University of Colorado **Boulder**

August 13, 2025

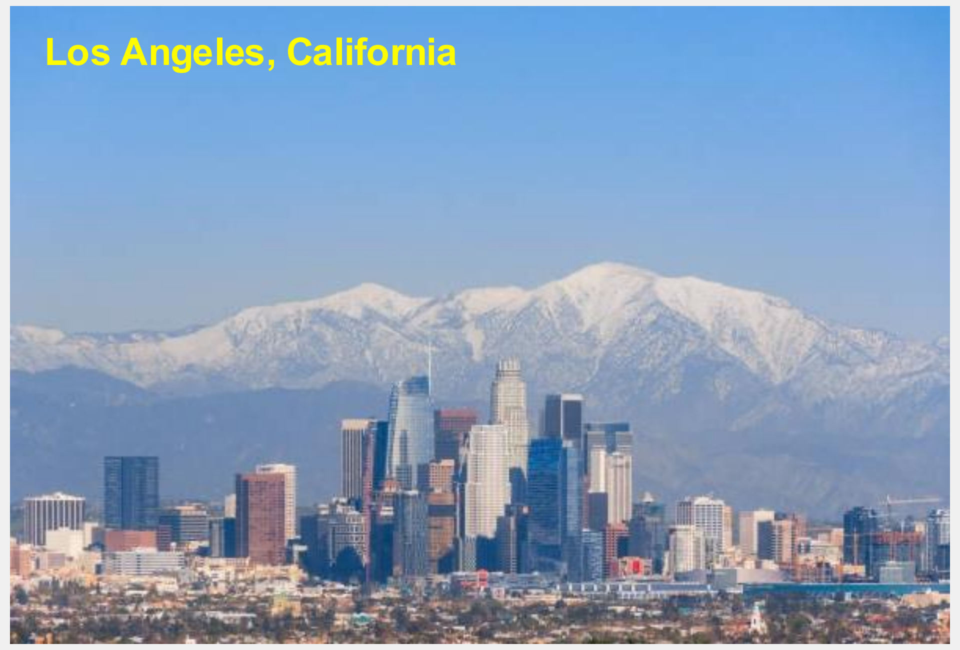
The Ionosphere

Origins, Structure, and Variability

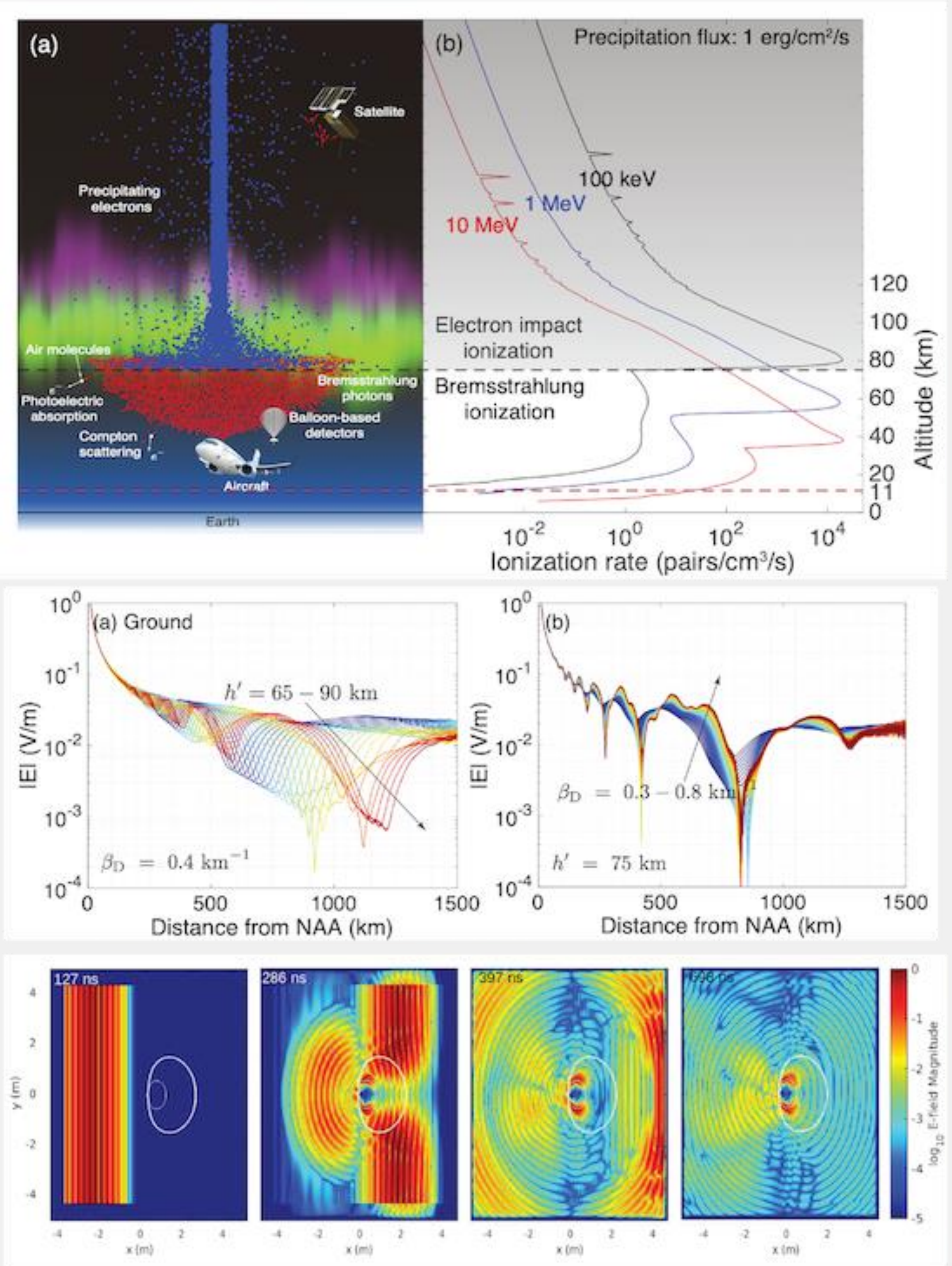
Robert A. Marshall

A bit about me

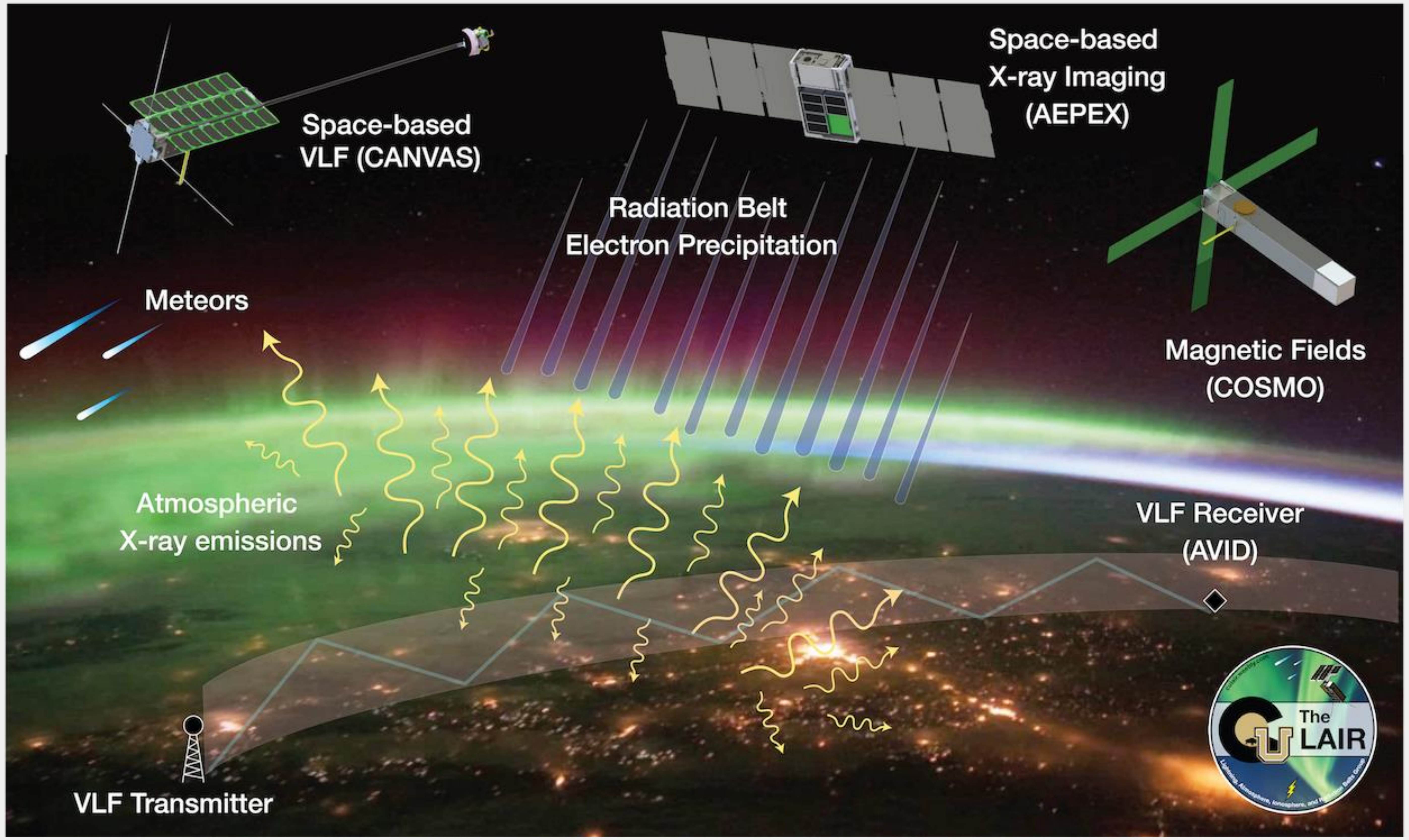
- **Grew up in Vancouver, BC, Canada**
- BS: Electrical Engineering, University of Southern California
- MS/PhD: Electrical Engineering, Stanford University
- Postdoc (< 2 years) at Boston University
- Research Associate (4 years) back at Stanford
- **Now 10 years at University of Colorado Boulder, Aerospace Engineering Sciences**
  - Tenured in 2022
  - Sabbatical in 2023: Orléans, France
  - Associate Chair for Graduate Studies: 2023—present



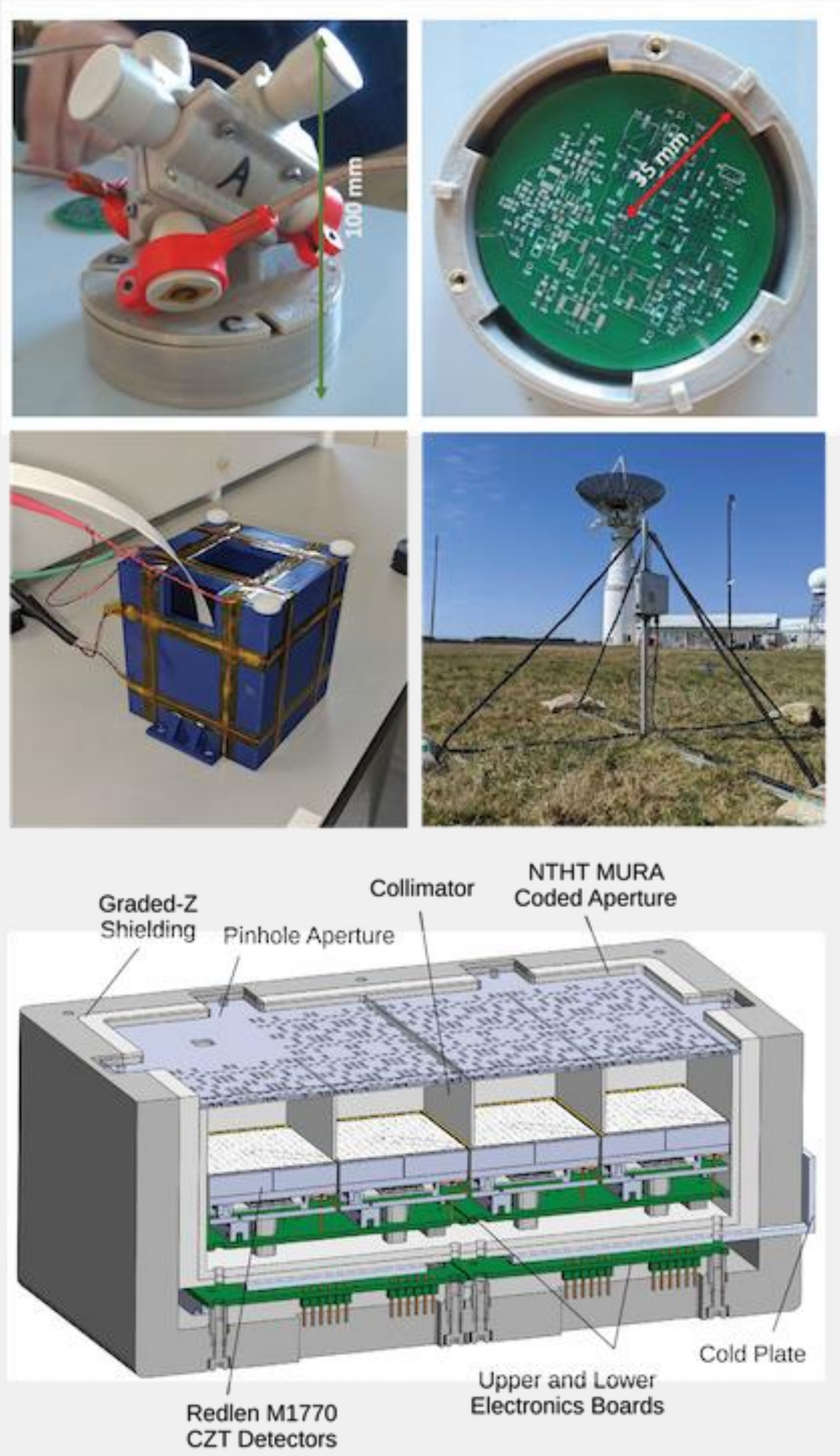
The LAIR Research Overview



Modeling, Simulation, and Data Analysis



CubeSats for Space Science



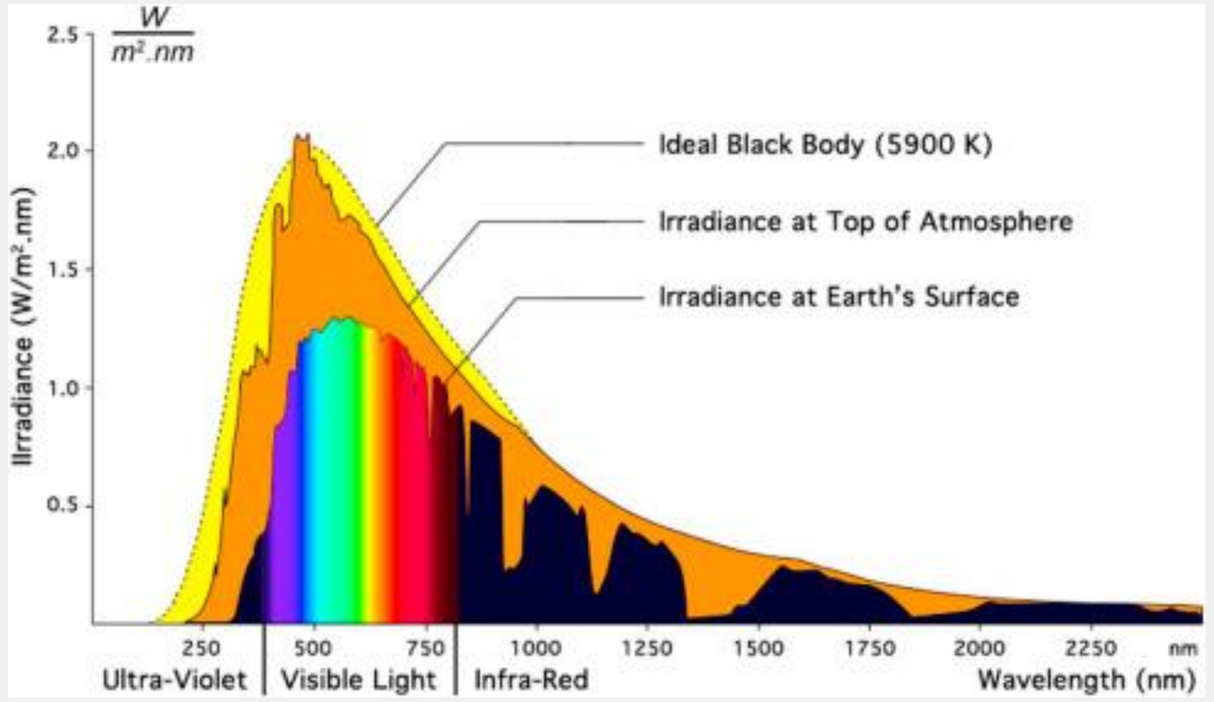
Instrumentation

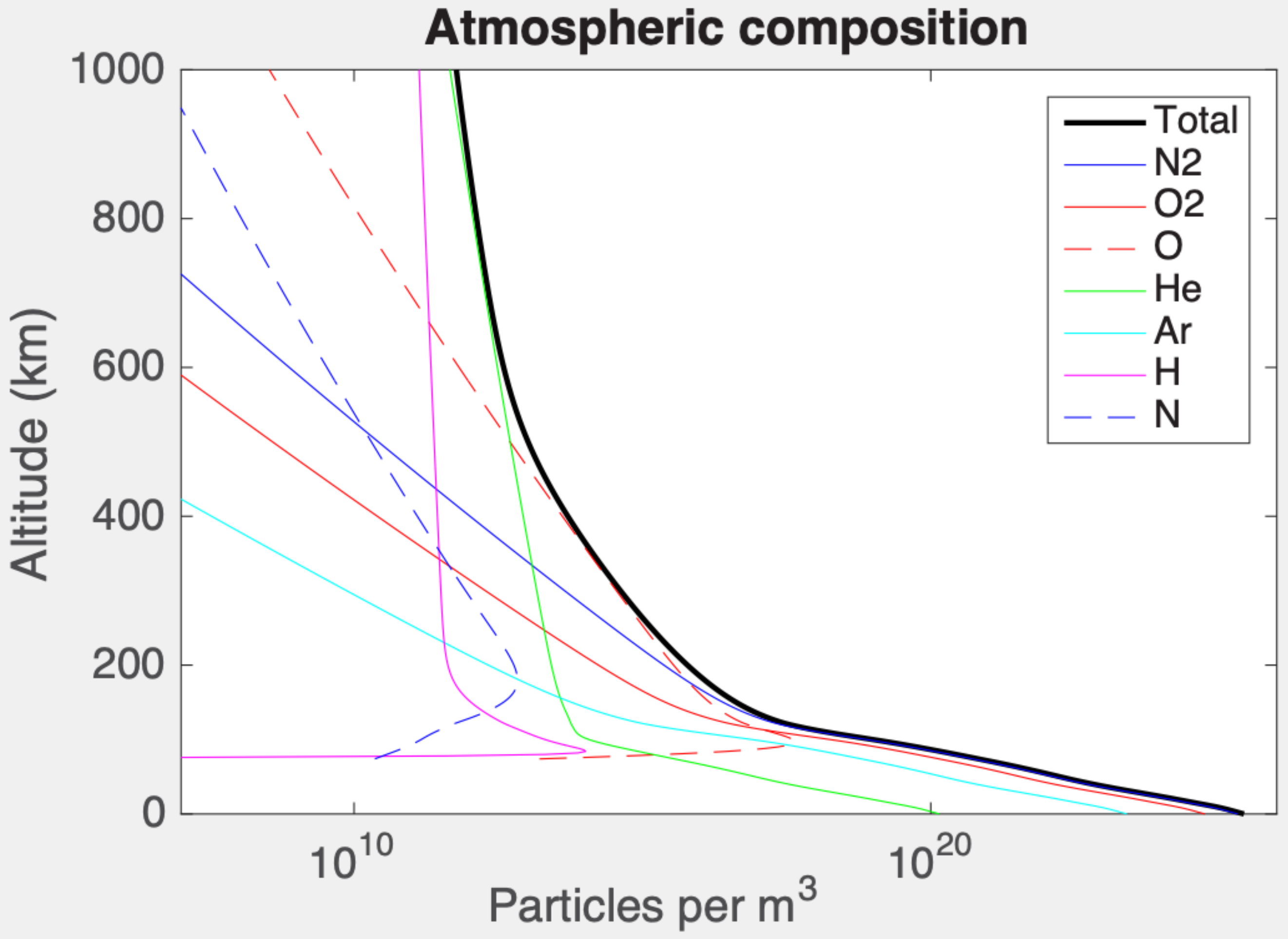
Ionosphere Lectures: Goals

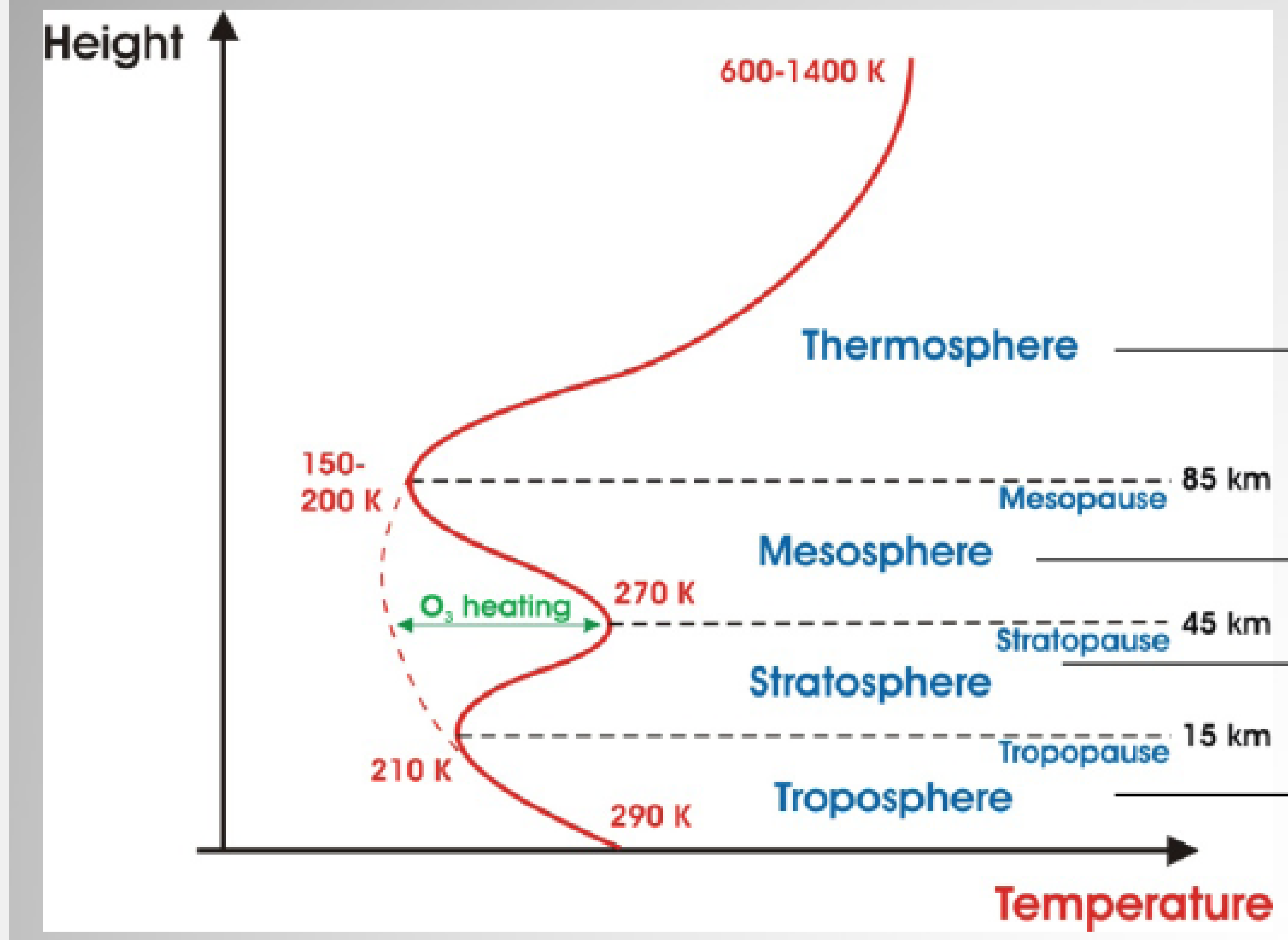
- **Understand basic physics of the Earth's ionosphere**
  - Origin, composition, layers
  - Variations: diurnal, seasonal, solar cycle, plus other anomalies
- **Effects of the Ionosphere on Spacecraft and technology**
  - Radio communications and GPS

Origin of the Ionosphere

- The Ionosphere is a product of two regions: the **Sun** and the **Atmosphere**







Thermosphere:
- **Energy sources:**
  - **Absorption of EUV (20-100 nm; photoionizing O, O_2, N_2) and UV (120-200 nm), photodissociating O_2), leading to chemical reactions and particle collisions, liberating energy**
  - **Joule heating by auroral electrical currents**
  - **Particle precipitation from the magnetosphere**
  - **Dissipation of upward propagating waves (tides, planetary waves, gravity waves)**
- **Energy sinks:**
  - **Thermal conduction into the mesosphere, where energy is radiated by CO_2, O_3 and H_2O**
  - **IR radiation by CO_2 NO, O**

