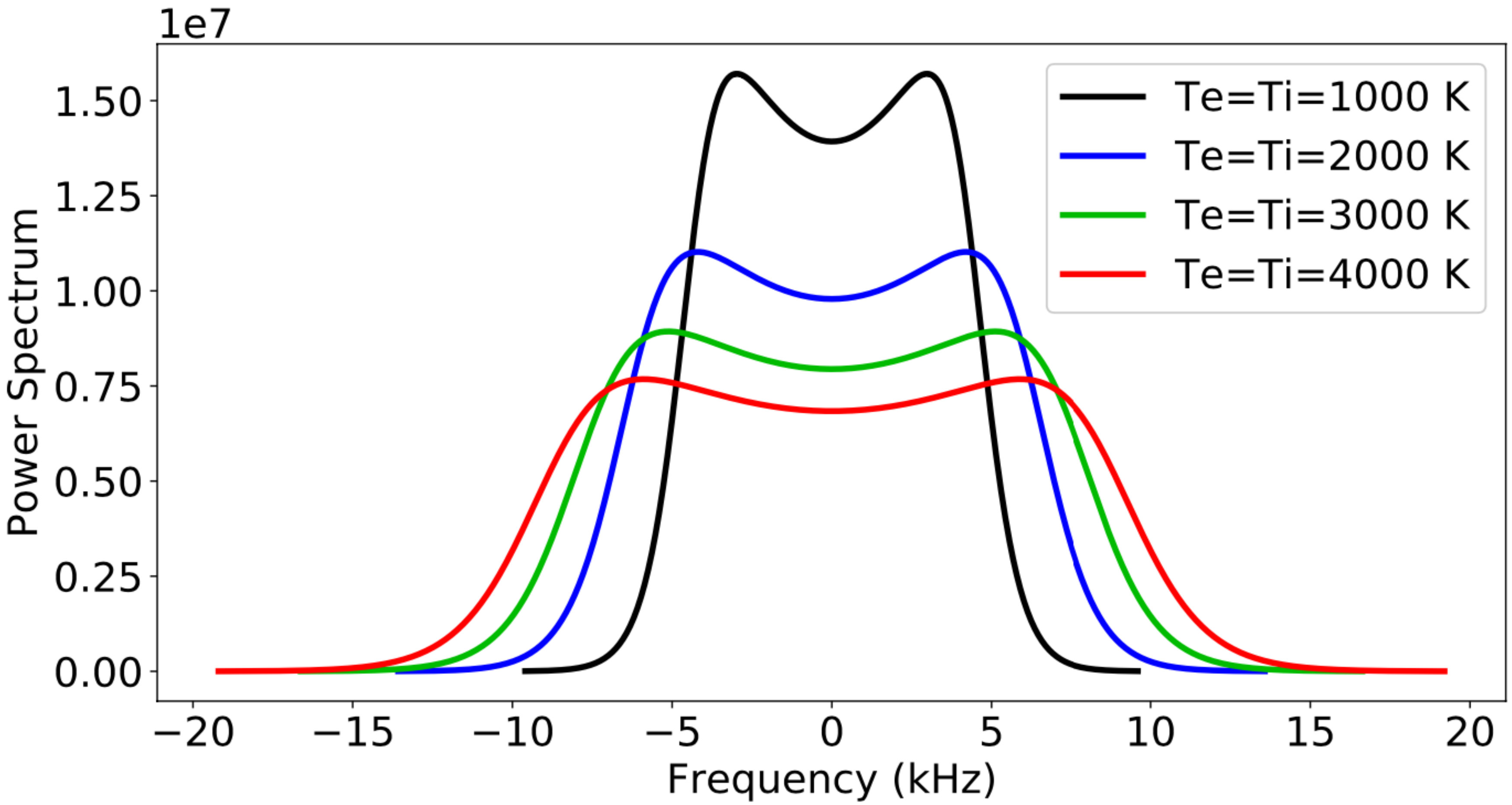
Plasma Line Spectra: Millstone Hill (60 sec integration)



Power Spectral Example: Dependence on Plasma Temperature (Te=Ti Case)

Basic parameters:
Electron density
Plasma temperature
LOS velocity
Ion composition

More exotic:
Field-aligned currents
Photoelectron spectra
Unequal ion temperatures
Non-Maxwellian plasmas
Etc.

