University of Colorado **Boulder**

August 21, 2024

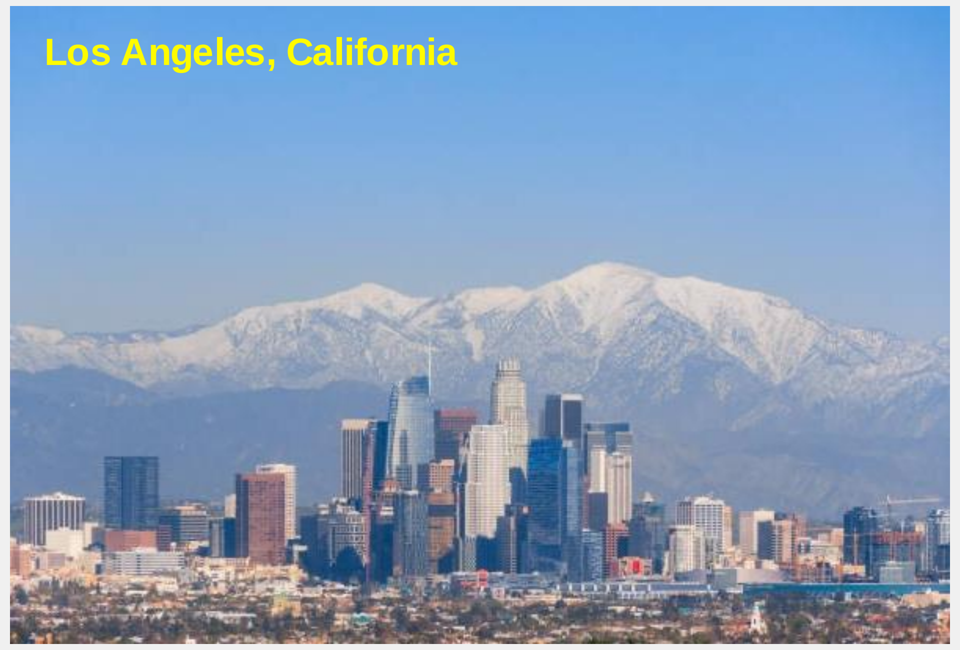
The Ionosphere

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 9 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