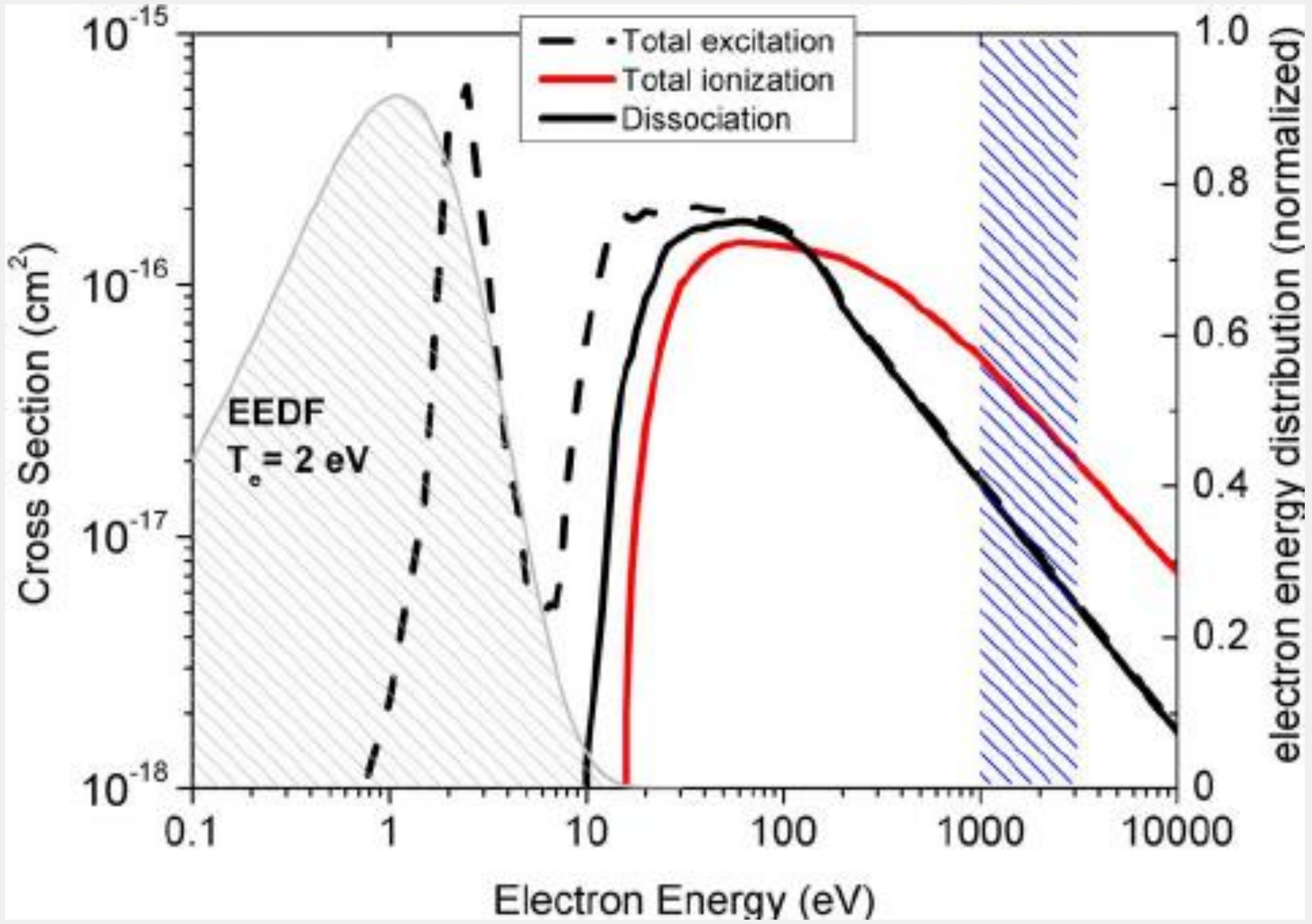
Mesosphere:
- **Energy sources:**
  - **Some UV absorption by O_3 (lower heights)**
  - **Heat transport down from thermosphere (minor, upper heights only)**
  - **Chemical heating**
- **Energy sinks:**
  - **IR radiation by CO_2 H_2O, OH**

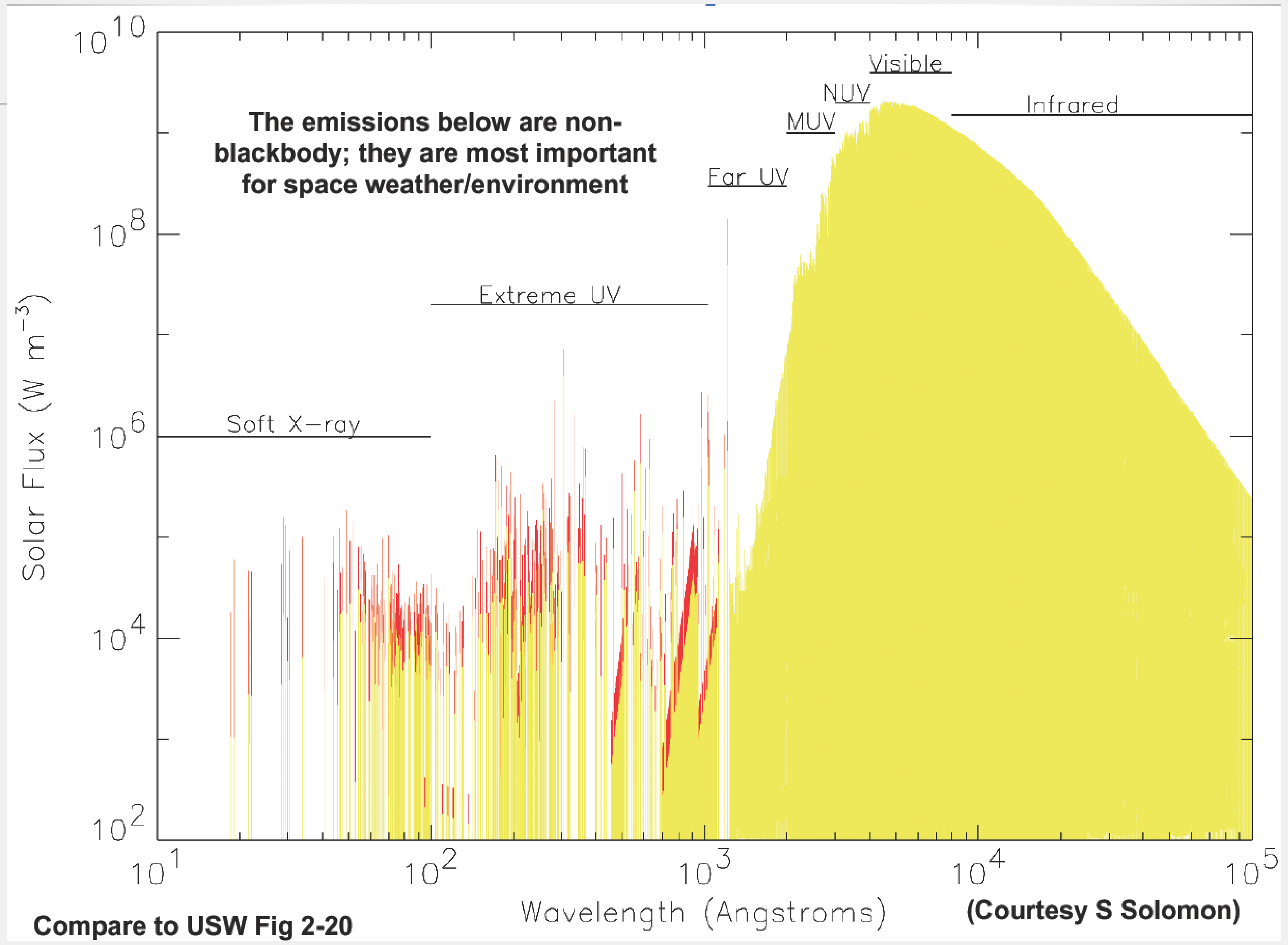
Stratosphere:
- **Energy sources:**
  - **Strong absorption of UV by ozone (causing stratopause temperature peak)**
- **Energy sinks:**
  - **IR radiation by O_3 , CO_2 , H_2O**

Troposphere:
- **Energy sources:**
  - **Planetary surface absorption (IR, visible), convection & conduction to atmosphere**
  - **Atmospheric absorption of terrestrial and solar IR**
  - **Latent heat release by H_2O**
- **Energy sinks:**
  - **IR radiation**
  - **Evaporation of H_2O**

Ionization thresholds

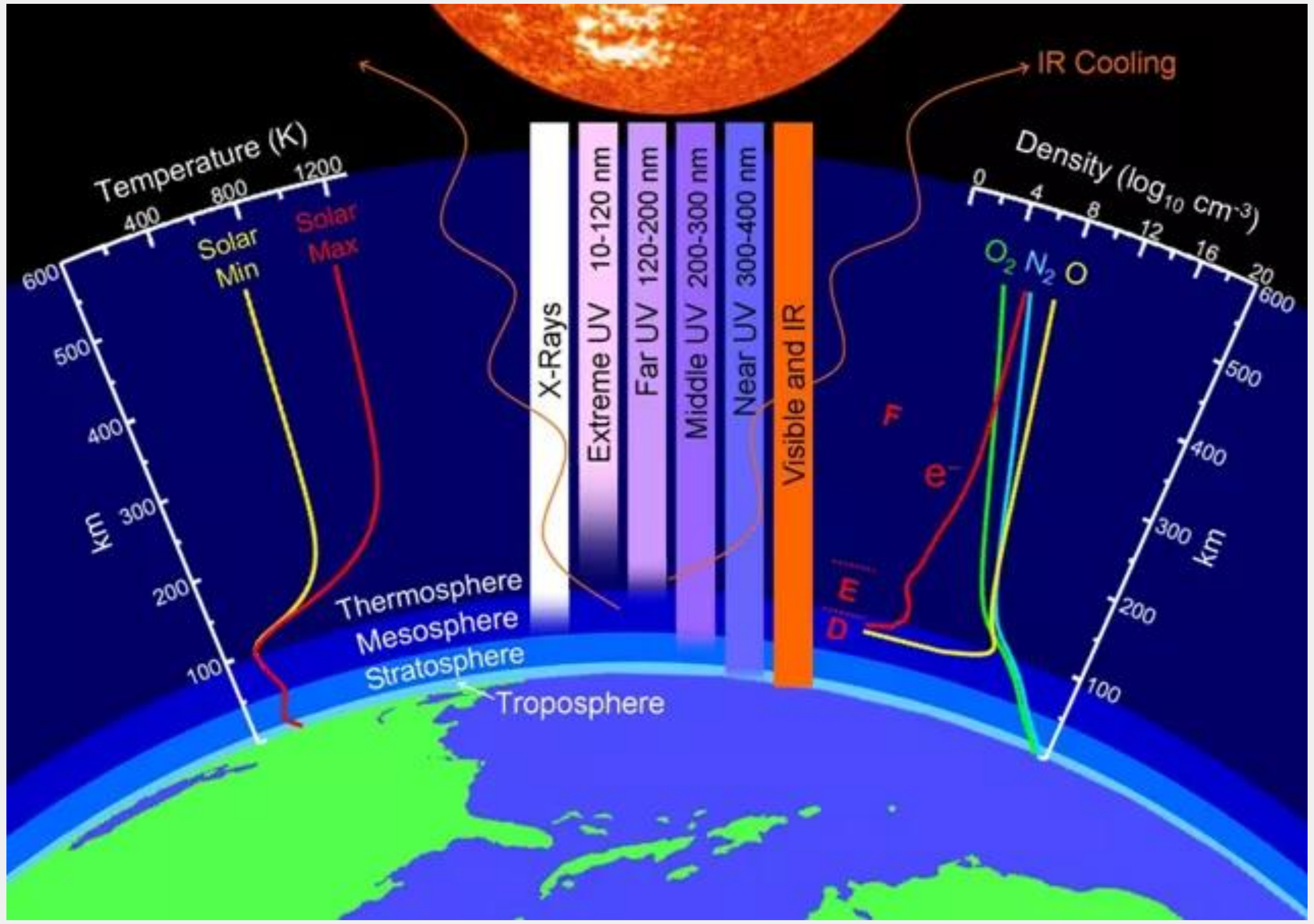
- Require a minimum energy to free an electron from an atom or molecule
- Require a photon with at least this minimum energy: "**ionizing radiation**" or sometimes just "**radiation**"
- **Ionization cross section** provides energy-dependent picture of ionization probability



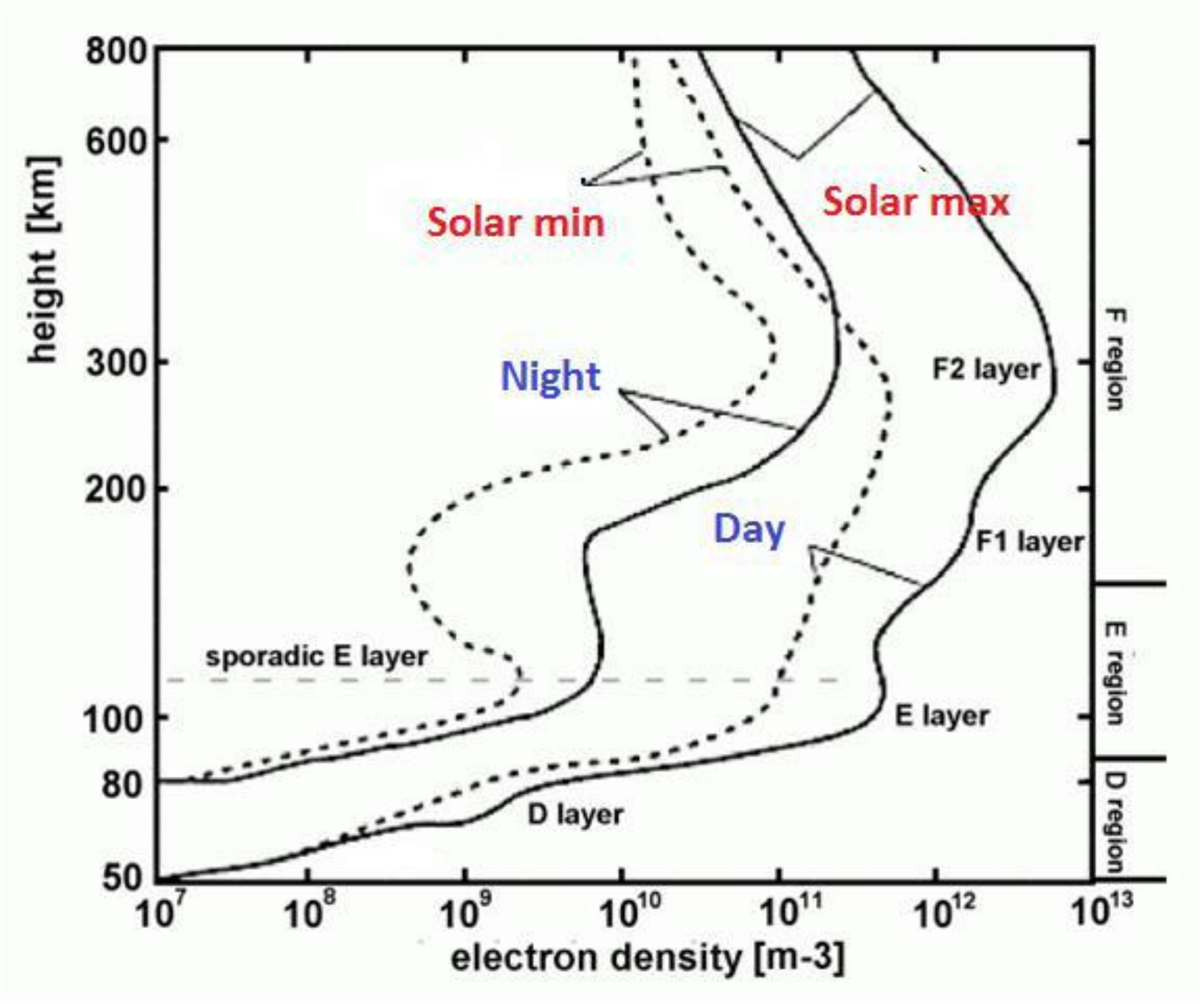


	Ionization Energy	Minimum photon wavelength
H	13.6 eV	91 nm (910 A)
He	24.6 eV	50 nm
O	13.62 eV	91 nm
Ar	15.76 eV	79 nm
N2	15.6 eV	80 nm
O2	12.1 eV	103 nm

Earth's Ionosphere

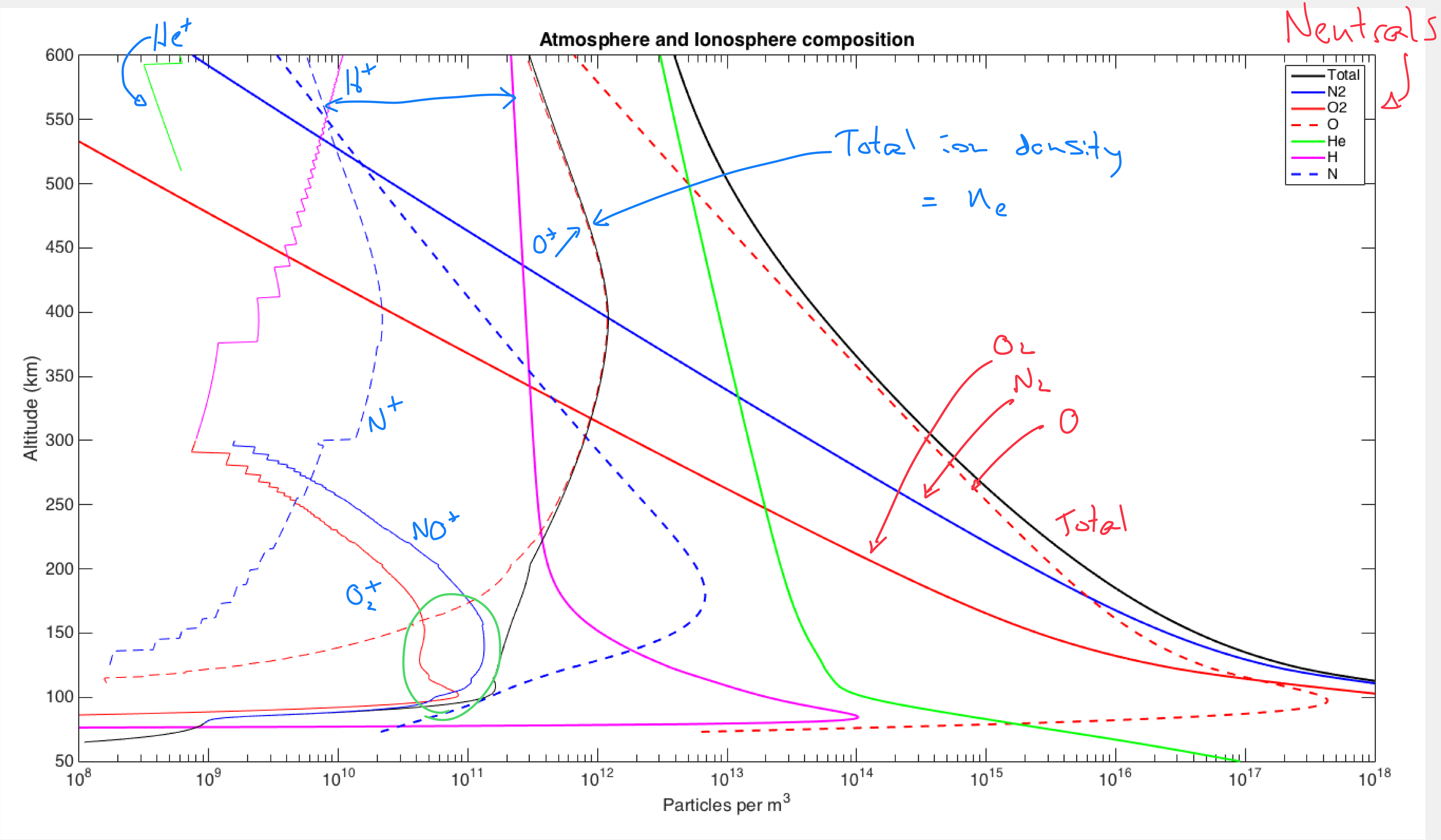


- Ionosphere altitudes and layers have a lot to do with where solar radiation is absorbed!



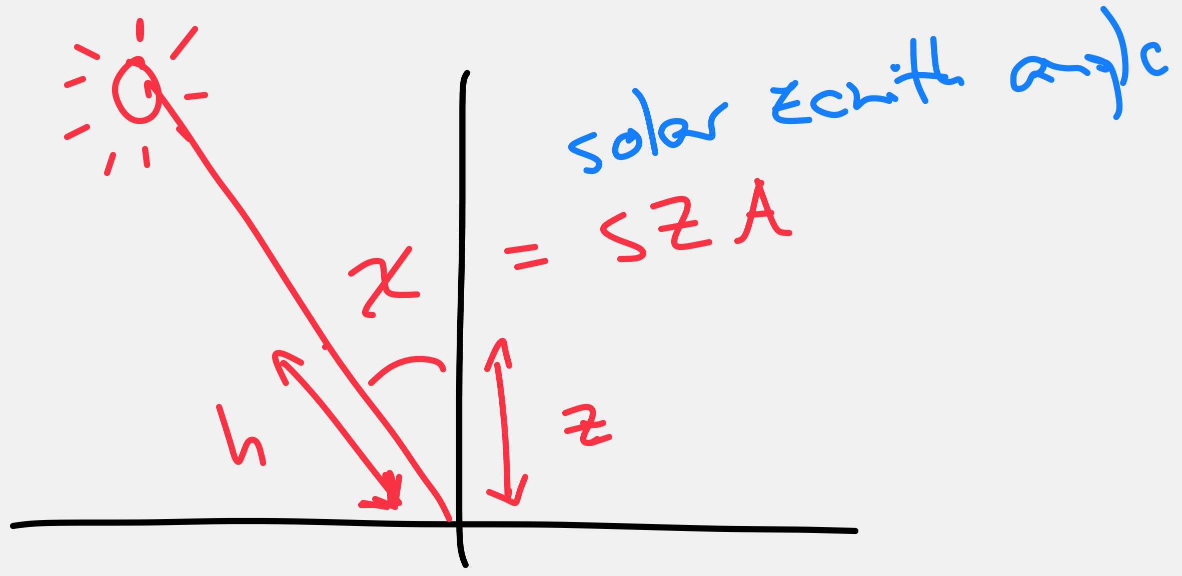
- Right: ionization density changes by 100x day vs night, and 10x or more with solar cycle

Ionosphere Composition and Density



Why does the Ionosphere have a peak at some altitude?

- The atmosphere is exponentially increasing all the way to the ground. What about the ionosphere?



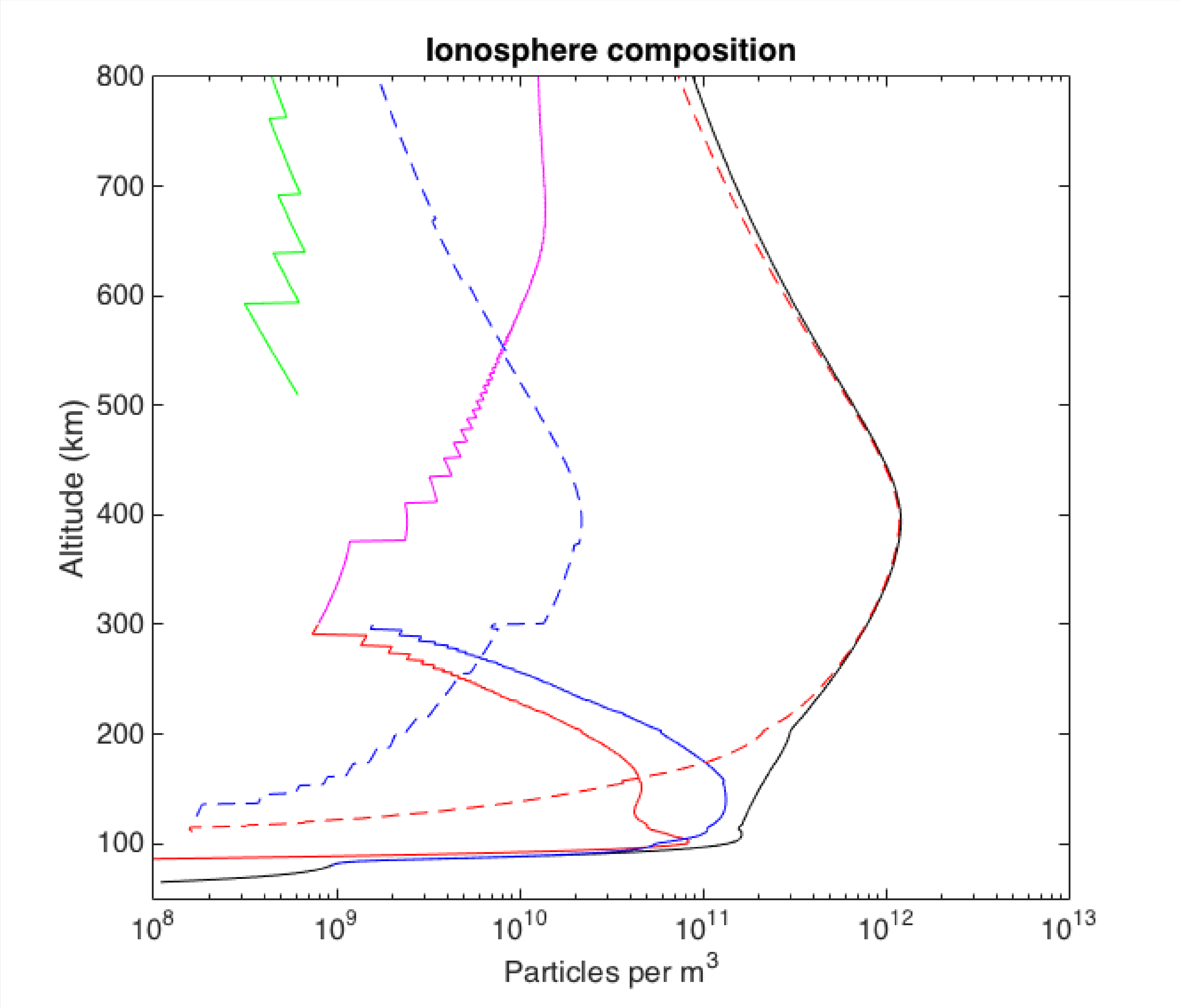
$$dI = -\sigma n(h) I \, dh$$

$$= \sigma n(z) I \, dz \sec\chi$$

$$I(z) = I_\infty e^{-\int_\infty^z n(z)\sigma \sec\chi \, dz}$$

$$\text{if } n(z) = n_0 e^{-z/H}$$

$$I(z) = I_\infty e^{-Hn(z)\sigma\sec\chi}$$



$$I(z,\lambda,\chi) = I_\infty(\lambda) \exp\left[-\int_\infty^z \sum_s n_s(z)\sigma_s(\lambda)\sec\chi \, dz\right]$$