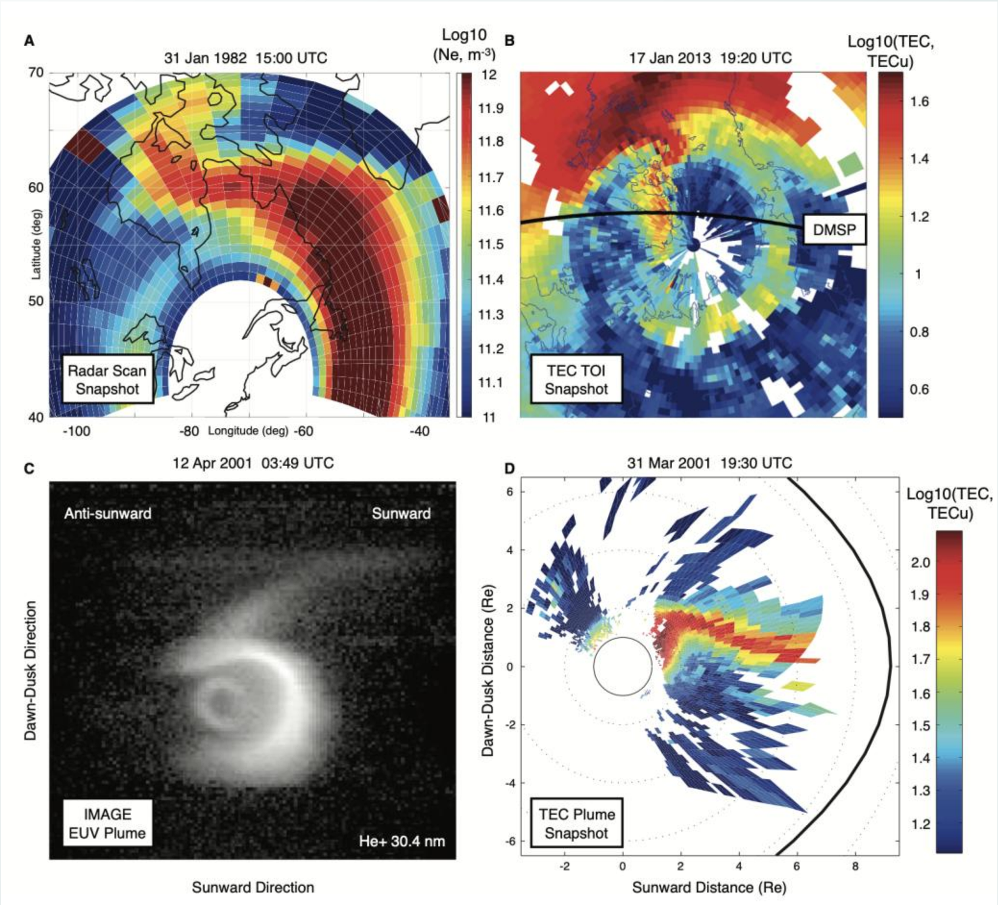


$$f = 449.3 \text{ MHz} \quad N_e = 3 \times 10^{11} \text{ m}^{-3} \quad m_i = 16 \text{ amu}$$