$$= I_\infty(\lambda) e^{-\tau(z,\lambda,\chi)}$$

Chapman Layer

Ionization Production Rate, P (Q), pairs/m³/sec

$$P = I(z, \lambda, \chi) \cdot n(z) \cdot \sigma \cdot \eta_i$$

η_i: ionization efficiency, 0 – 1

σ_i (cm²), ioniz. cross section

$$P = I_\infty e^{-Hn(z)\sigma \sec\chi} \cdot \sigma \eta_i \, n(z)$$

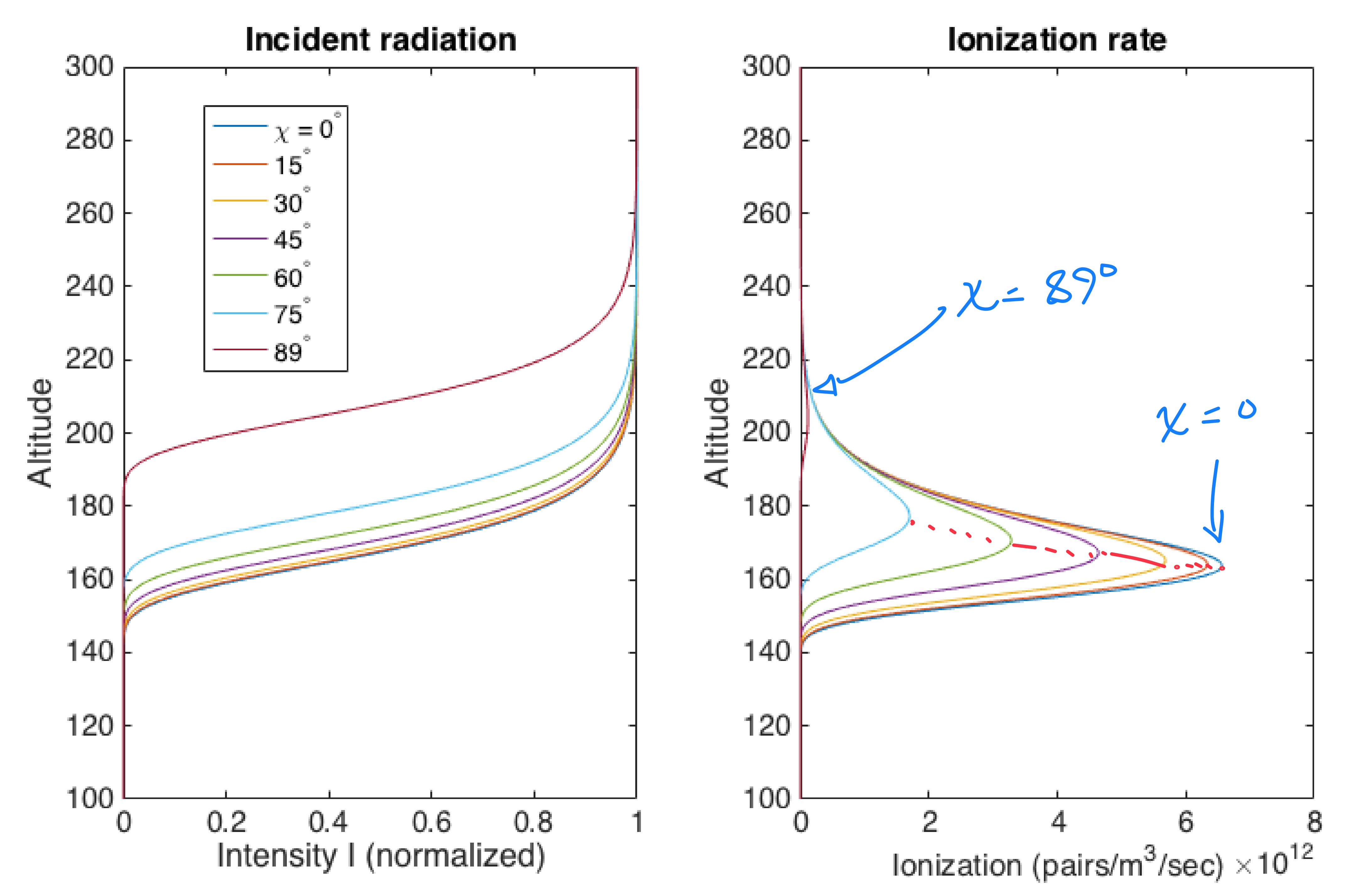
$n(z) = n_0 e^{-z/H}$

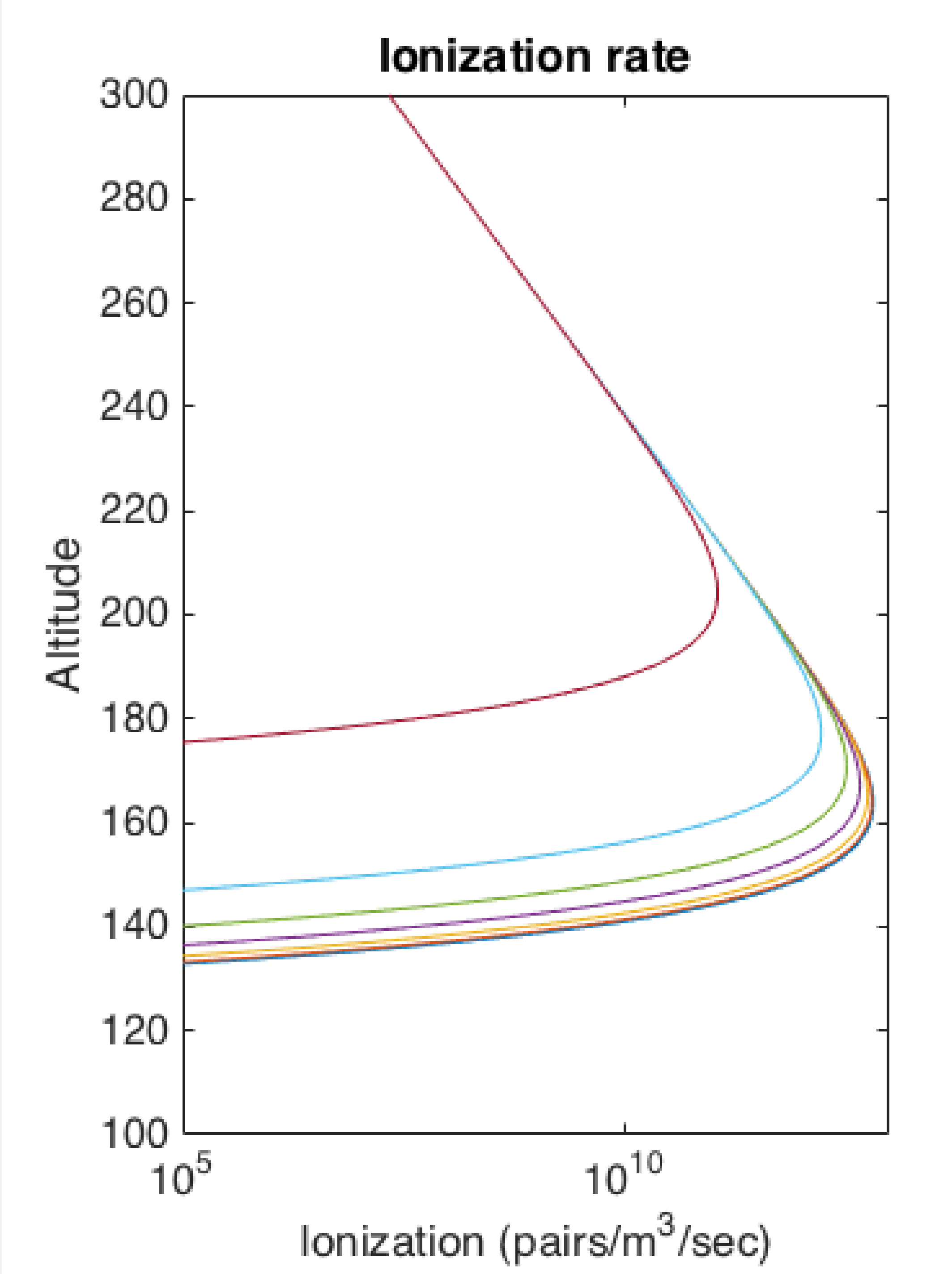
$$P = I_\infty \sigma \eta_i n_0 e^{-z/H} \exp\left(-H\sigma \sec\chi \, n_0 e^{-z/H}\right)$$

Chapman Layer

- Production higher, and lower in altitude, for lower zenith angle (i.e. noon)
- Peak in production is near where intensity is about **half** the incident value

$$z_{max} = H \ln(n_0 \sigma H \sec \chi) \qquad P_{max} = \eta_i \frac{I_\infty}{H} \cos\chi \, e^{-1}$$





Ionospheric Chemistry

- Ionosphere is in equilibrium when ionization production and loss mechanisms balance
  - Production: **photoionization**; energetic particle precipitation; collisions
  - Loss: **recombination**; charge exchange; chemistry ; transport

$$\frac{dn_e}{dt} = P - L$$

$P: \quad O + \gamma \rightarrow O^+ + e^-$

$L: \quad O^+ + e^- \xrightarrow{\alpha} O + \gamma$

at equilibrium, $\frac{dn_e}{dt} = 0$, $P = L$

$$L = \alpha n_{O^+} n_e = \alpha n_e^2$$

$$P = L \Rightarrow P = \alpha n_e^2 \Rightarrow n_e = \sqrt{\frac{P}{\alpha}}$$

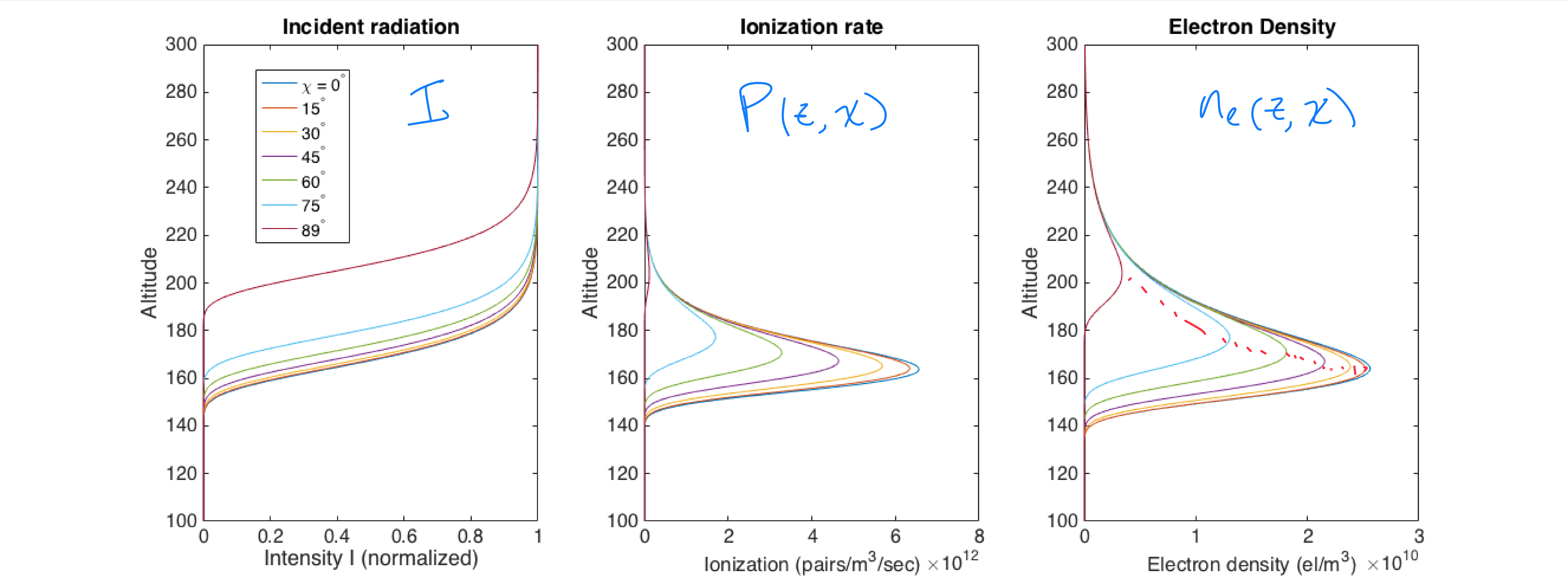
Electron Density Profile

- Balancing production (ionization) with loss (recombination), we get an equilibrium electron (or ion) density below

$$n_e = \sqrt{\frac{P}{\alpha}} = \sqrt{\frac{P_{max}}{\alpha}} \exp\left(0.5\left(1 - z_1 - e^{-z_1}\right)\right)$$

- Higher, less dense for increasing zenith angle
  - Reminder: this is for a single species, and single photon wavelength!

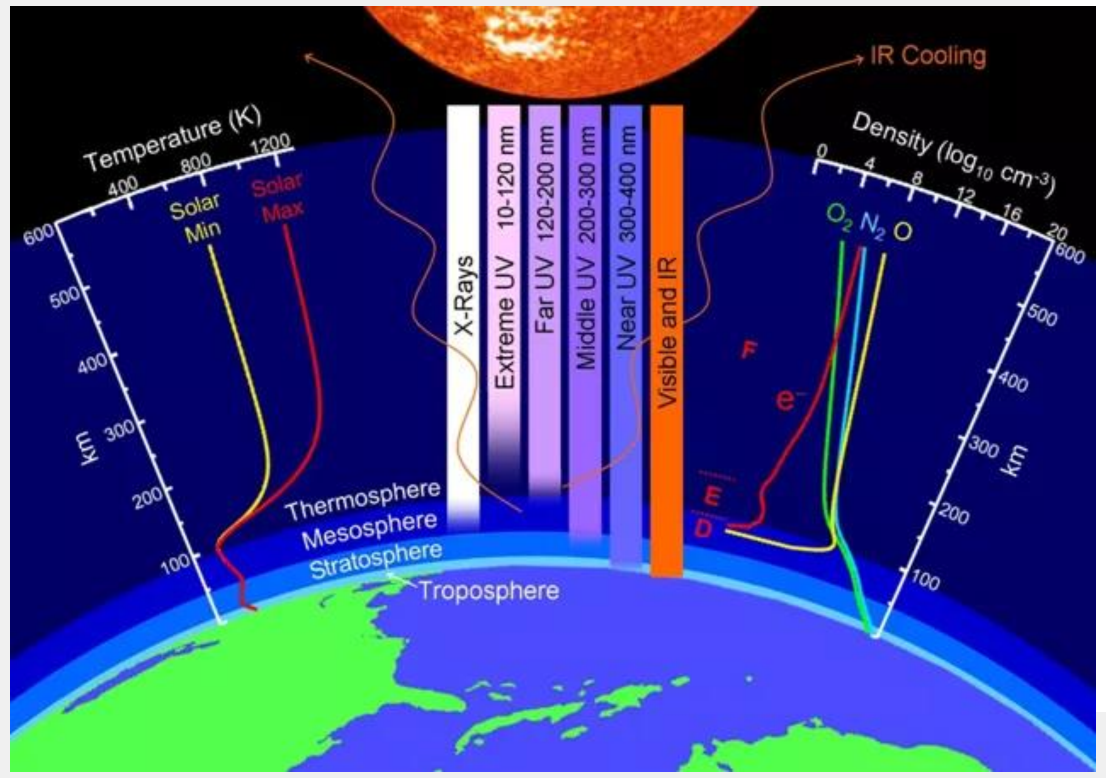
$$z_1 = \frac{z - z_{max}}{H}$$

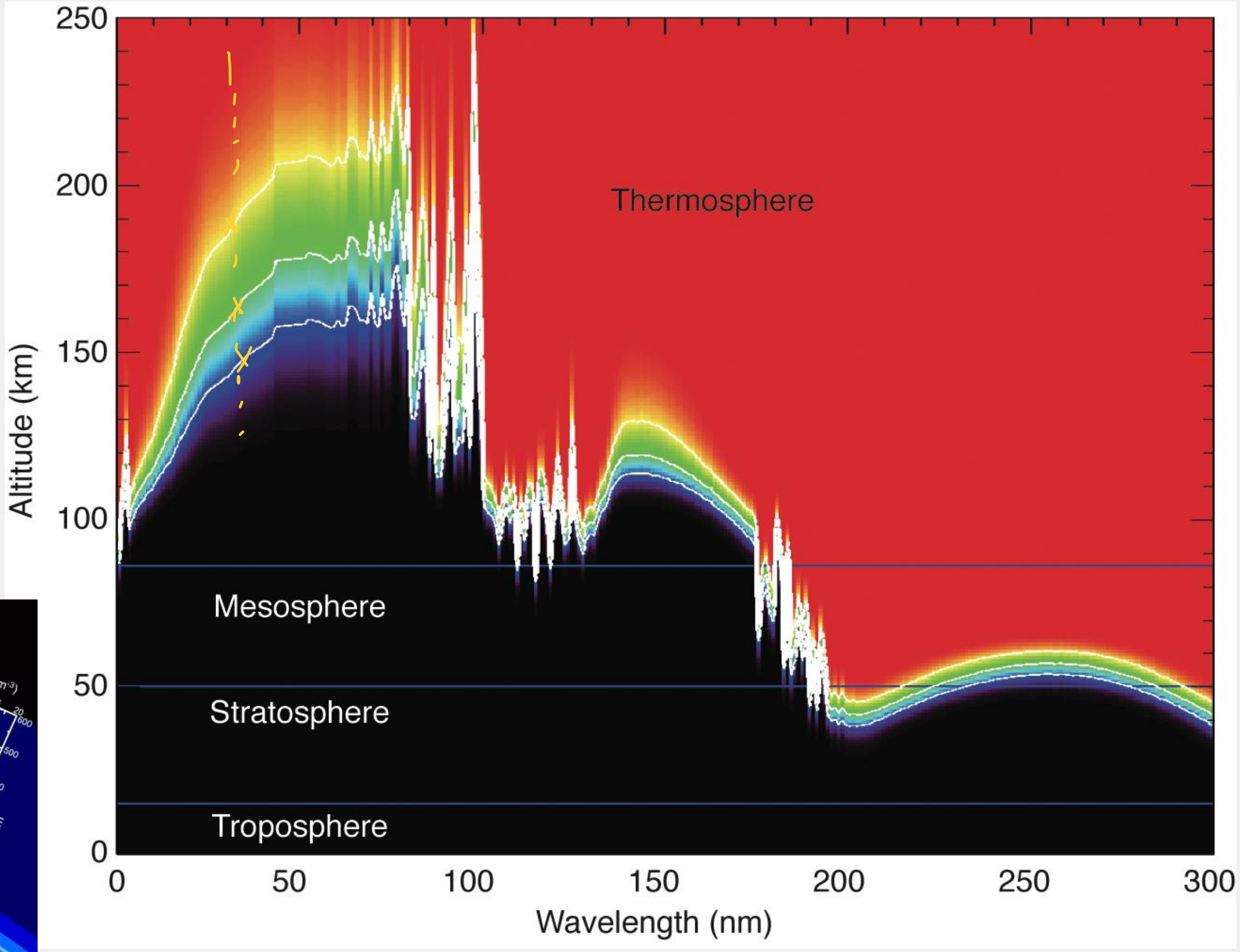


Ionosphere Layers

- Different wavelengths are absorbed at different altitudes, by different species
- I(z) depends on wavelength-dependent absorption for each species
- P(z) depends on wavelength-dependent ionization cross sections for each species

- Right: top white curve is I(z) decay by $e^{-0.5}$;
  middle white curve by e^{-1};
  bottom white curve by $e^{-1.5}$
- Red areas: I(z) is basically I_∞
  Black areas: I(z) is basically zero





Primary Production / Loss channels

$O + \gamma \rightarrow O^+ + e^-$

$O_2 + \gamma \rightarrow O_2^+ + e^-$

$N_2 + \gamma \rightarrow N_2^+ + e^-$

Charge Transfer

$O_2 + O^+ \rightarrow O_2^+ + O$

$N_2 + O^+ \rightarrow N_2^+ + N$

$N_2^+ + O \xrightarrow{k} NO^+ + N \rightarrow$ fast

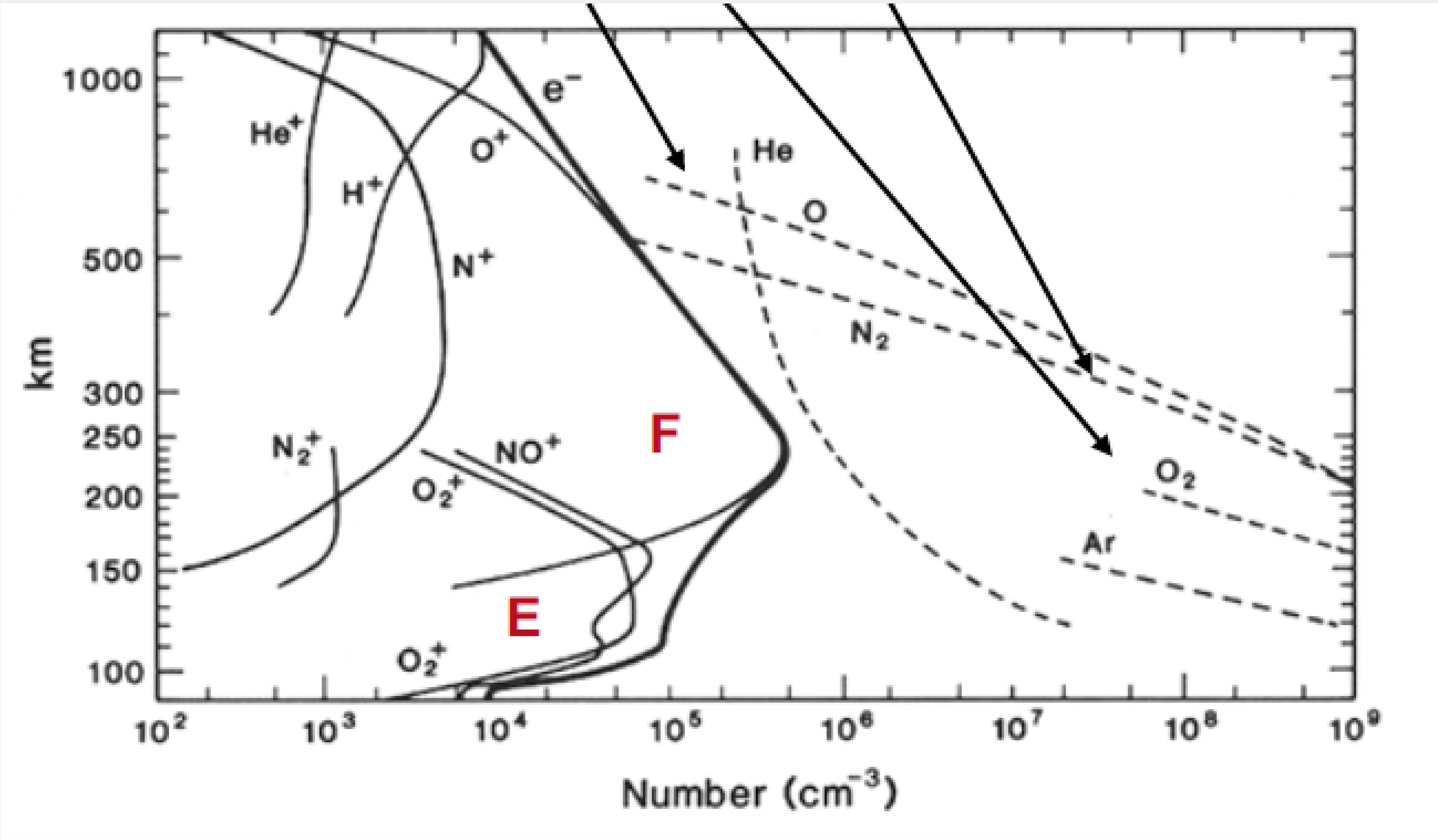
Recombination

$O_2^+ + e^- \rightarrow O + O$ fast

$NO^+ + e^- \rightarrow N + O$

$O^+ + e^- \rightarrow O^* \rightarrow O + \gamma$ ↗ 630 nm, 577.7 nm

meta-stable



E-region

Below 150 km, $[O_2] \gg [O]$, so E-region dominated by

$$O_2 + \gamma \rightarrow O_2^+ + e^-$$

$$O_2^+ + e^- \xrightarrow{\alpha} O + O$$

$$L = \alpha n_{O_2^+} n_e \simeq \alpha n_e^2$$

if $P = L$, $n_e = \sqrt{\frac{P}{\alpha}}$

also $N_2 + \gamma \rightarrow N_2^+ + e^-$

$$N_2^+ + O \rightarrow NO^+ + N$$

$$NO^+ + e^- \rightarrow N + O$$

F-region (F1)

$O + \nu \rightarrow O^+ + e^-$ $\lambda < 91.1$ nm

(some N_2 ionization)

$O^+ + e^- \rightarrow O + h\nu$ is very slow; not dominant

instead

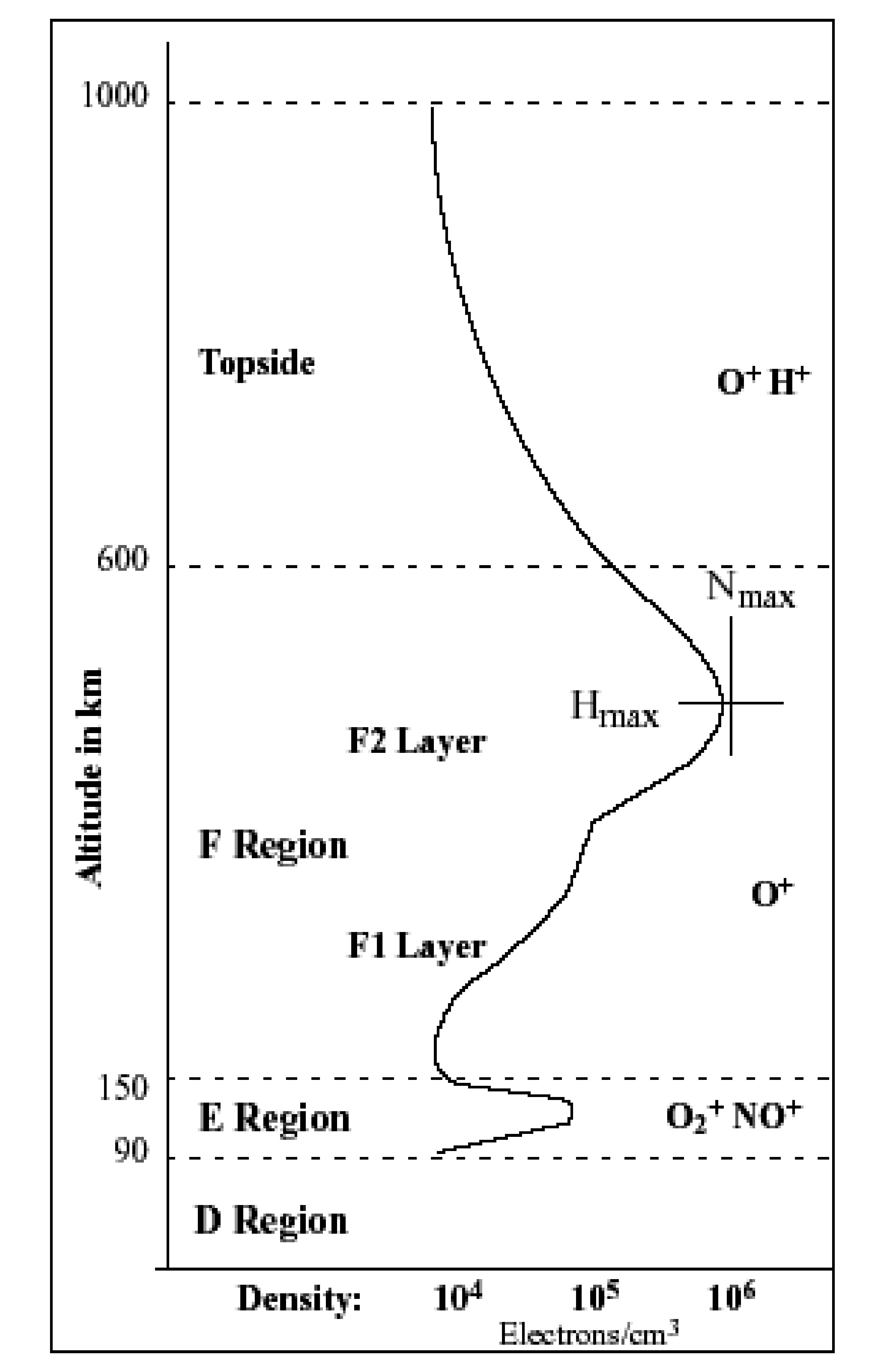
$O^+ + O_2 \rightarrow O_2^+ + O$

$O^+ + N_2 \rightarrow NO^+ + N$

then:

☆ $O_2^+ + e^- \xrightarrow{\alpha_1} O + O$

$NO^+ + e^- \xrightarrow{\alpha_2} N + O$



$L = \alpha_1 n_{O_2^+} n_e + \alpha_2 n_{NO^+} n_e \simeq \alpha' n_e^2 \Rightarrow$ Chapman!

F-region (F2)

$O + h\nu \rightarrow O^+ + e^-$

charge exchange

$O^+ + O_2 \xrightarrow{\alpha_1} O_2^+ + O$

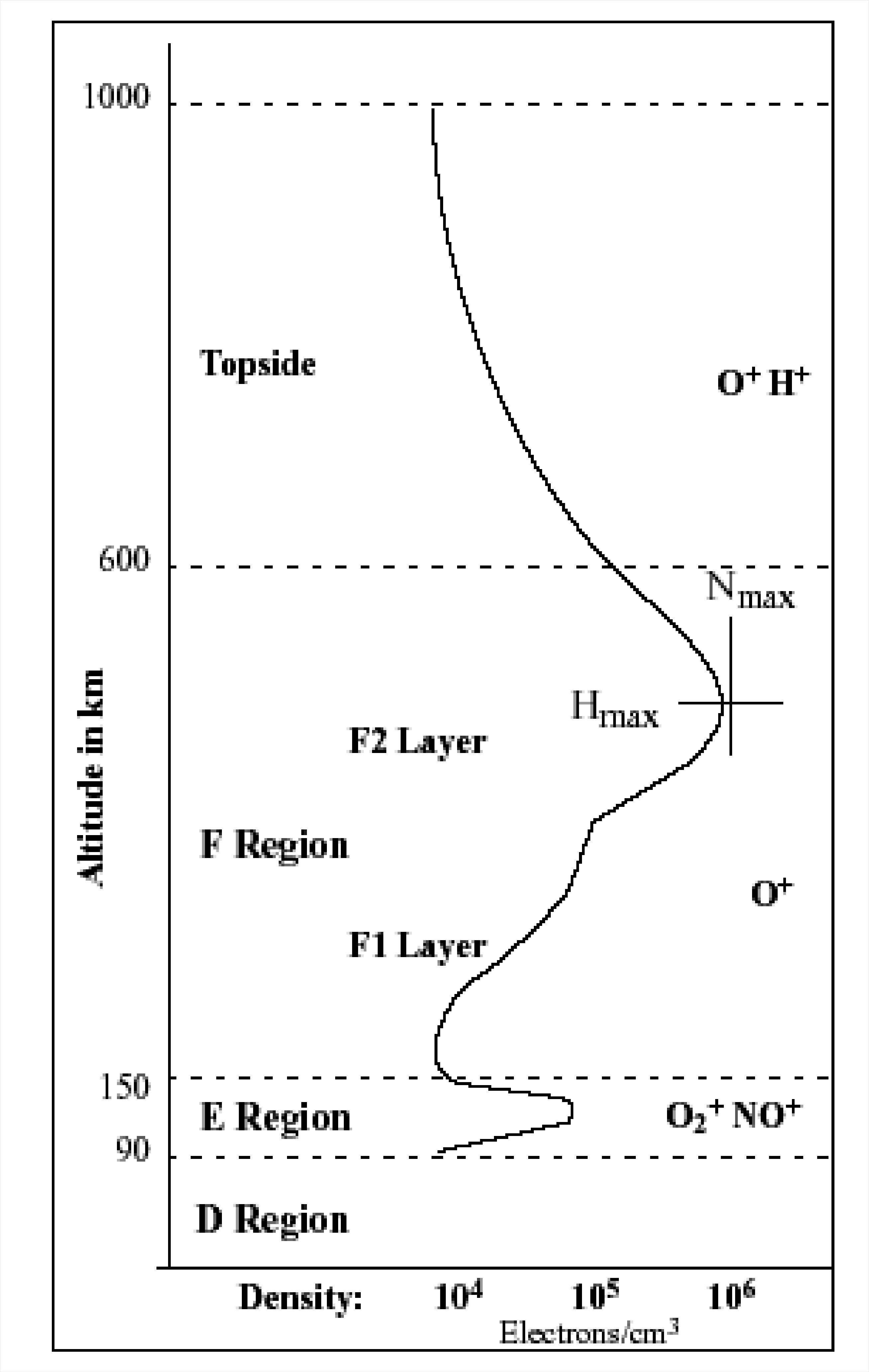
$O^+ + N_2 \rightarrow NO^+ + N$

$\text{Loss} = \alpha_1 n_{O^+} n_{O_2} \simeq \alpha_1 n_{O_2} n_e \neq \alpha n_e^2$

$\neq$

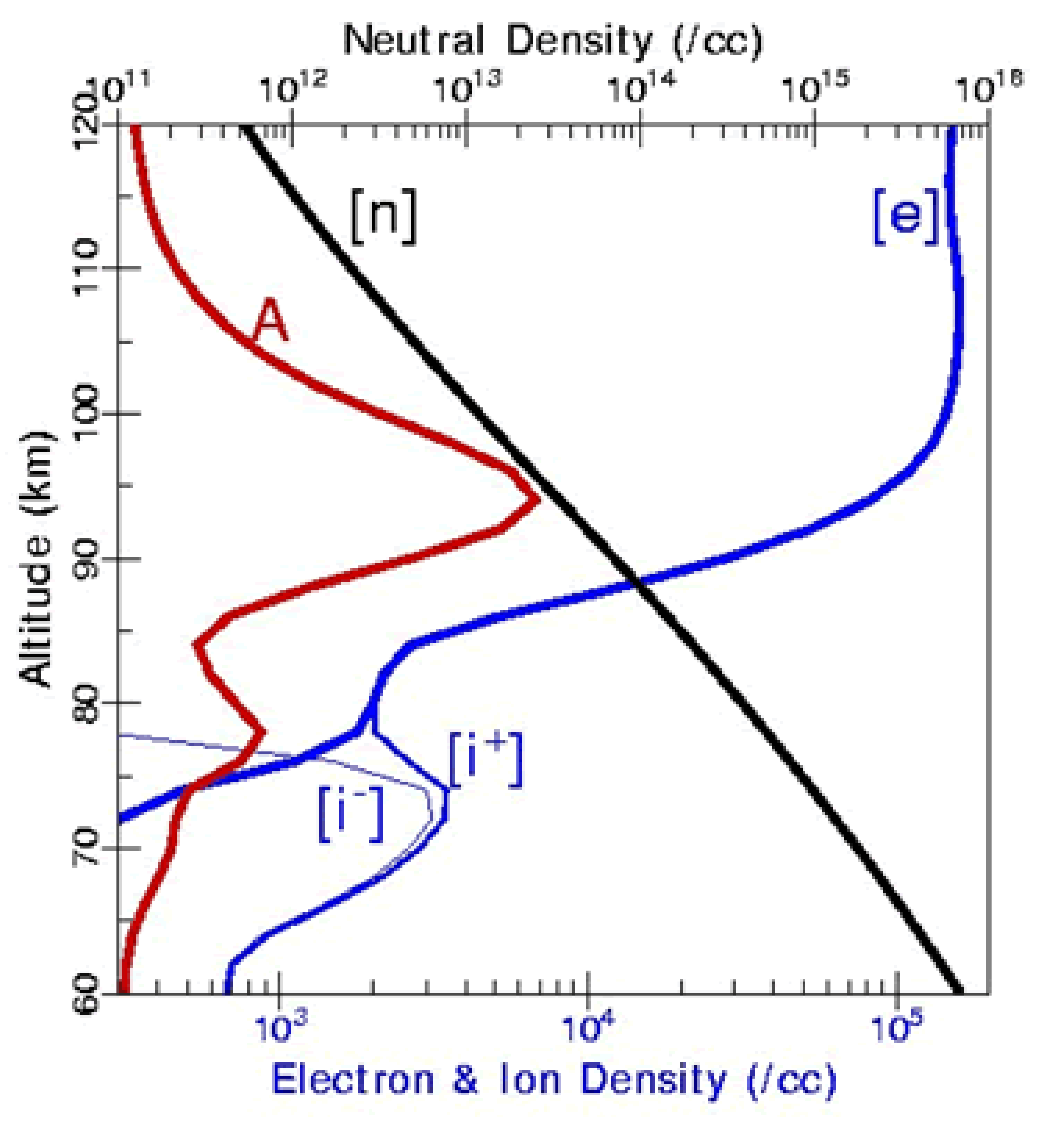
other factors

* dynamics : vertical transport
  - diffusion
* electrostatic forces



D-region

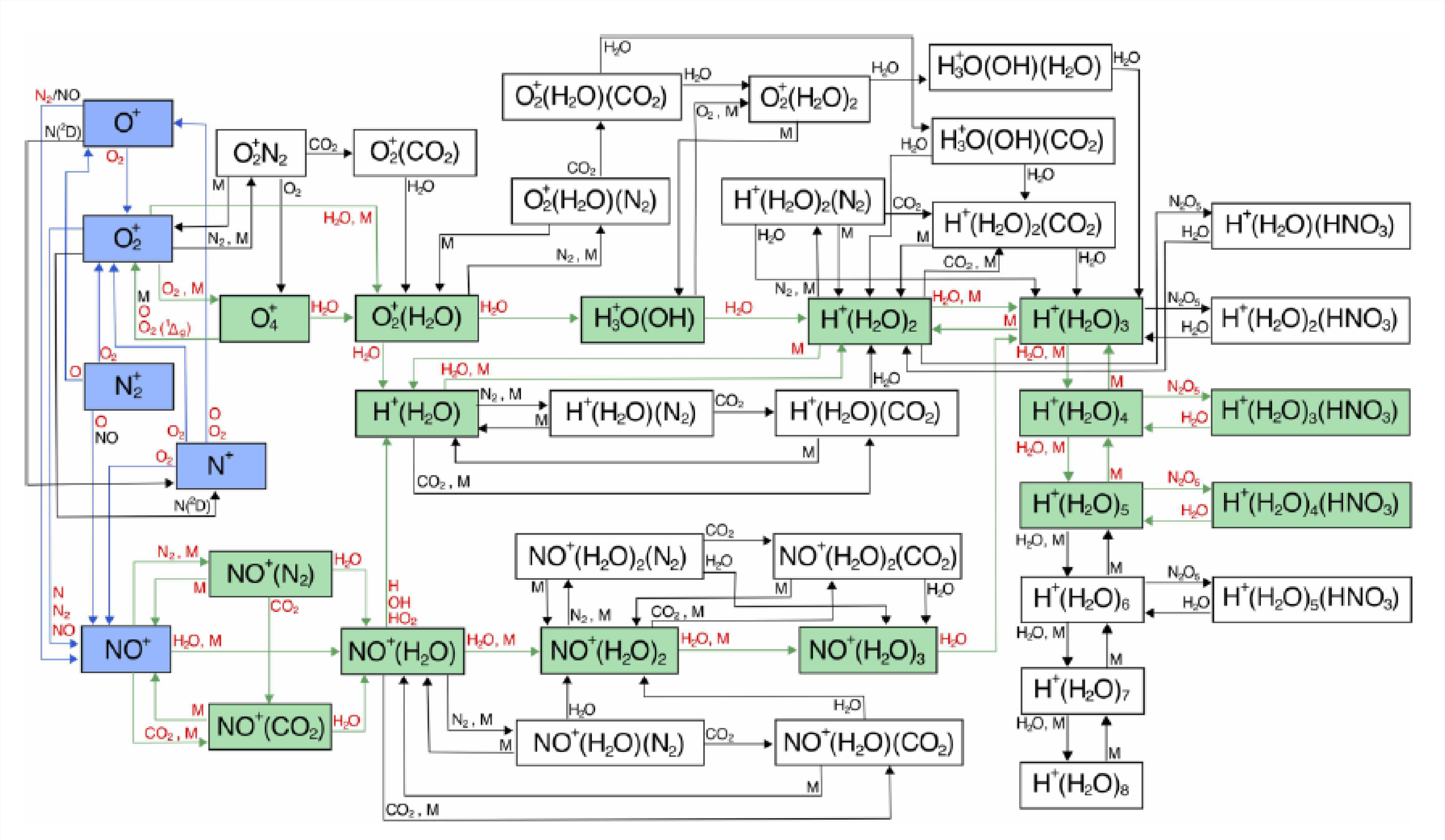
- D-region is known for low electron densities, light and heavy positive and negative ions, and complex chemistry.
- **Production:**
  - $N_2 + \gamma \longrightarrow N_2^+ + e^-$
  - $O_2 + \gamma \longrightarrow O_2^+ + e^-$
  - $NO + \gamma \longrightarrow NO^+ + e^-$
- **Negative ions formed by attachment processes:**
  - $O_2 + e^- + O_2 \longrightarrow O_2^- + O_2$
  - $O_2 + e^- \longrightarrow O_2^- + \gamma$
- **Detachment:**
  - $O_2^- + \gamma \longrightarrow O_2 + e^-$
  - $O_2^- + O_2 \longrightarrow O_2 + e^- + O_2$

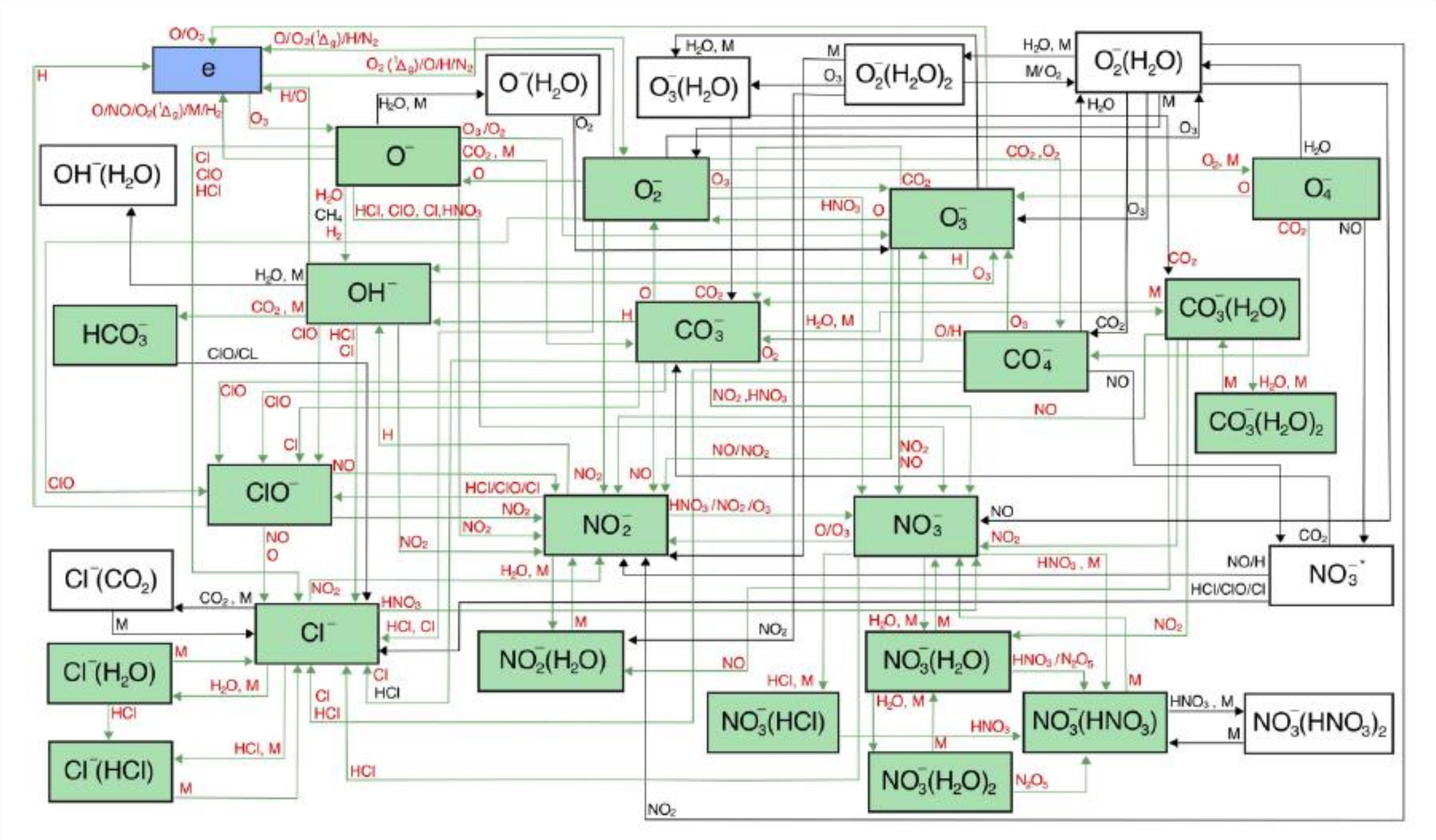


D-region chemistry and "cluster ions"

- D-region also contains heavy water cluster ions of the form $(H_2O)_nH^+$
- Requires more complex chemistry models to evaluate n_e profiles

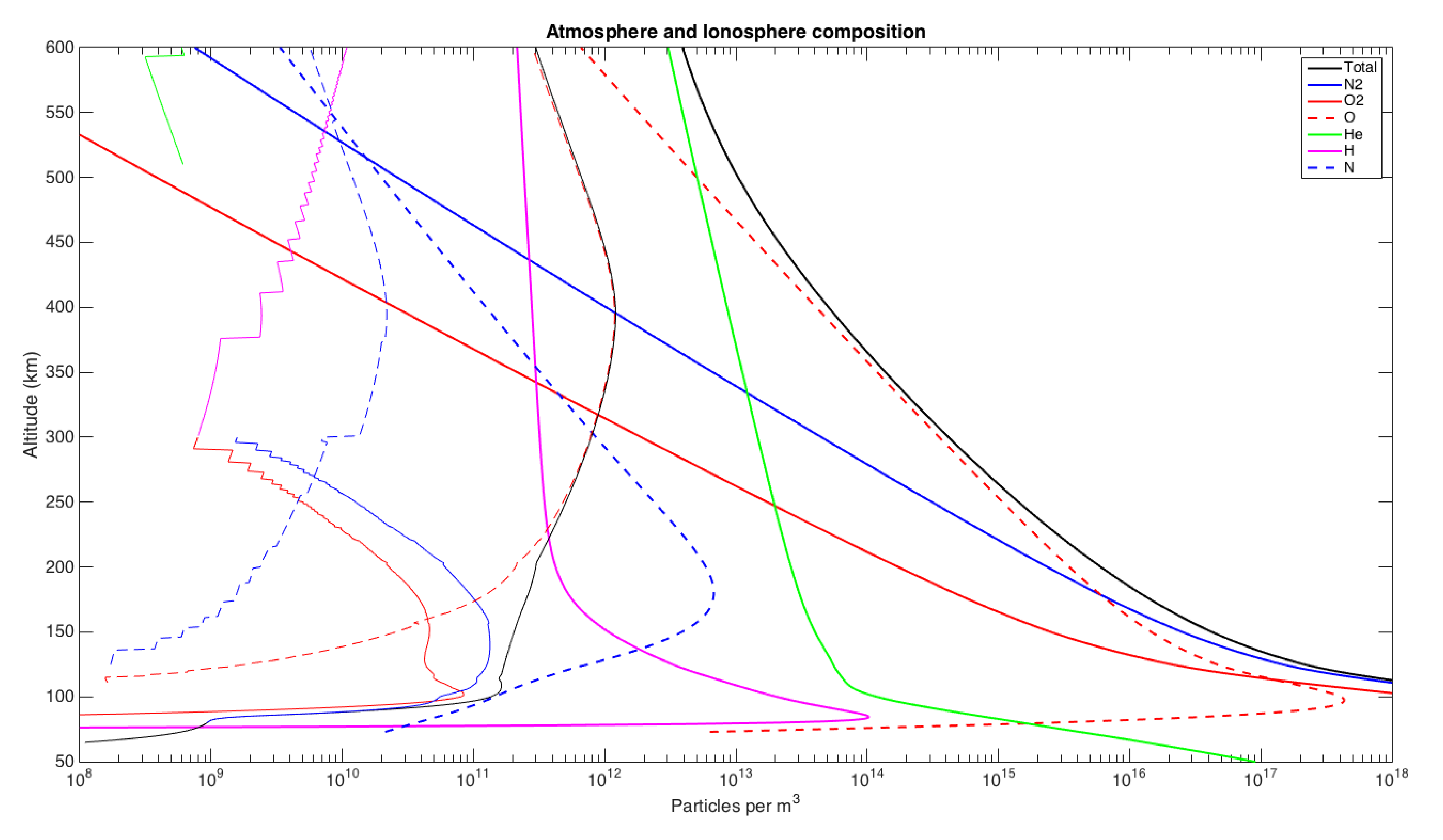
Sodankyla Ion and Neutral Chemistry (SIC) model:

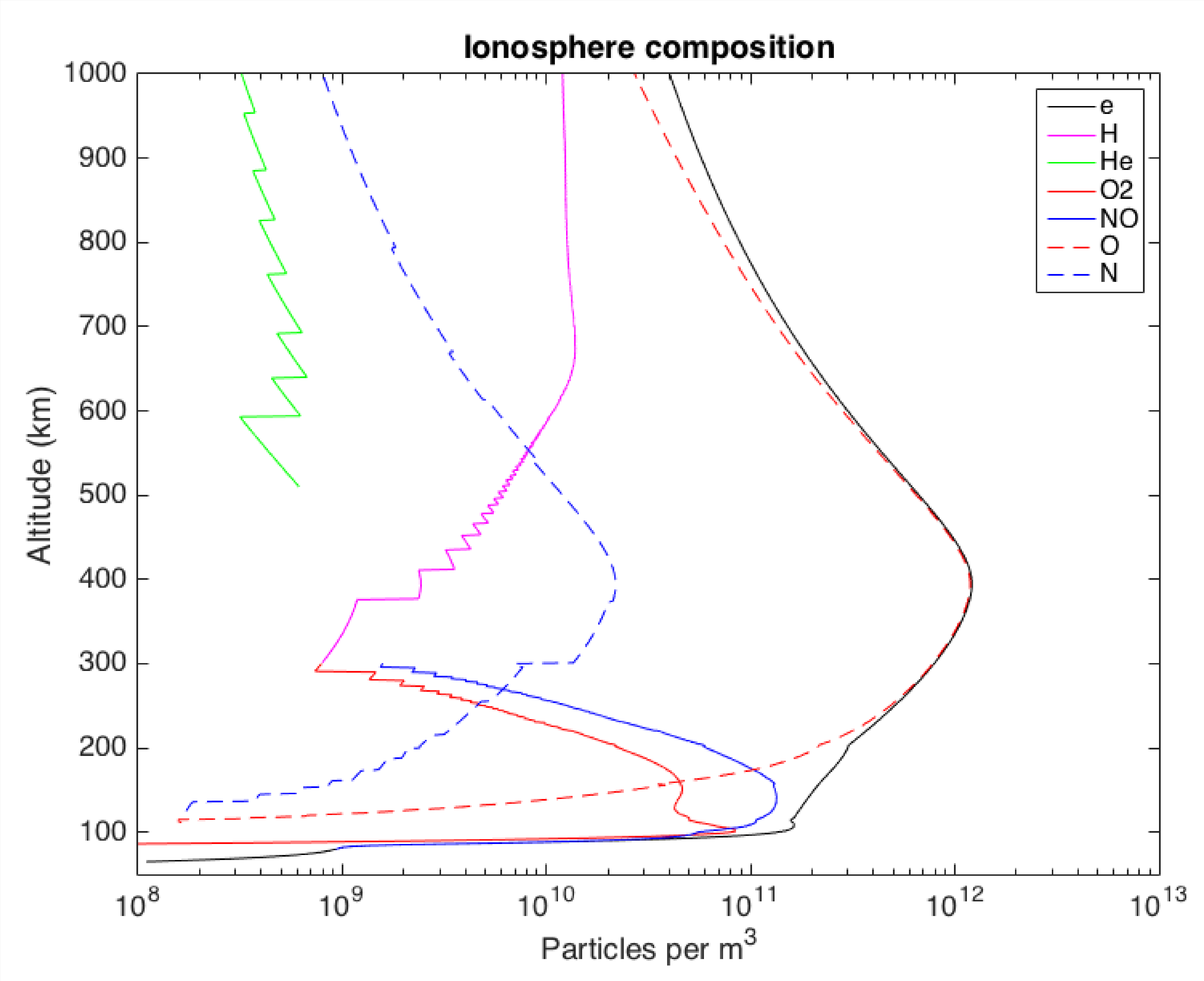




Topside Ionosphere

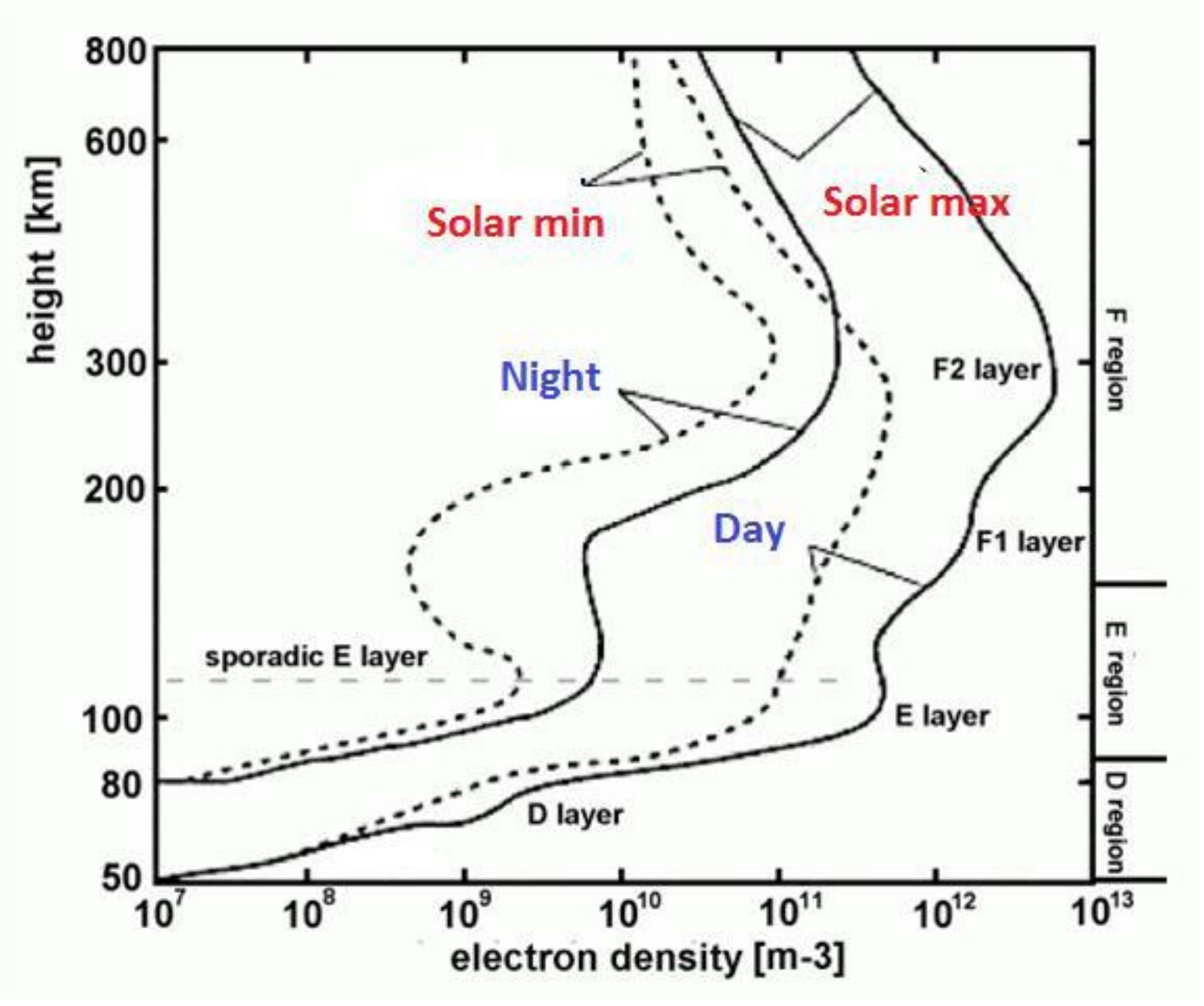
- Above ~350 km, densities are so low that ions are not dominated by chemistry, but **hydrostatic equilibrium**