System Scale Application: The Geospace Plume

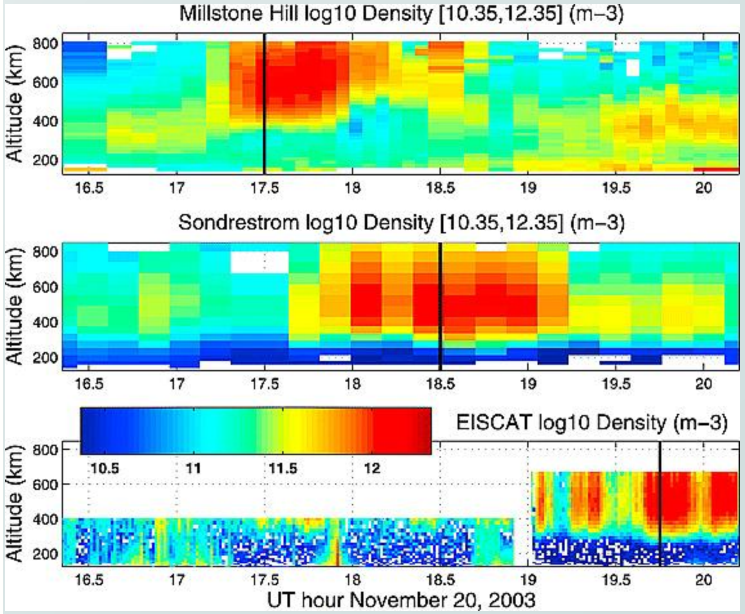
- SED base/plume formation
- Roles of SAPS, convection, PEF, and winds
- Global M-I-T Coupling context: Subauroral plasma influences on high latitude (polar) ionosphere via SED
  - Polar cap patches
  - Tongues of Ionization
  - Delivery of cold heavy O+ to cusp outflow regions, inner magnetosphere
- GDC upcoming: multi-plane ion, neutral sampling of crucial dynamic structures

Magnetosphere / Ionosphere / Plasma
Cold Plasma Flows



Foster et al 2020

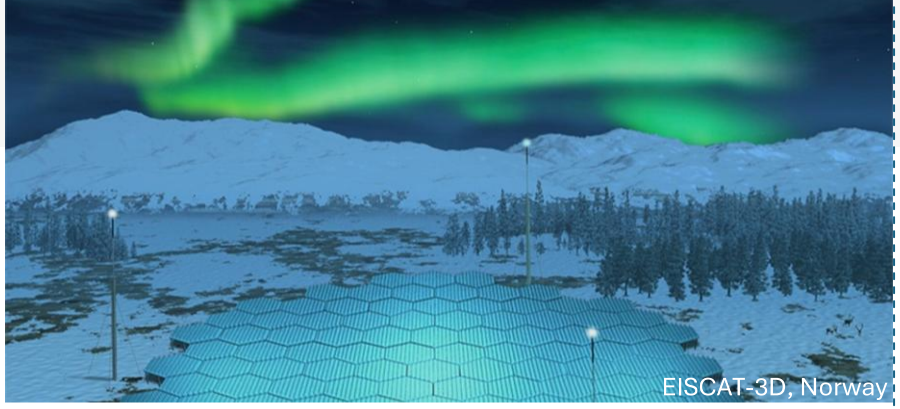
SED Passage through
Multiple Ground-Based Diagnostics:
More sampling needed!



Foster et al 2005

MIT HAYSTACK OBSERVATORY

ISSI Working Group: Incoherent scatter - An invaluable tool in the field of space and plasma physics



Outcome:

- Textbook will be **open access** (downloadable pdf) in the ISSI Scientific Report Series
- Supplementary computer code / exercises online
- Aimed at a broad audience, including plasma physicists, radio scientists, space physicists, and engineers.
- Suitable for Masters/PhD students and above.
- Publication expected ~2027/2028