Summary of Layers

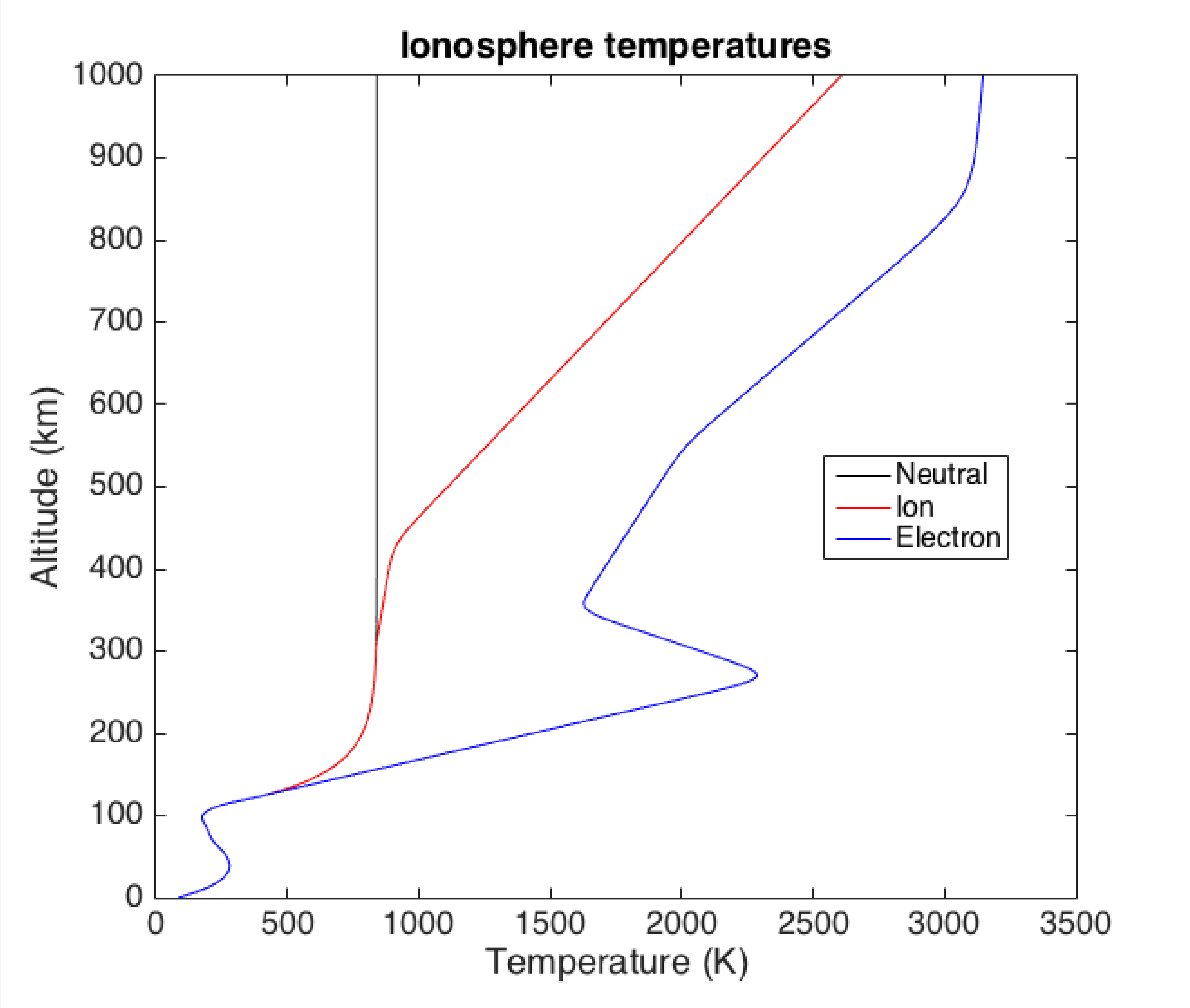
- Layers are dominated by different ions
- Ion densities controlled by balance between production and loss; depends on chemical reactions in each altitude range
- Decay of layers at night depends on recombination rates and densities: low densities at high altitudes mean few collisions



Ionospheric Layer	Altitude Range (km)	Major Constituents	Notable Characteristics
D	70–90	NO+ O_2+ (molecular)	Disappears (recombines) very rapidly−minutes after sundown
E	90–140	O_2+ (molecular) NO+	Recombines rapidly−often disappears before midnight
F1	140–200	O+ (atomic) NO+	Mostly recombines after sundown, but pockets of ionization may remain
F2	200–400	O+ (atomic)	Persistent because of low collision rates, but density decreases after sundown
Topside	> 400	O+ (atomic) H+	Merges into the plasmasphere, atomic oxygen dominates at lower altitudes, and hydrogen dominates at higher altitudes.

Ionosphere Temperatures

- Below 110 km, temperatures are made equal by collisions
- Above ~110 km, collisions are rare, so each species gets its temperature through different heating processes (radiation absorption, convection, etc)
- Above ~110 km: ions, electrons, and neutrals have different temperatures
  - Remember: this simply means they have different velocity / energy distributions



Ionosphere Variability

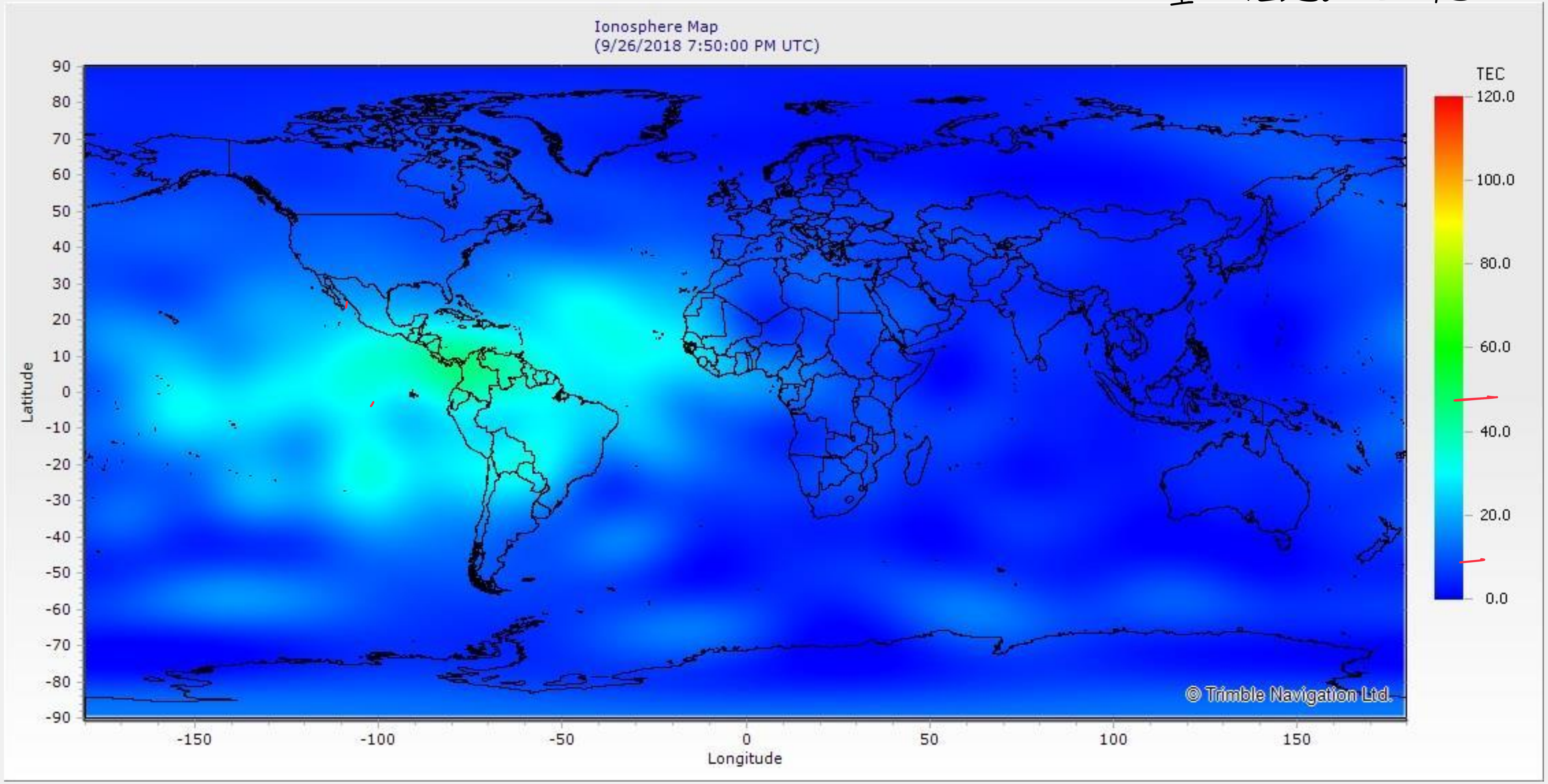
Transport

- **A variety of processes move plasma in the ionosphere:**
  - **Winds**: neutral winds drag ions along with them, if collision frequency is high enough
  - **Drifts**: various forces cause plasma to “drift”:
    - electric and magnetic fields;
    - gravity;
    - pressure; etc.
- **These contribute to complex spatial and temporal variations in the ionosphere**

Global variation: Snapshots

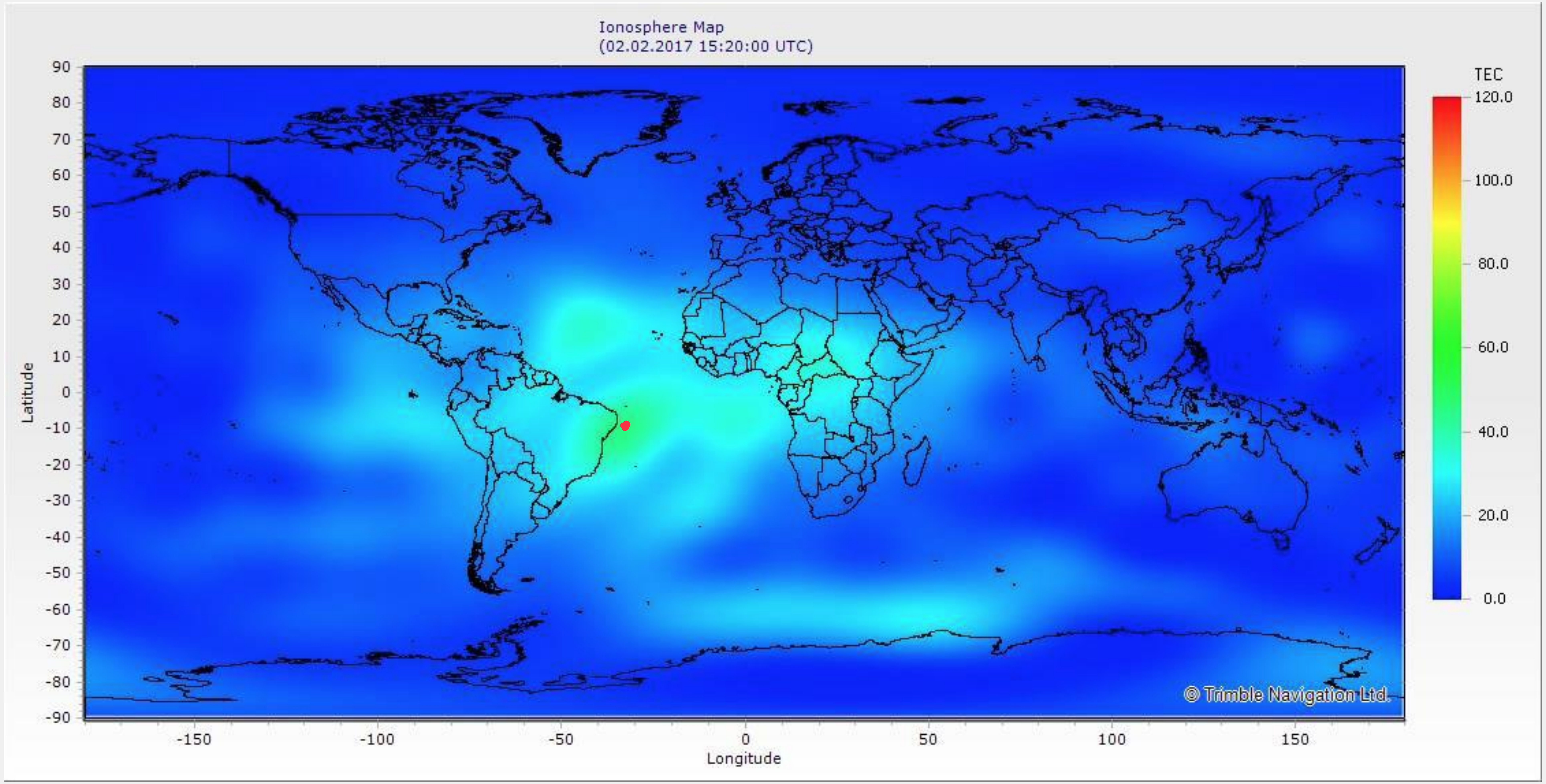
TEC = Total Electron Content = $\int_0^\infty n_e(z)\,dz$, e^-/m^2

$1\ \text{TECU} = 10^{16}\ e^-/m^2$



Global variation: Snapshots

- TEC = Total electron content; integrated in altitude, 1 TECU = 10^{16} el/m^2



foF2 and hmF2

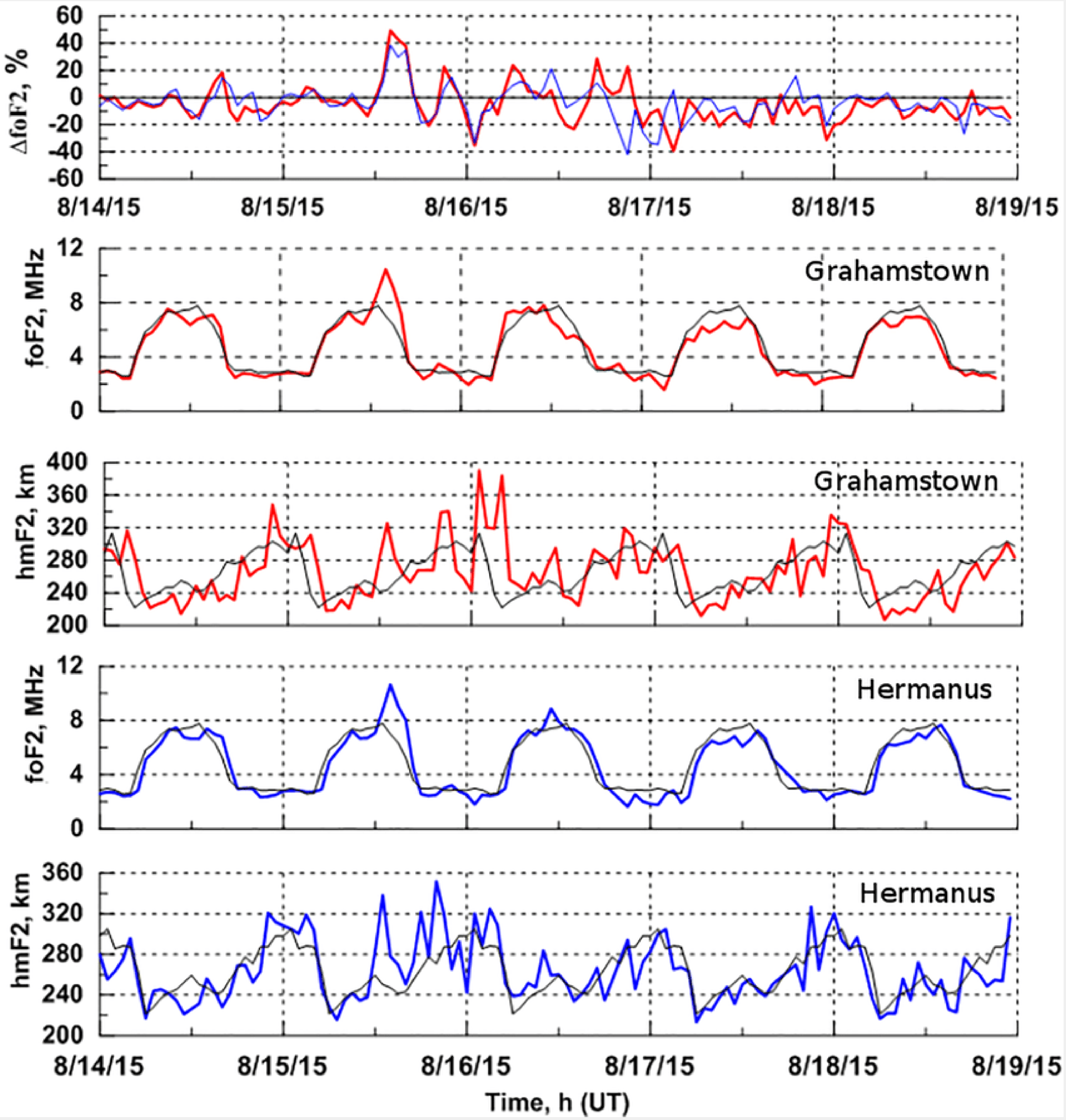
- We often characterize the ionosphere by its peak density, foF2, and the altitude where that occurs, hmF2
- foF2 is a frequency in MHz. related to electron density:

$$\omega_{pe} = \sqrt{\frac{n_e q_e^2}{m_e \epsilon_0}} \sim \sqrt{n_e}$$

(kHz)

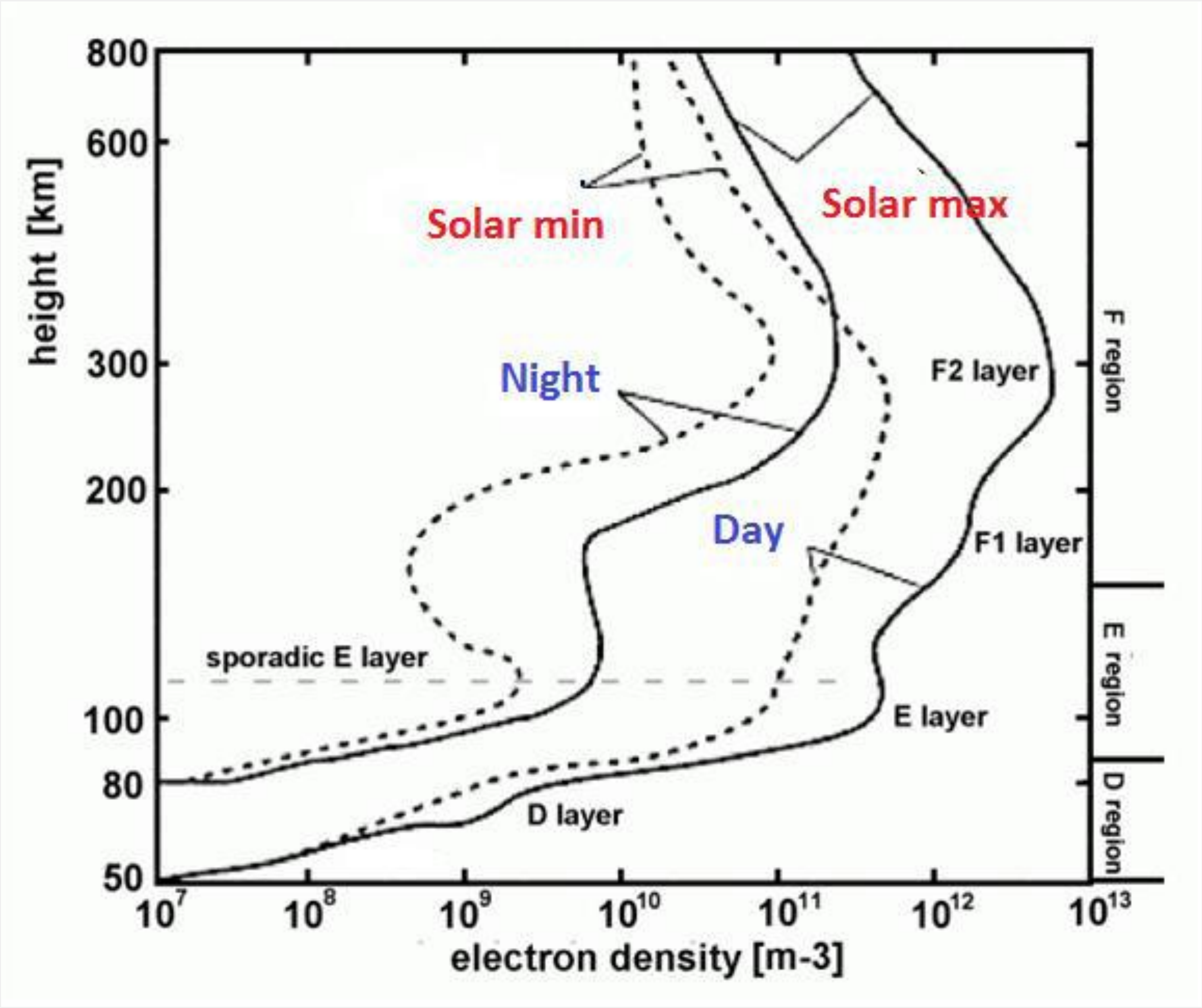
$$f_{pe} = \frac{\omega_{pe}}{2\pi} \simeq 9\sqrt{n_e\,(cm^{-3})}$$

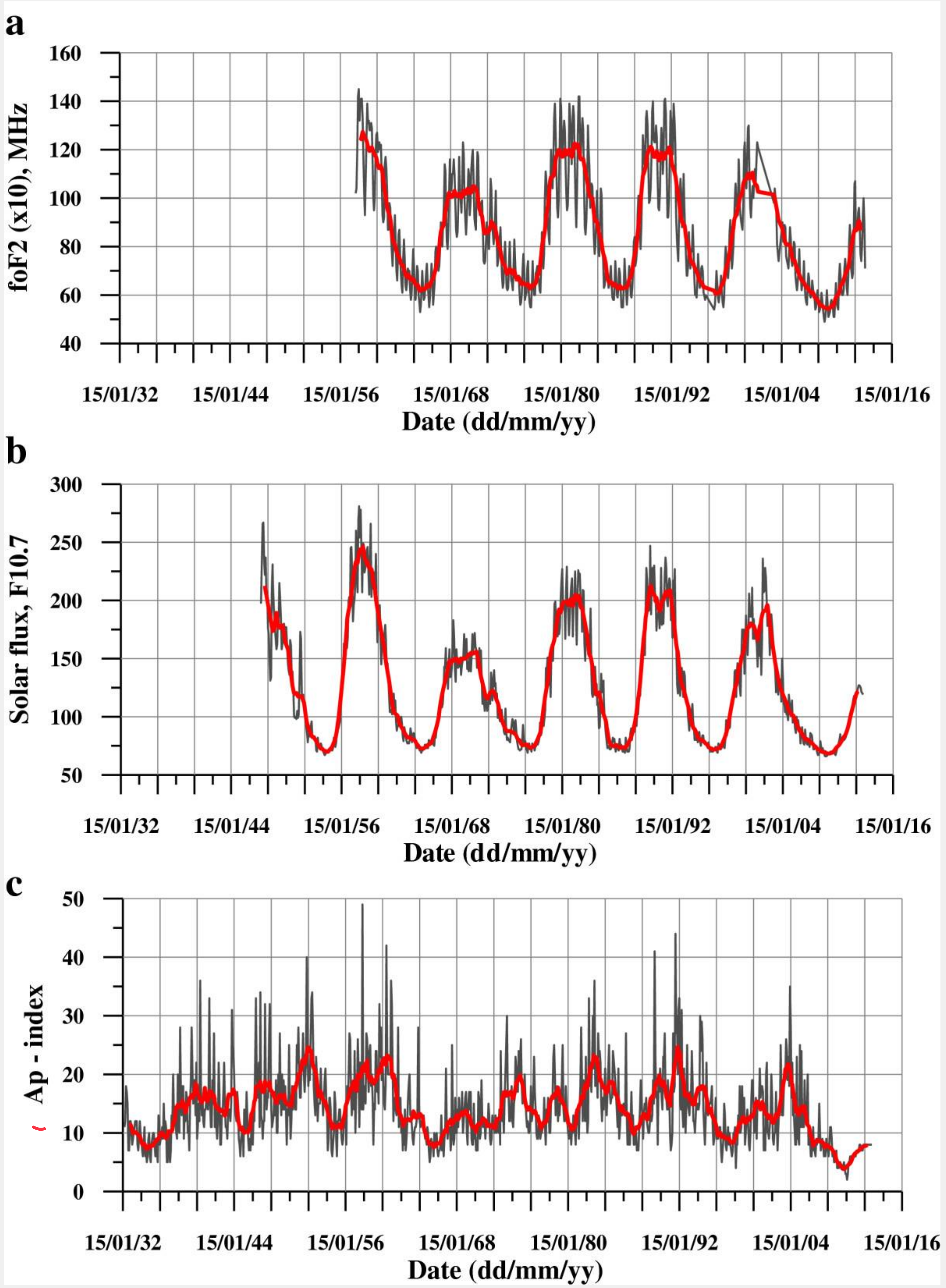
- hmF2 is simply altitude in km



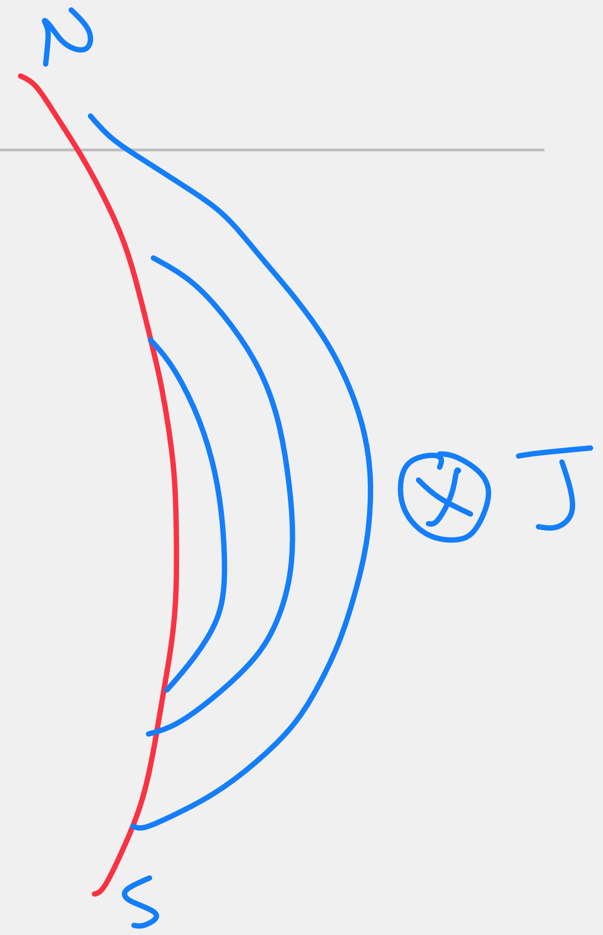
Solar Cycle Variation

- Densities are much higher (order of magnitude) at solar maximum compared to solar minimum
- Higher EUV / X-ray fluxes lead to higher ionization rates



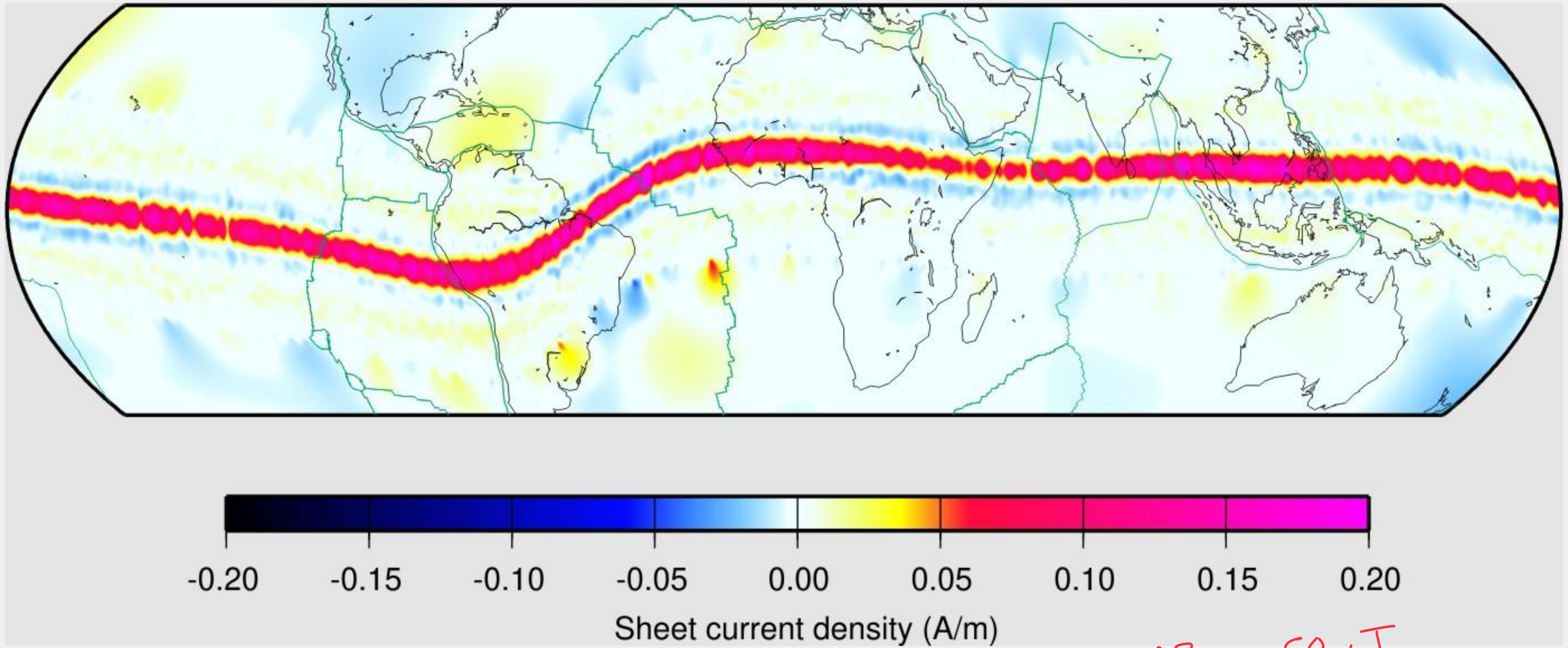


Equatorial Electrojet



$J = \sigma E$

- Plasma physics involving B-field lead to an intense **current** that flows East in the dayside ionosphere
- Restricted to narrow region in latitude; 110-130 km altitude



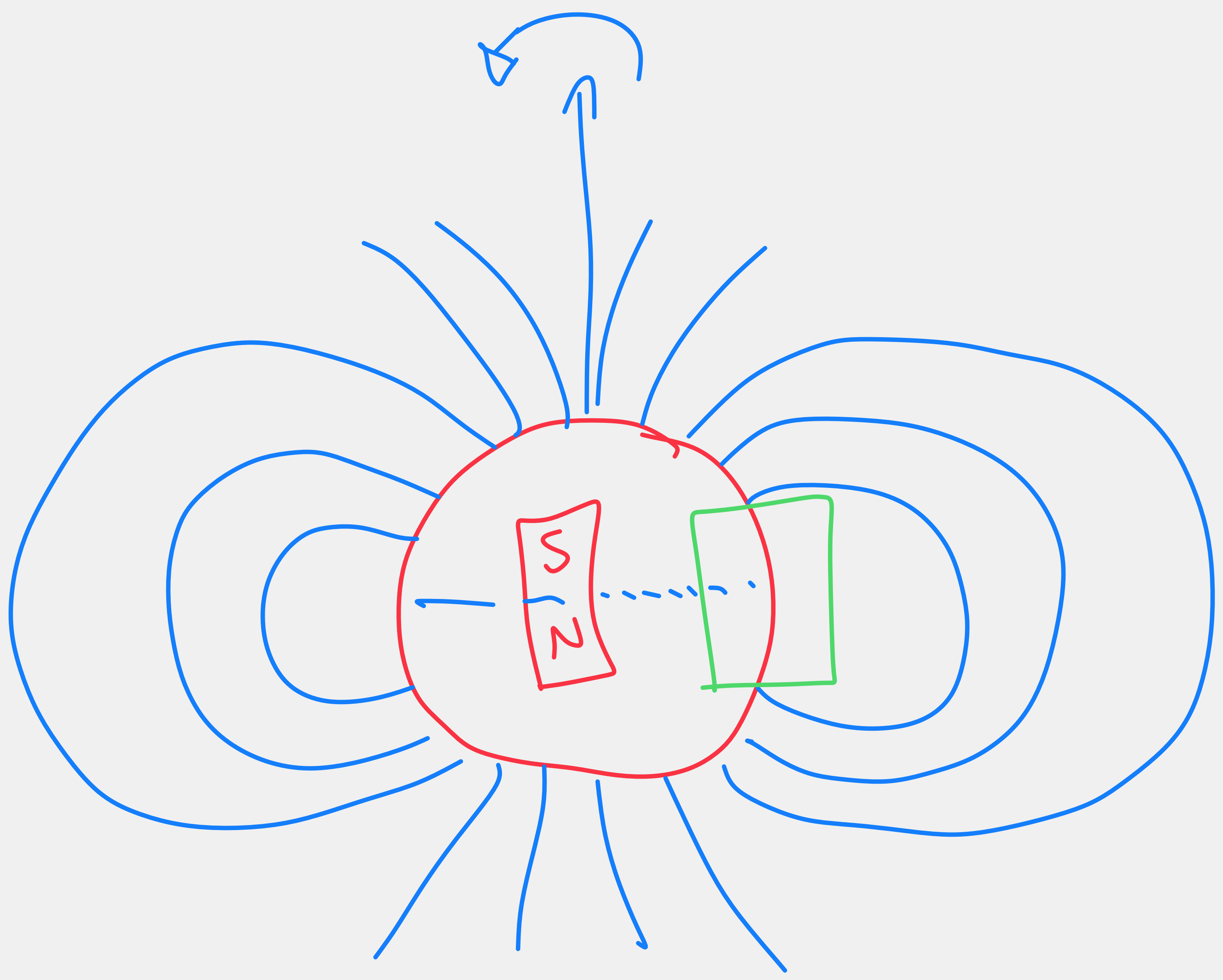
J

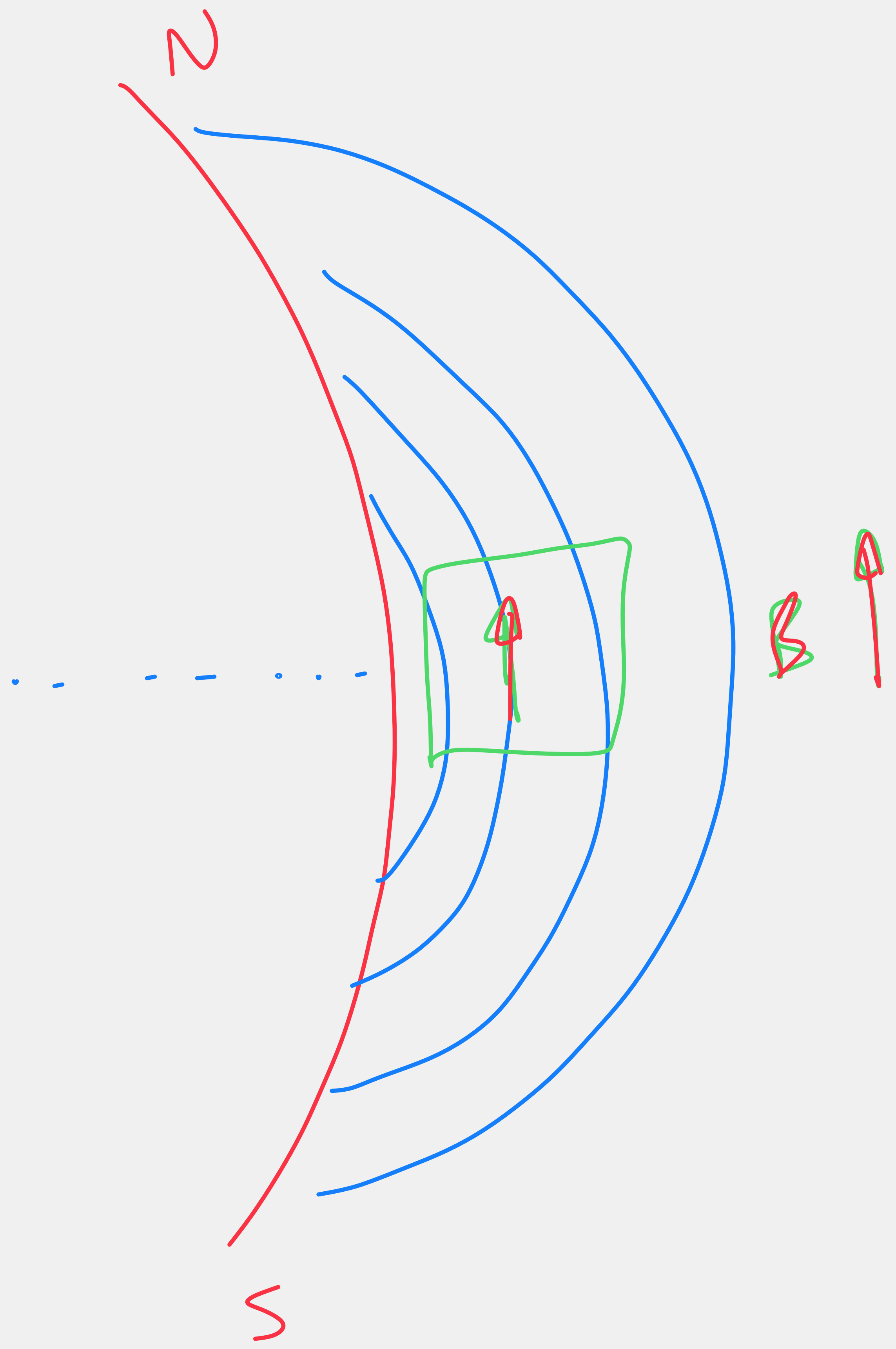
E

~ 100 kA

ΔB ~ 50 nT

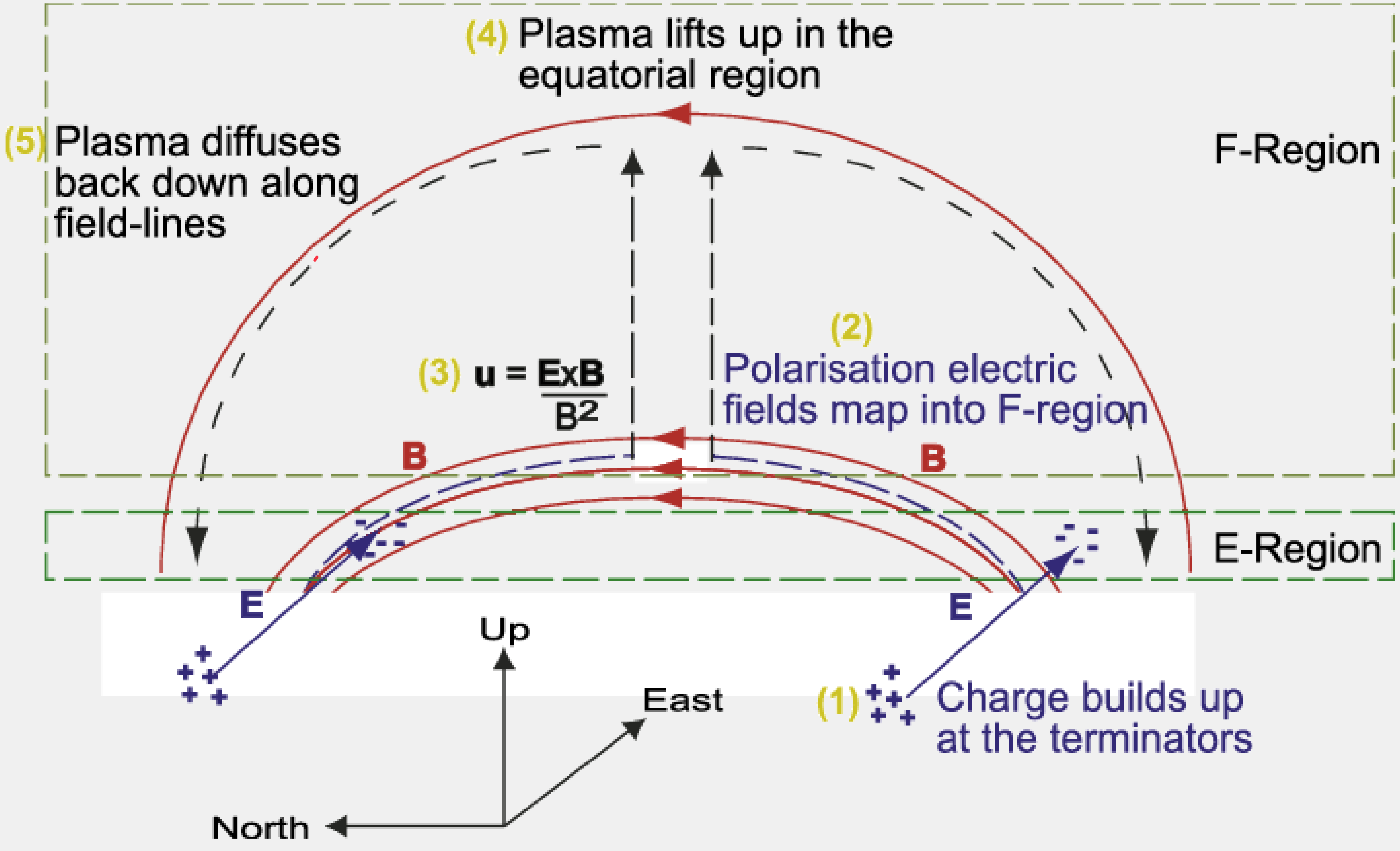
Magnetic field





Equatorial Anomaly

- Due to the EEJ current, an electric field arises
- E x B leads to a **drift** (known as E x B drift) in the vertical direction
- Plasma rises, but then above some altitude, falls back down along field lines
- “Fountain effect”

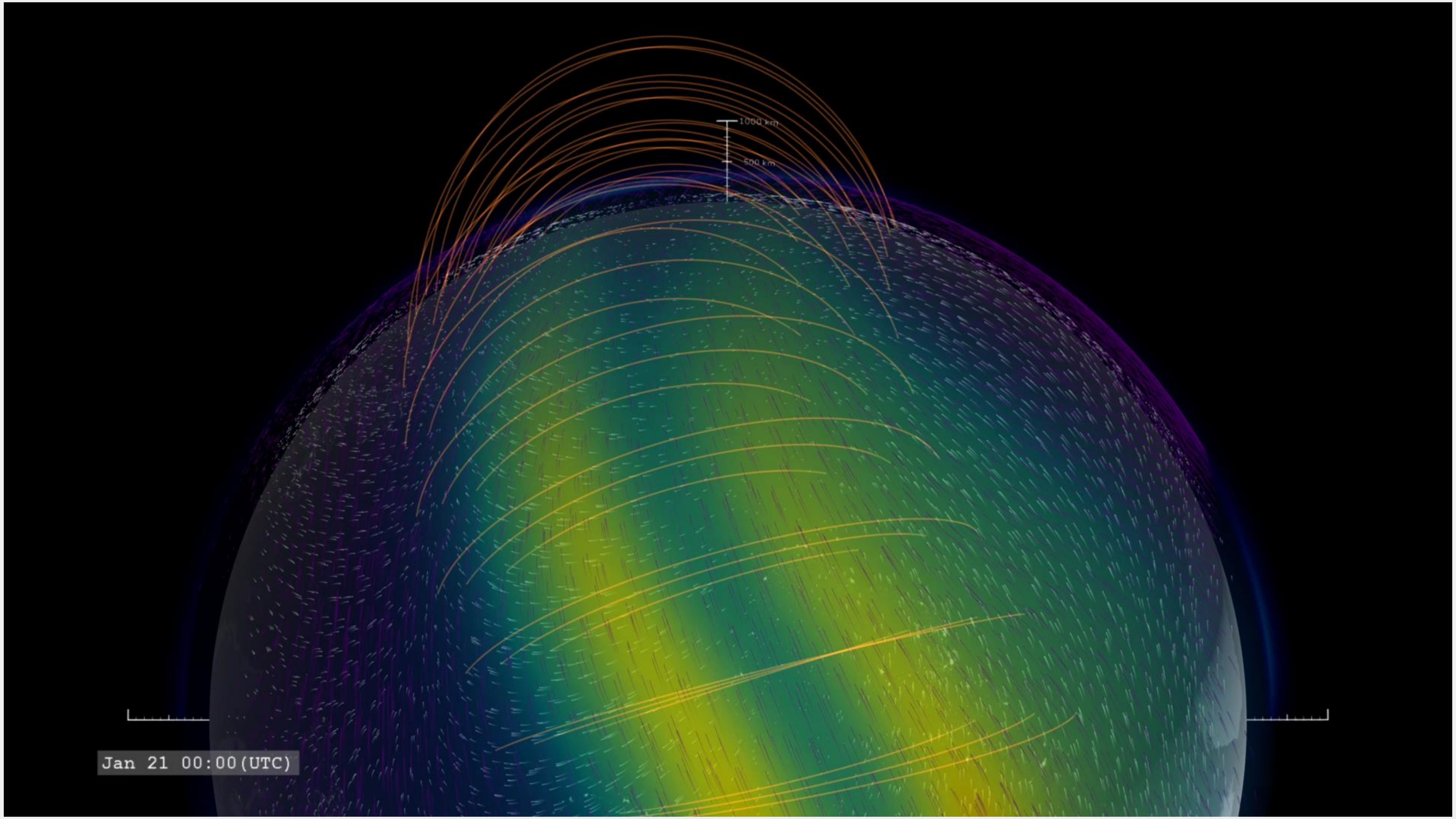


$$\bar{V}_d = \frac{\bar{F} \times \bar{B}}{qB^2}$$

$$\bar{F} = q\bar{E}$$

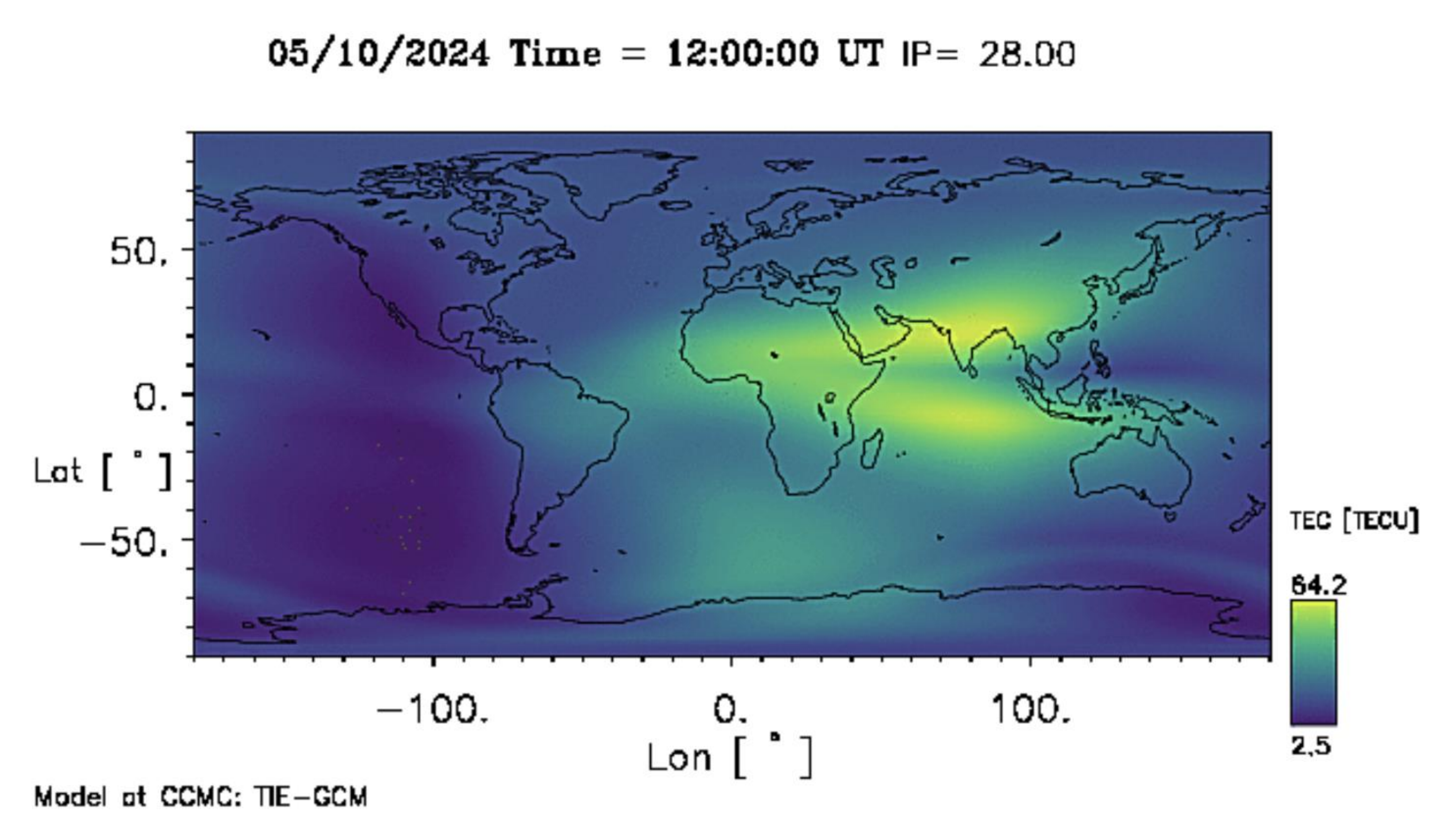
$$\bar{V}_d = \frac{\bar{E} \times \bar{B}}{B^2}$$

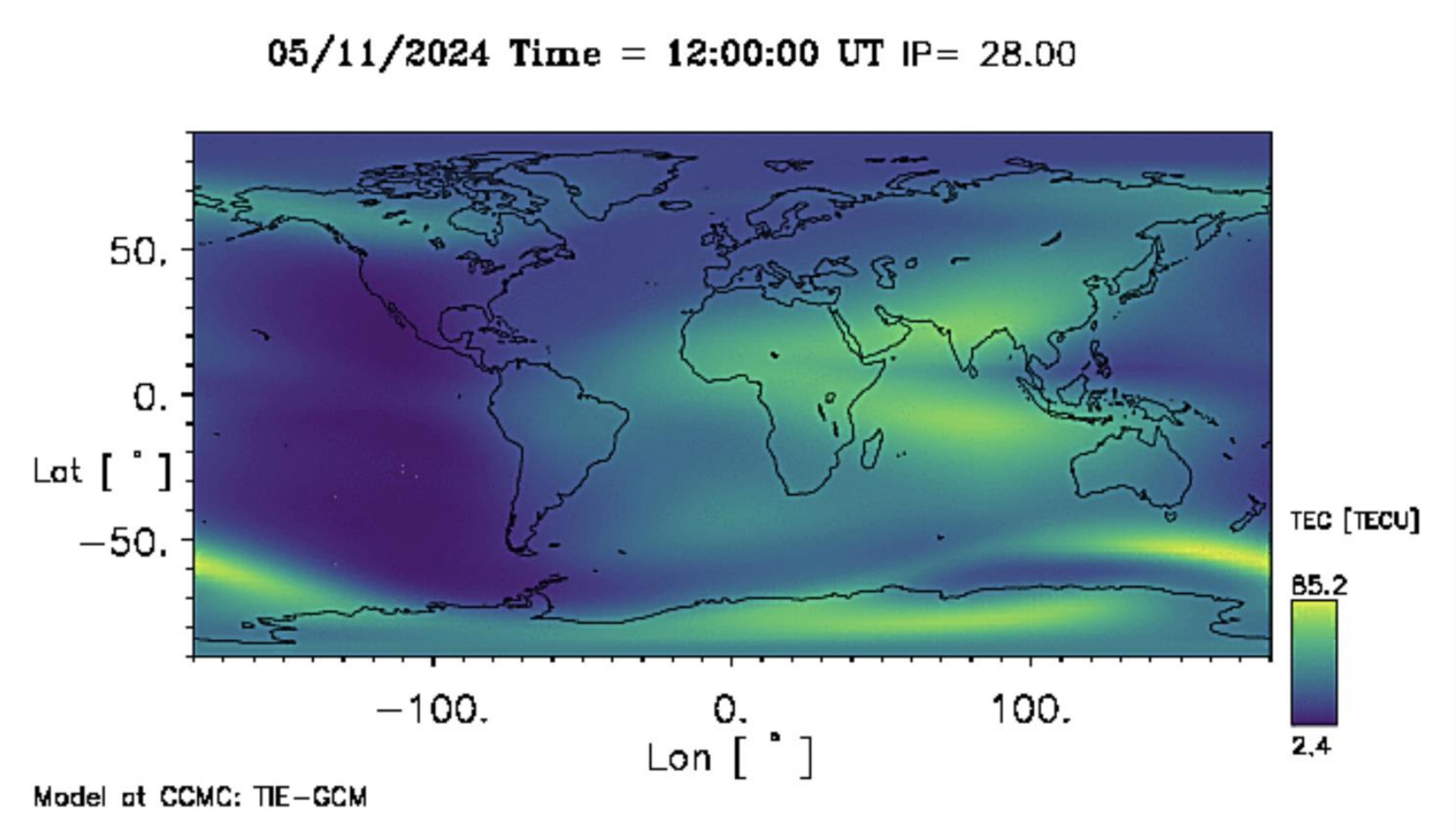
Equatorial Anomaly



Storm-time variability: Gannon Storm 2024

- **TIE-GCM model runs**
- Considerably higher TEC at high latitudes: energetic particle precipitation (EPP)
- TEC at low latitudes not significantly different here…
- Equatorial anomaly prominent in evening sector, less so in dawn / noon sector