The Working Group

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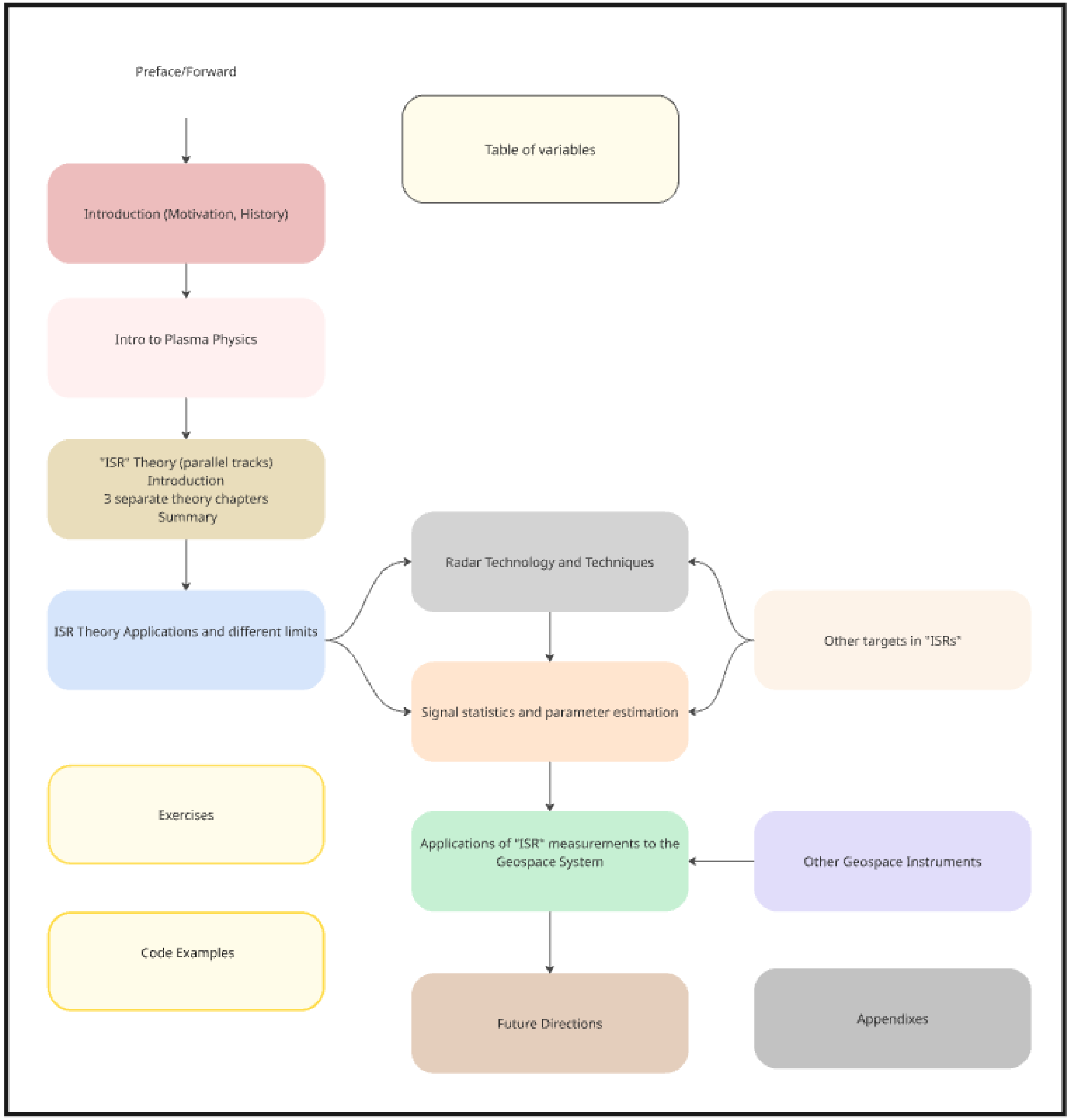
First meeting at ISSI: April 2025