Storm-time variability: Gannon Storm 2024

- **TIE-GCM model runs**
- Storm associated with increased EUV, X-ray: leads to higher ionization rates
- Higher temperature in the thermosphere raises the entire ionosphere

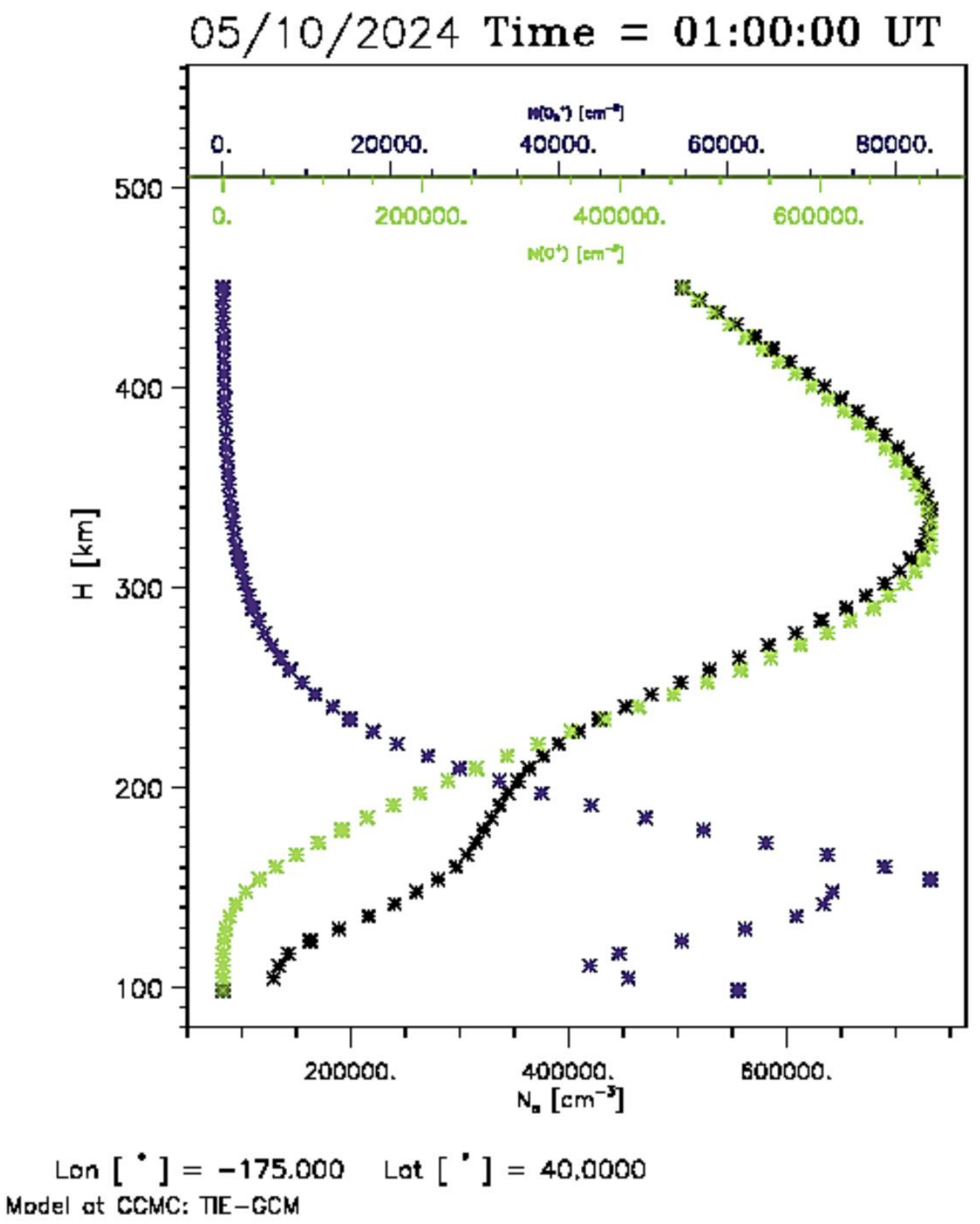


Figure: Simulation of the ionosphere/thermosphere of the Earth.
EPS image (684.44 KB)

Model: TIE-GCM
Run: TIEGCM-Heelis-01_2024-05-TP-02_071624_IT_1

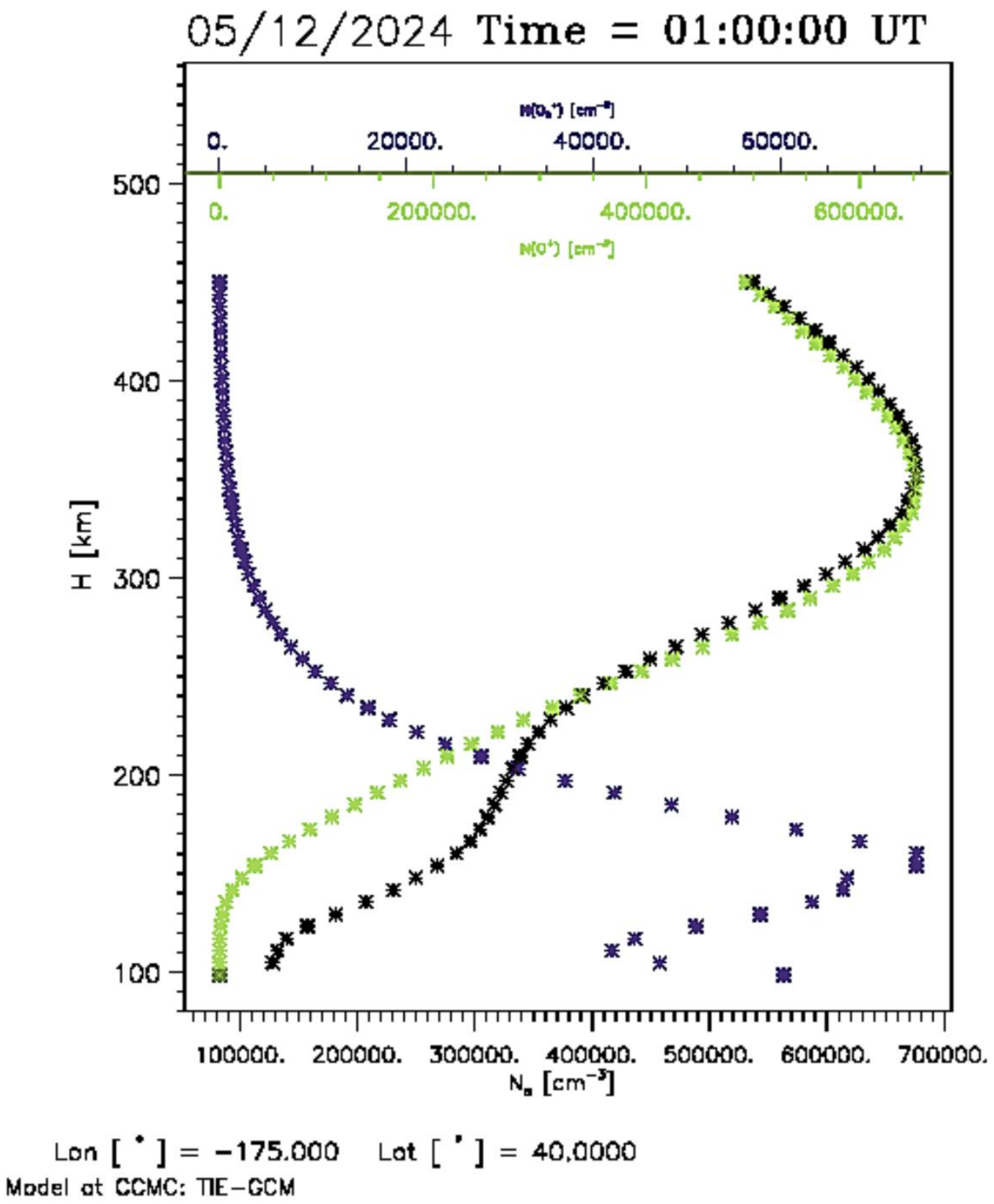
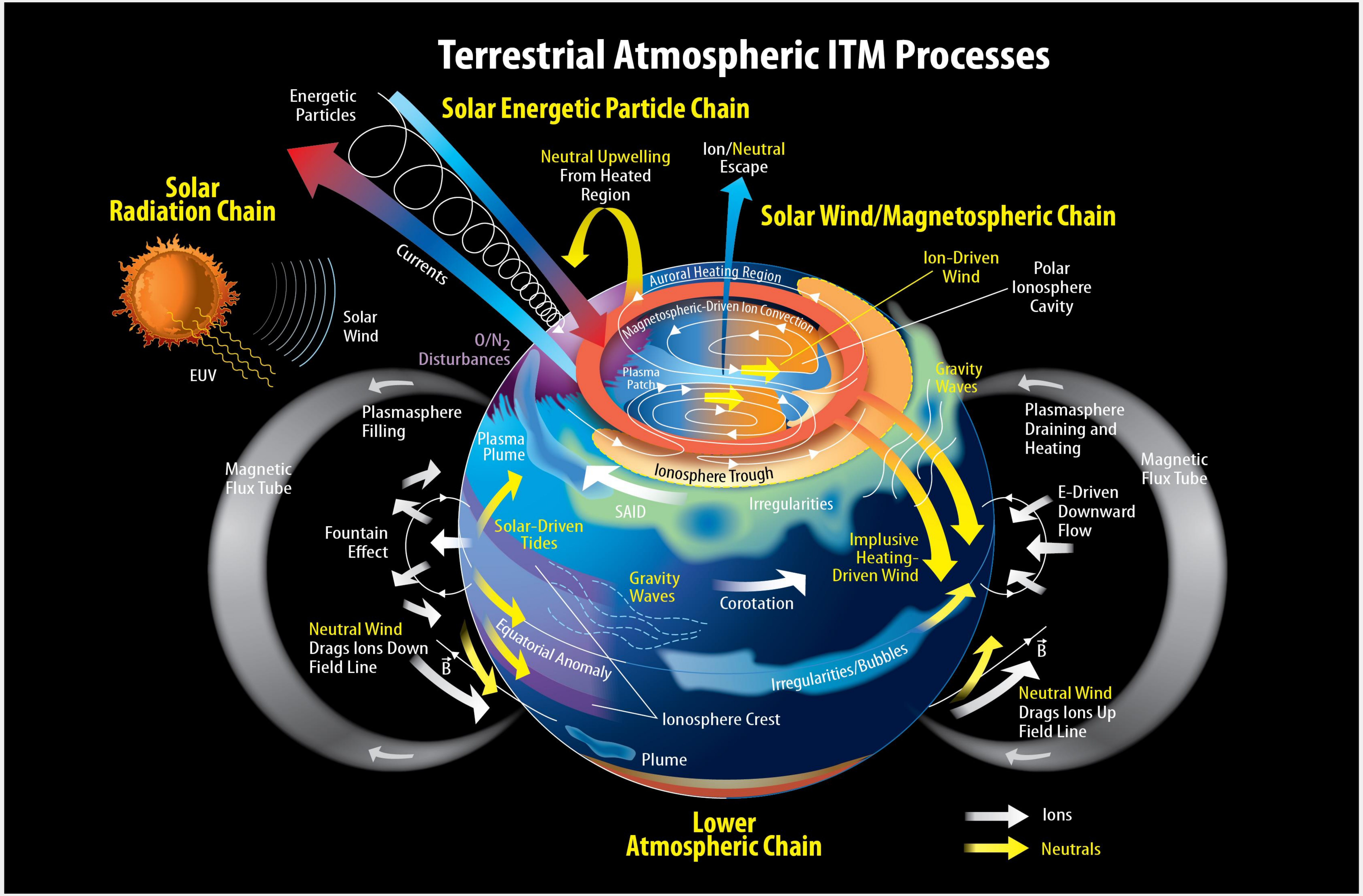


Figure: Simulation of the ionosphere/thermosphere of the Earth.
EPS image (688.14 KB)

Model: TIE-GCM
Run: TIEGCM-Heelis-01_2024-05-TP-02_071624_IT_1

Lots more to the Ionosphere / Atmosphere system…

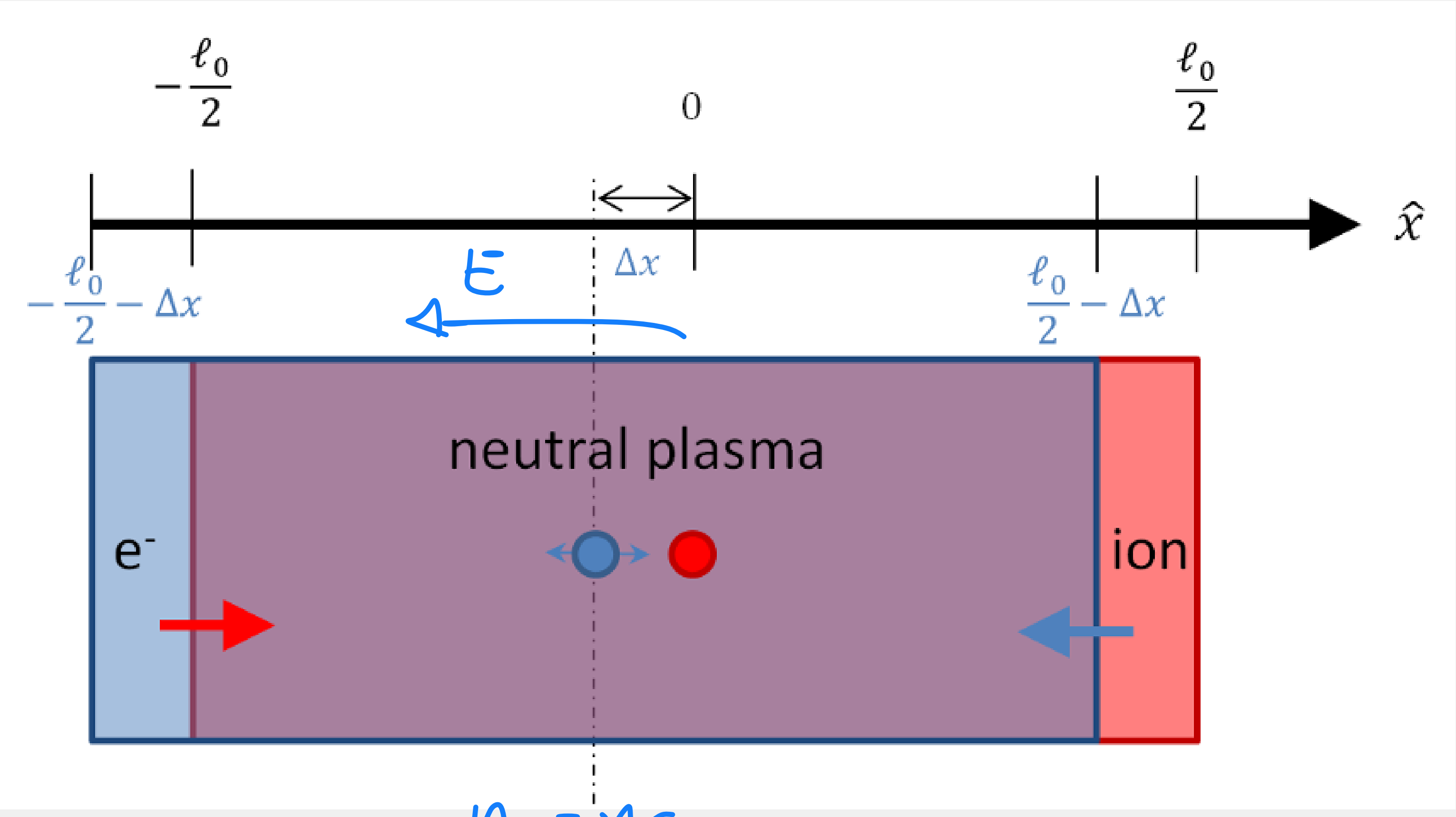


Ionosphere Effects:
Radio Wave Propagation

Radio Wave Propagation

- **Time for some (more) plasma physics!**
  - Plasma oscillations
  - Plasma frequency
  - index of refraction (from Maxwell's equations)
  - Add collisions: absorption
  - MUF, LUF, X-ray effect

Plasma Oscillations



$n_e = n_i$

$$E = -\frac{q_e n_e}{\epsilon_0} x$$

$$ma = F = q_e E$$

$$m_e \frac{dv}{dt} = m_e \frac{d^2x}{dt^2} = -\frac{q_e^2 n_e}{\epsilon_0} x$$

$$\frac{d^2x}{dt^2} + \underbrace{\frac{q_e^2 n_e}{m_e \epsilon_0}}_{\omega_p^2} x = 0 \Rightarrow x(t) = A\cos(\omega_p t)$$

$$\omega_p = \sqrt{\frac{q_e^2 n_e}{m_e \epsilon_0}} \simeq K\sqrt{n_e}$$

$$V_p = \frac{c}{n} = \frac{c}{\sqrt{\epsilon_r}}$$

ϵ (permittivity) $= \epsilon_0 \epsilon_r$

plasma: $$n^2 = 1 - \frac{\omega_p^2}{\omega^2}$$

$\omega = 2\pi f$ = radio wave freq

at $\omega = \omega_p$, $n = 0$

$V_p \to \infty$

if $\omega < \omega_p$

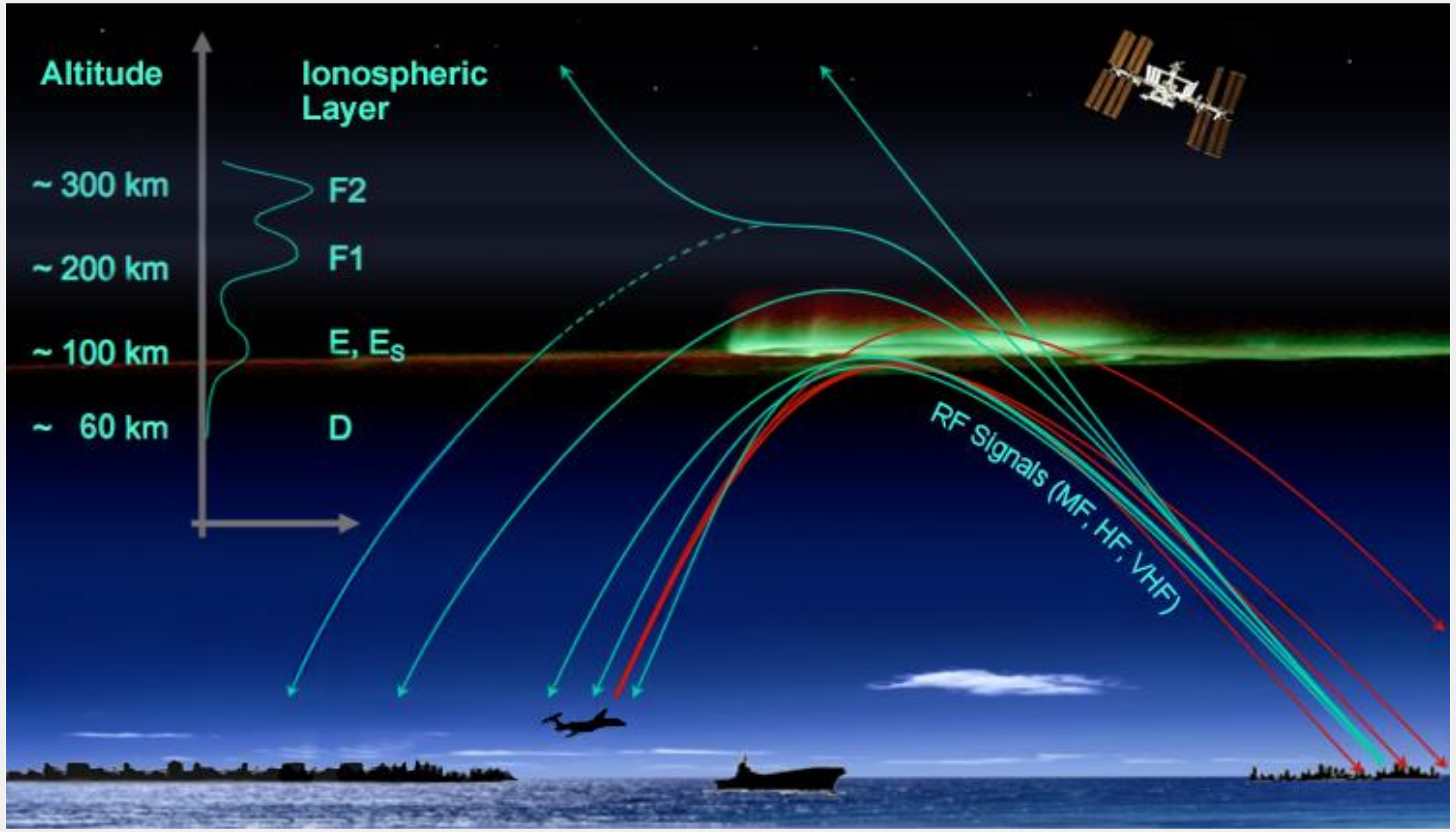
n = complex

$n = \alpha + j\beta$

Reflection of EM Waves

- Plasma frequency ω_p directly related to electron density
- Radio waves above ω_p pass through the ionosphere; electrons cannot respond fast enough
- Radio waves below ω_p are reflected; electrons are "shaken" and re-radiate

- **Implications:**
  - must use frequencies above ω_p to talk to satellites
  - Can communicate over-the-horizon with frequency near / below ω_p



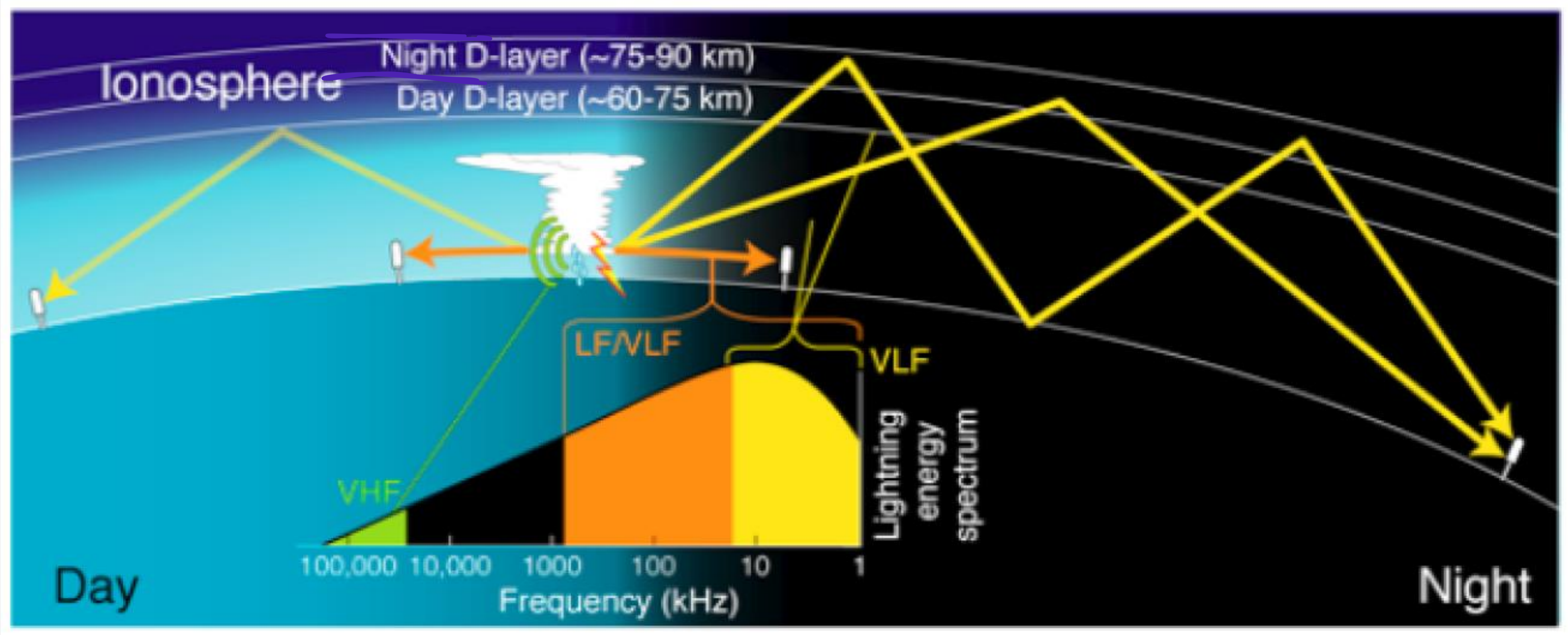
Critical Frequencies in the Ionosphere

- **In the F-region, f_c ~ 3—30 MHz**
  - higher frequencies pass through the ionosphere, with some refraction
  - over-the-horizon radio
- **In the E-region, f_c ~ 1—2 MHz**
  - but sporadic-E increases f_c up to 100 MHz
- **In the D-region, our model breaks.**
  - Lots of neutrals means high collision frequency; our index of refraction is more complicated.
  - Absorption of MHz waves (next)
  - Reflection of waves below ~100 kHz; VLF waves (below ~50 kHz) used for long-range communications with submarines

$\omega_p = \sqrt{\frac{q_e^2 n_e}{m_e \epsilon_0}}$, $f_p = \frac{\omega_p}{2\pi}$ $\sim n_{e,max}$

$\times$ $n^2 = 1 - \frac{\omega_p^2}{\omega^2} \simeq 0$

e-n



Index of refraction in a cold plasma

- In general, index of refraction is given by the Appleton-Hartree equation:

$$n^2 = 1 - \frac{X}{1 - iZ - \frac{\frac{1}{2}Y^2 \sin^2\theta}{1-X-iZ} \pm \frac{1}{1-X-iZ}\left(\frac{1}{4}Y^4 \sin^4\theta + Y^2 \cos^2\theta \,(1 - X - iZ)^2\right)^{1/2}}$$

angle between $\bar{B}_o$ and $\bar{k}$

$$X = \frac{\omega_p^2}{\omega^2} = \frac{q_e^2 n_e}{m_e \epsilon_o \omega^2}$$

$$Y = \frac{\omega_c}{\omega} = \frac{q_e B_o}{m_e \omega}$$

ω_c → gyrofrequency

$$Z = \frac{\nu}{\omega}$$, ν = coll. freq. : collisions make n complex

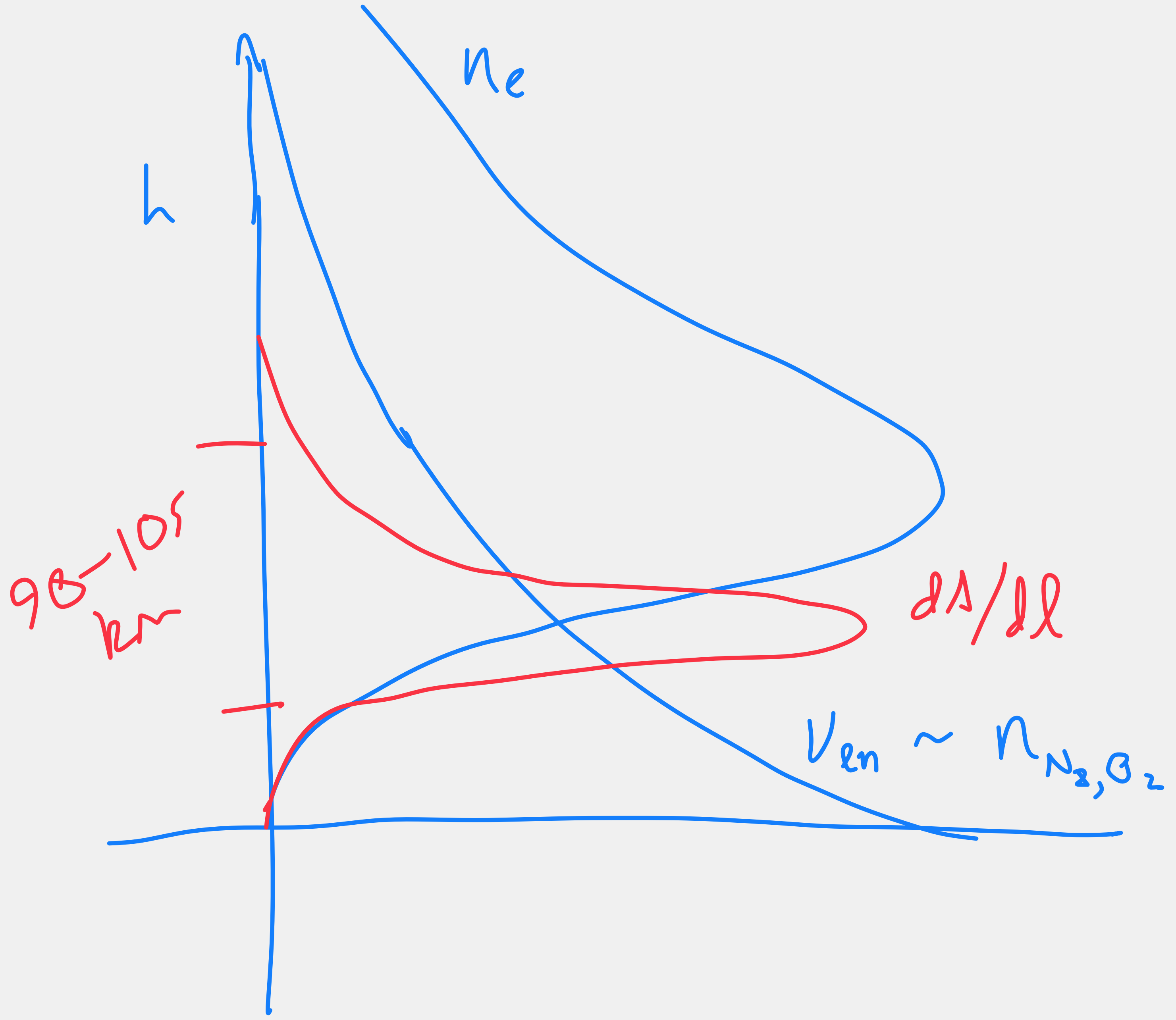
$$n = \alpha + j\beta$$

D-region absorption

- As electrons get excited by waves with f < fc, the collide with neutrals
- Some of the EM wave energy gets transferred to heat; radio waves suffers absorption
- How much absorption?

$$\frac{dA}{dl}\left(\frac{dB}{m}\right) = 4.61\times10^{-5}\,\frac{n_e \nu_{en}}{\nu_{en}^2 + (\omega \pm \omega_c)^2}$$

$\omega_c \rightarrow \frac{qB_0}{m_e}$, $f_c \sim 1-2$ MHz



Collision Frequency?