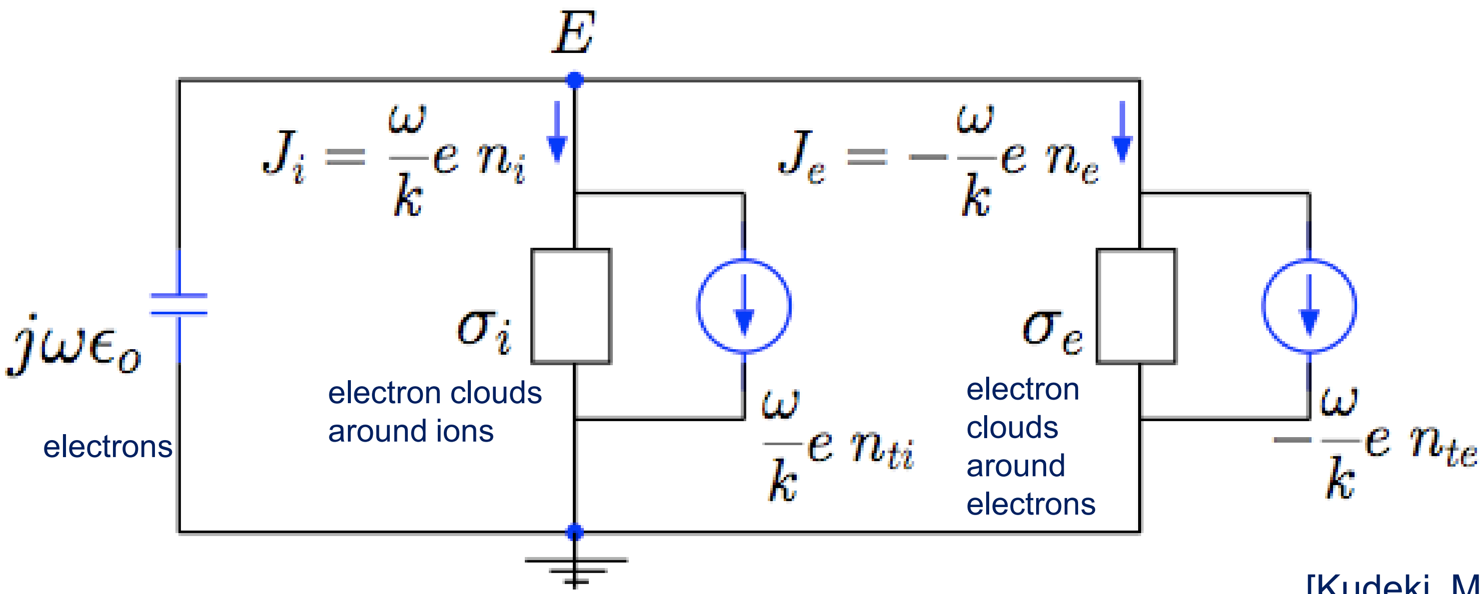
The Book Overview

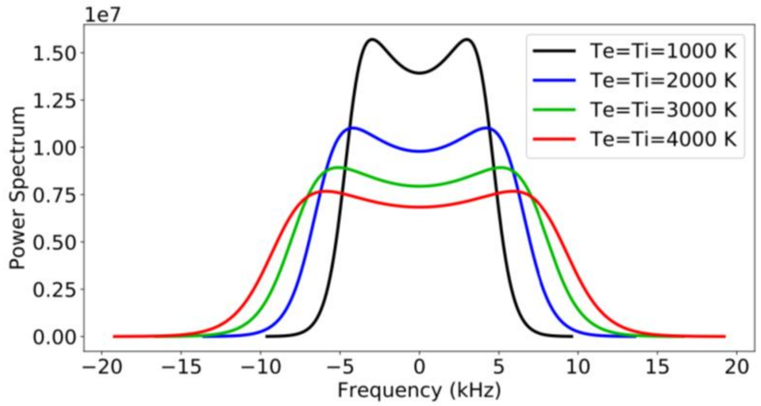


- Masters / PhD level
- Book will concentrate on aspects of ISR not covered **in depth** coherently**,** elsewhere
- Parallel theory chapters to provide students with a choice:
    - Dressed test particle (Hagfors, Pecséli)
    - Fluctuation – Dissipation (Farley, Kudeki,Milla)
    - Plasma kinetic (Salpeter, Sheffield)
    - Discussion of different approaches also included
- Aim to include full theoretical derivations
- Additional website with GUIs / computer code

Example: Circuit Based Derivation of Incoherent Scatter

$$\sigma_0(\omega_o + \omega)d\omega = N_0 r_e^2 \,\mathrm{Re}\left\{ \frac{y_e(y_i + jk^2\lambda_{de}^2)}{y_e + y_i + jk^2\lambda_{de}^2} \frac{d\omega}{\pi\omega} \right\}$$





[Kudeki, Milla]

Summary

- Textbook will be open access ISSI Scientific Report Series
- Masters / PhD level
- Publication date estimated 2027/2828
- Website / code repository in addition
- WG members will reach out to the community for co-authors / feedback etc.