- Electrons (few) randomly collide with neutrals (many)
- Radio wave energy converts to electron kinetic energy and then to neutral thermal energy (i.e., neutrals are "heated")
- This is collisional heating, and a sink for radio wave energy

- Collision frequency depends on neutral density (N2, O2) and on electron temperature
- Does not depend on electron density; **why**?

small ~Te

$$\nu_{av}(e, N_2) = 2.33 \times 10^{-17} N_{N_2} (1 - 1.21 \times 10^{-4}\, T_e)\, T_e$$

~Te

$$\nu_{av}(e, O_2) = 1.82 \times 10^{-16} N_{O_2} (1 + 0.036\, T_e^{1/2})\, T_e^{1/2}$$

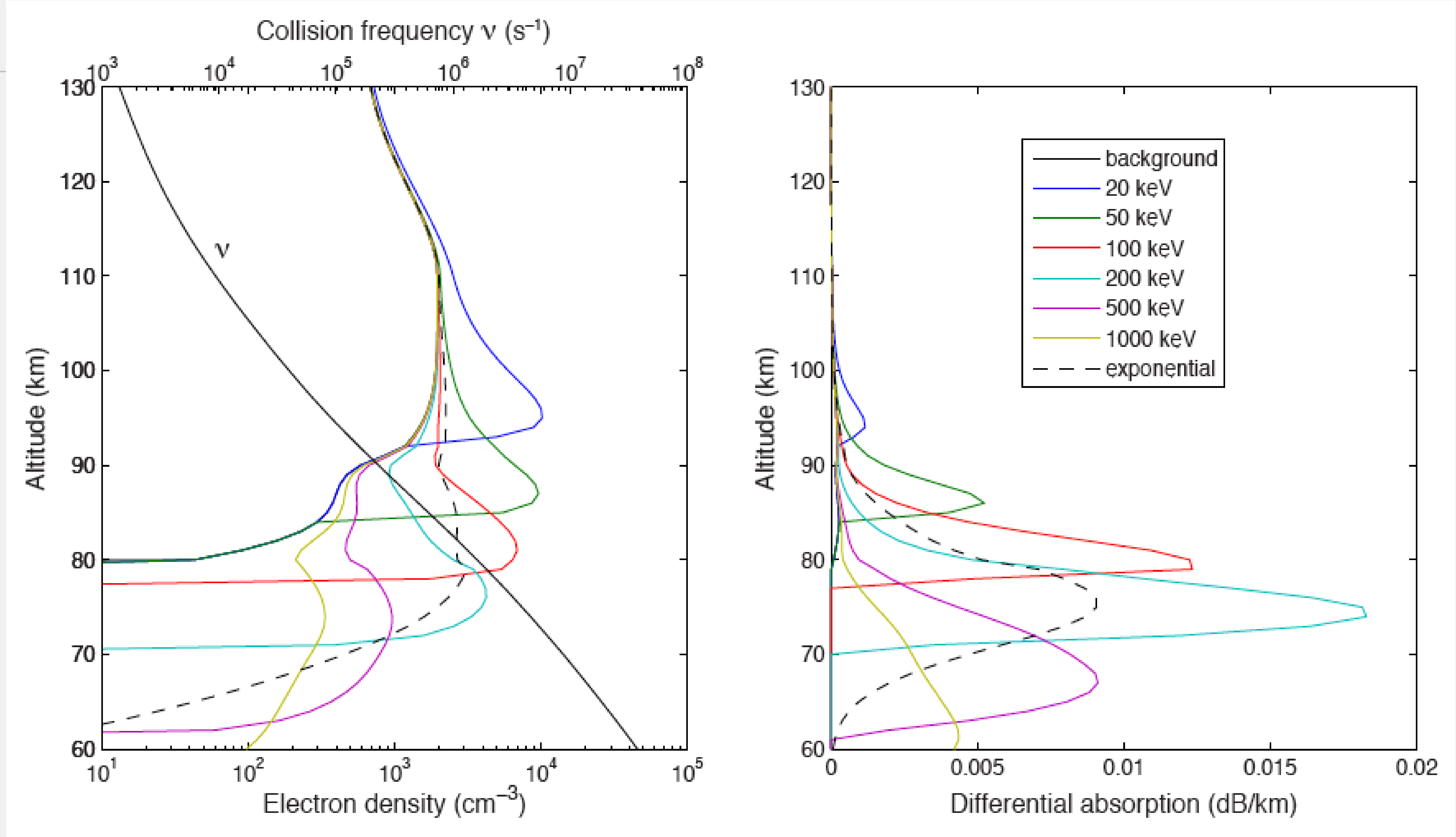
$$\nu_{en} = \nu_{av}(e, N_2) + \nu_{av}(e, O_2)$$

1/sec

per electron

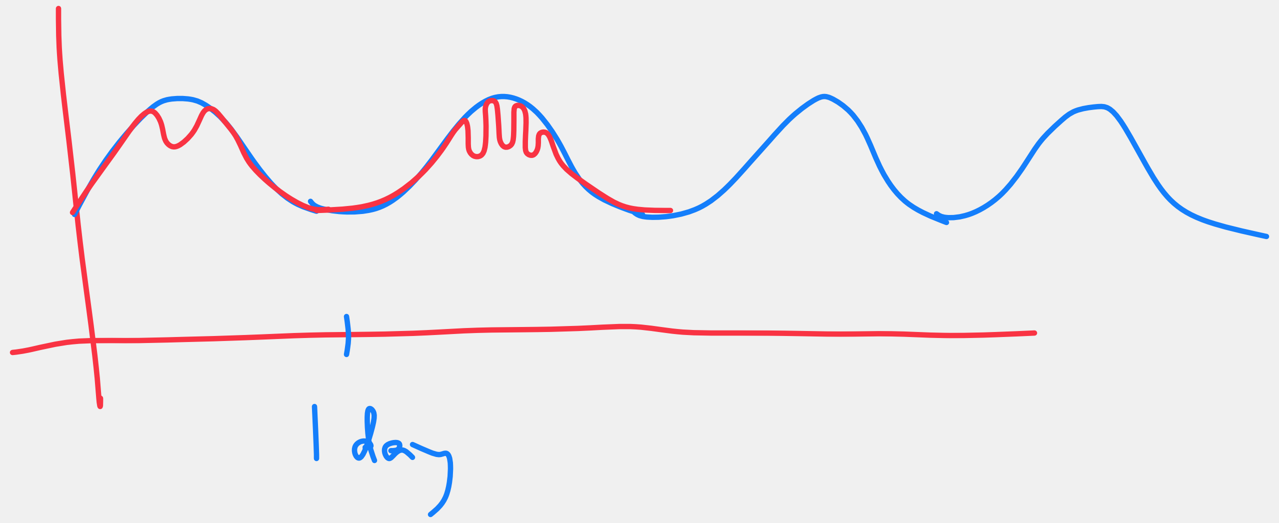
D-region absorption

- Shown here: absorption of 30 MHz radio wave due to electron precipitation from the radiation belts



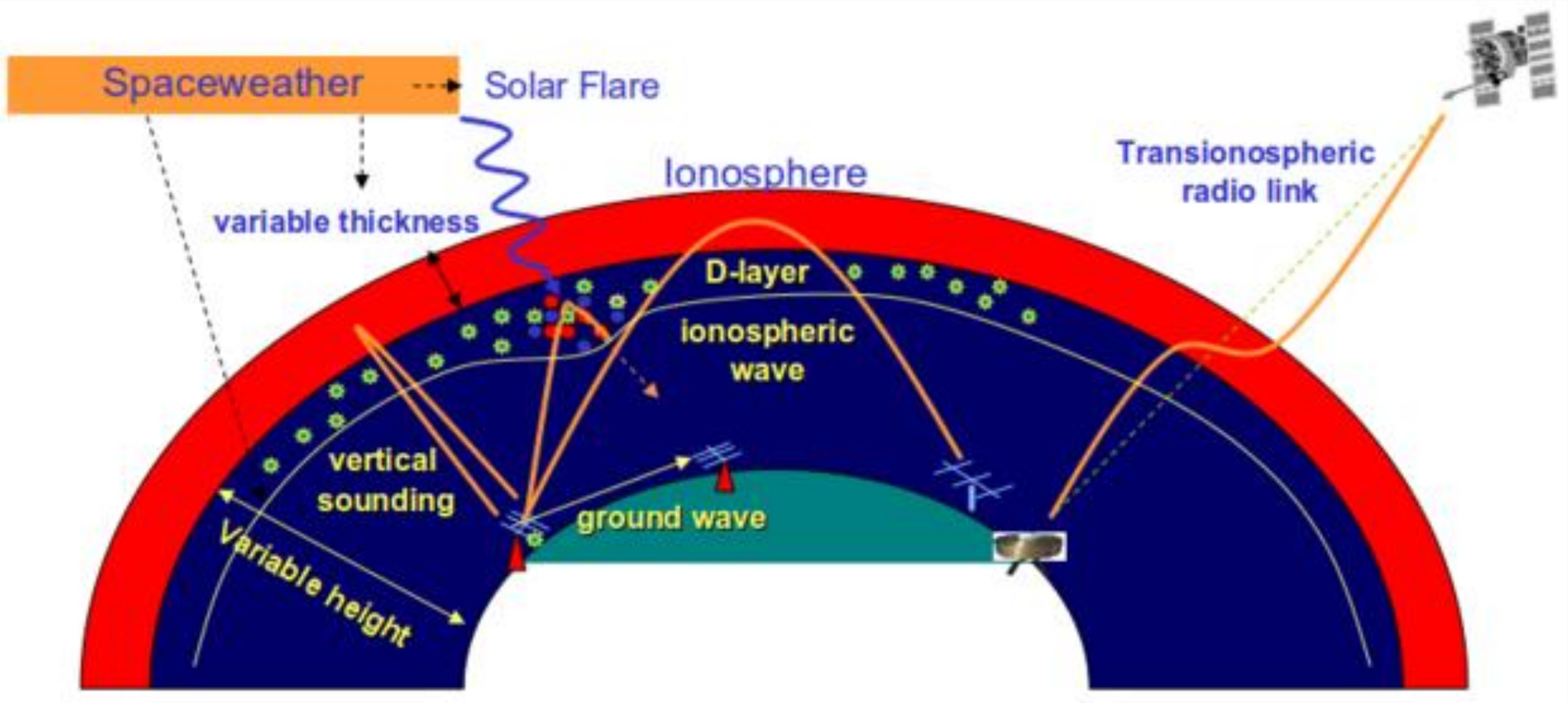
Alaska

- **Riometer**: passive instrument that measures D-region absorption by monitoring cosmic noise at ~30 MHz



Sudden Ionospheric Disturbances (SIDs)

- SID is ionospheric response to a solar flare (X-rays)
  - X-rays ionize the D-region, causing a huge increase in D-region electron density (orders of magnitude)
  - Higher n_e leads to higher radio wave absorption
  - Lower D-region reflection height perturbs VLF signals

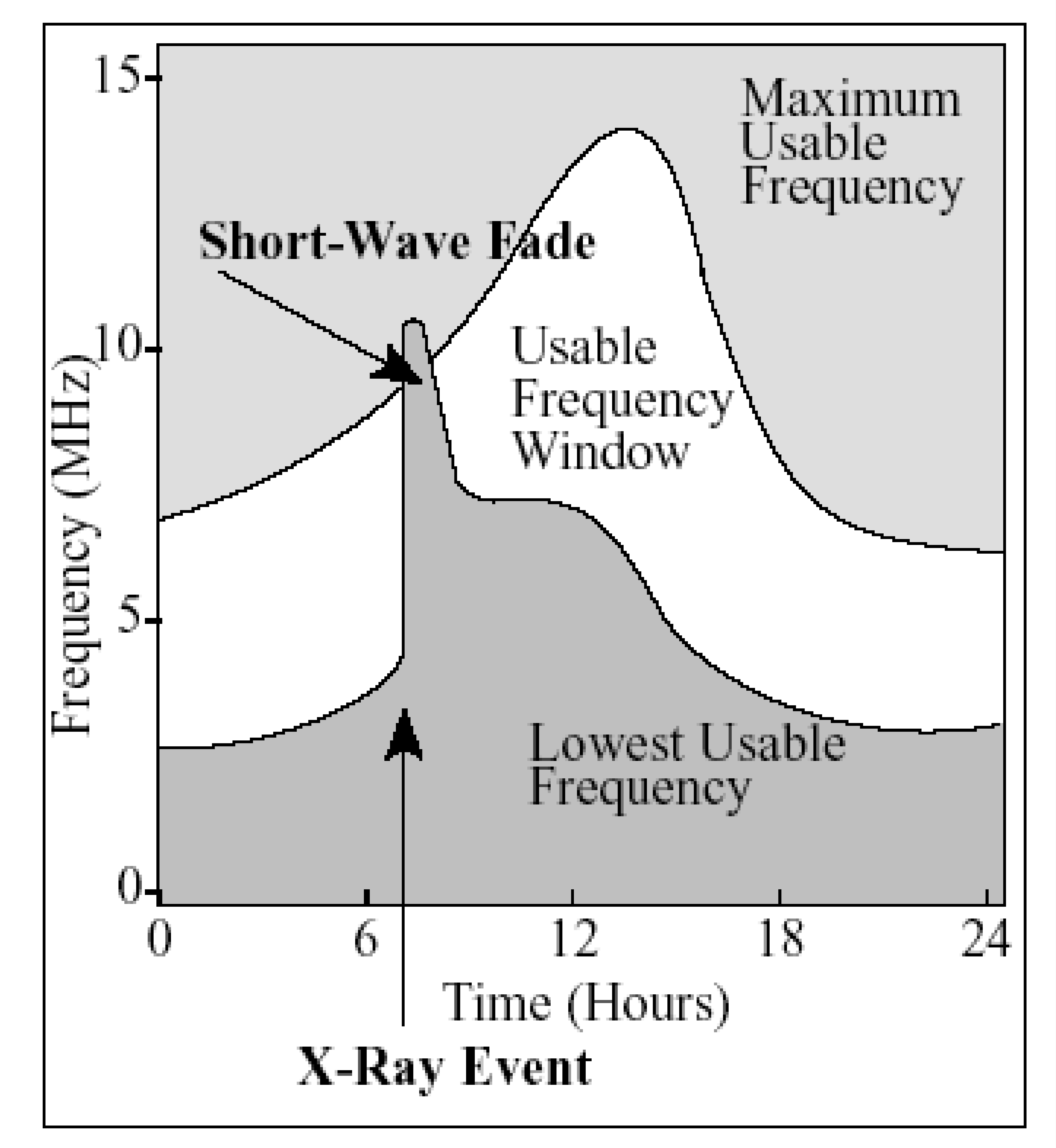


Short-Wave Fade

- **Issue for over-the-horizon radar**
  - There is a maximum frequency we can use, above which waves pass through the F-region
  - There is a minimum frequency we can use, because
    - lower frequencies suffer too much absorption

$$\frac{dA}{dl} = 4.6 \times 10^{-5} \frac{n_e \nu}{\omega^2}$$

  - Usable "Frequency Window"
  - After a major X-ray flare, Absorption can increase to prevent any useful communication



GPS and TEC

$f \sim 1$–1.5 GHz, $f \gg f_p, f_c$

- Even for frequencies above f_c, the ionosphere introduces some interesting effects
  - Small change in index of refraction from

$$n^2 = 1 - \frac{\omega_p^2}{\omega^2}$$

  - Expand in Taylor series:

$$n = 1 + \frac{c_2}{f^2} + \frac{c_3}{f^3} + \frac{c_4}{f^4} + \ldots$$

  - Cut off after first term:

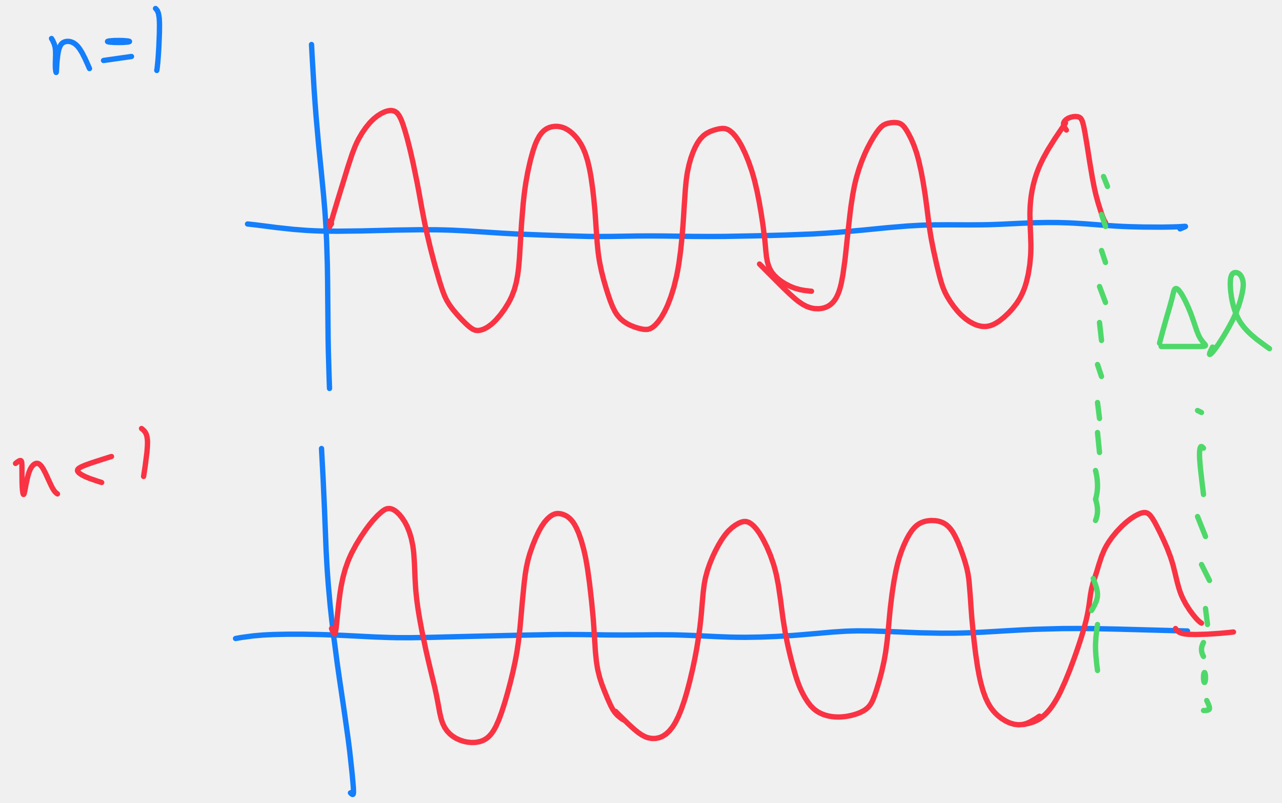
$$n = 1 + \frac{c_2}{f^2}$$

  - Change in path length:

$$\Delta l_{\text{iono}} = -\frac{40.3}{f^2} TEC$$

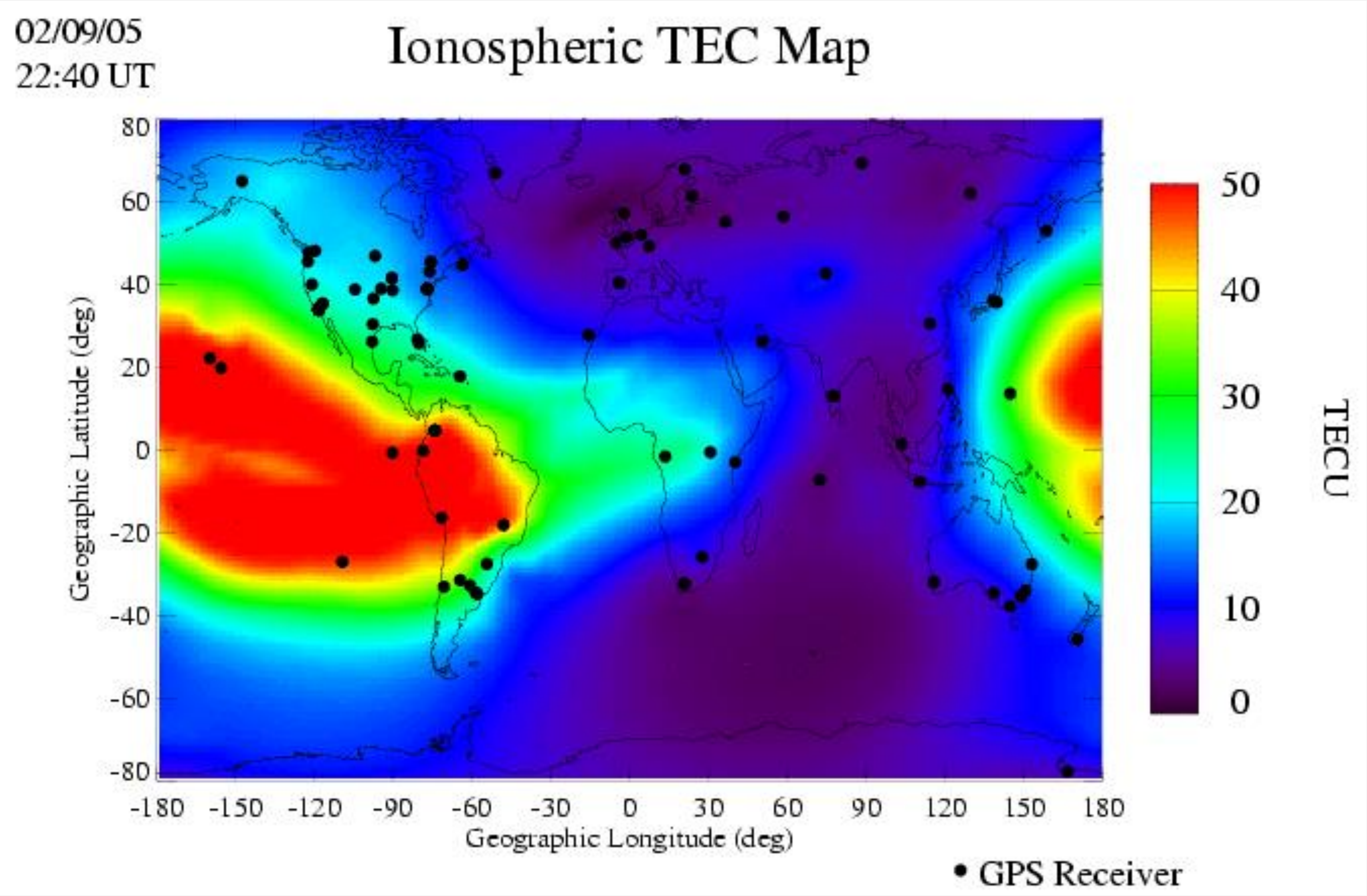
$$TEC = \int_{\infty}^{0} n_e(l)\, dl \quad (m^{-2})$$

  - Where TEC is total electron content, integrated along signal path



TEC maps

- 1 TECU = 10^{16} el/m^2
- receivers all over the Earth's surface; 20+ satellites to provide pierce-points
- Interpolate results onto 2D (or 3D) map



GPS TEC and ionospheric science

- GPS TEC can be used to observe ionospheric disturbances
- “Plume” here, extending over North America, is footprint of plasmasphere “plume” during geomagnetic storm