The Lightning, Atmosphere, Ionosphere, and Radiation Belts (LAIR) Research Group

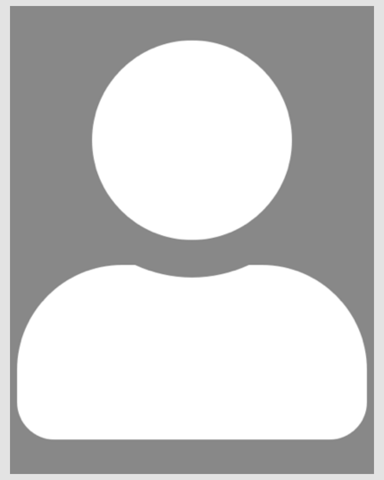
PhD students

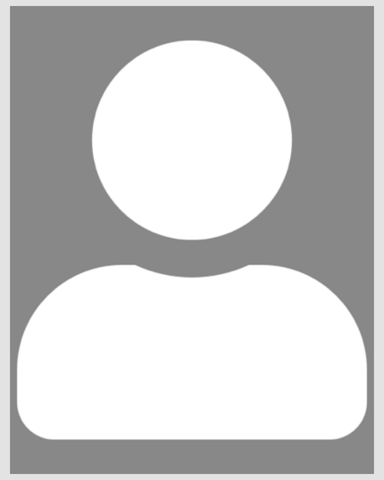

Alex Wold


James Cannon


Paraksh Vankawala


Wyatt Spies


Julia Claxton


Anant Telikicherla


Tzu-Hsun Kao

Postdoctoral Scholars


Alex Shane


Carolina Peña

Research Engineers


Sebastian Wankmueller


Siwani Regmi

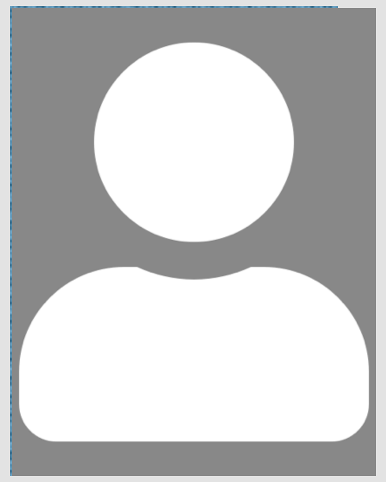

Conor Cunningham


Joe Buescher

Undergraduates


Tai Matayay


Ryan Dick

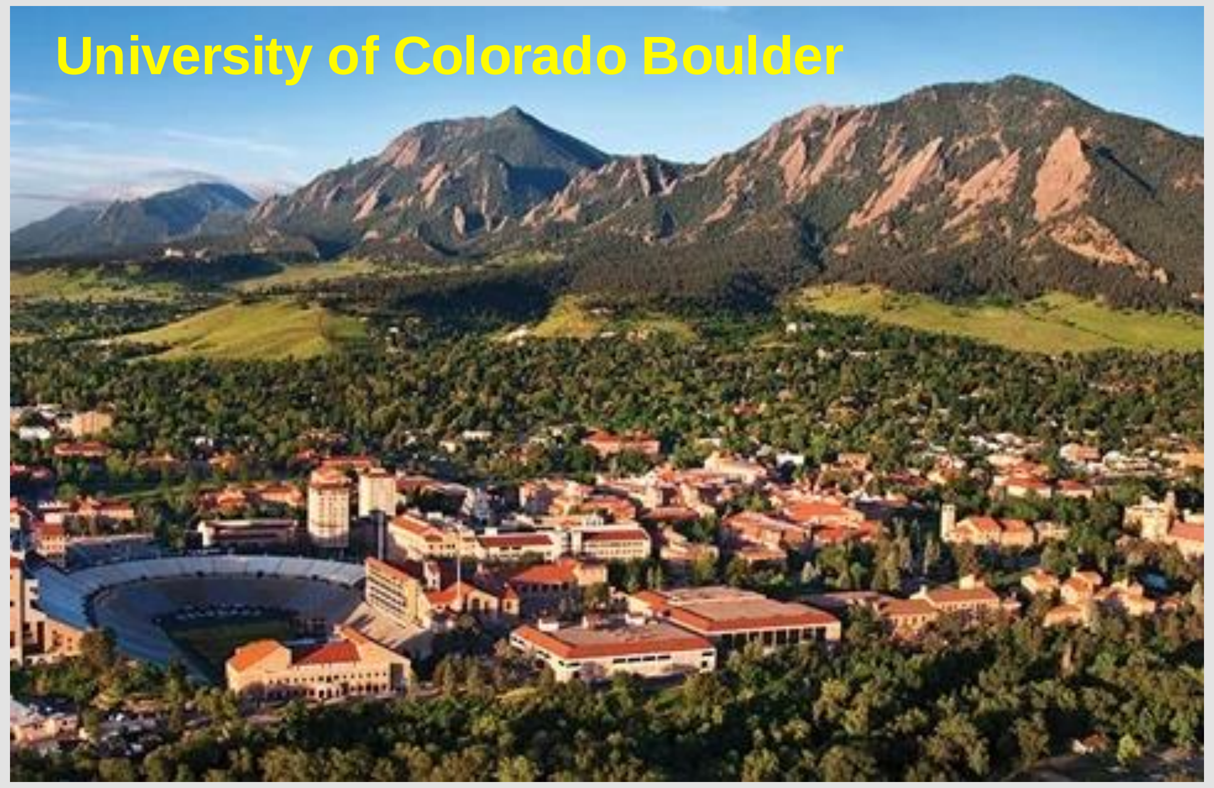

Ash Tribble

LAIR Alumni:

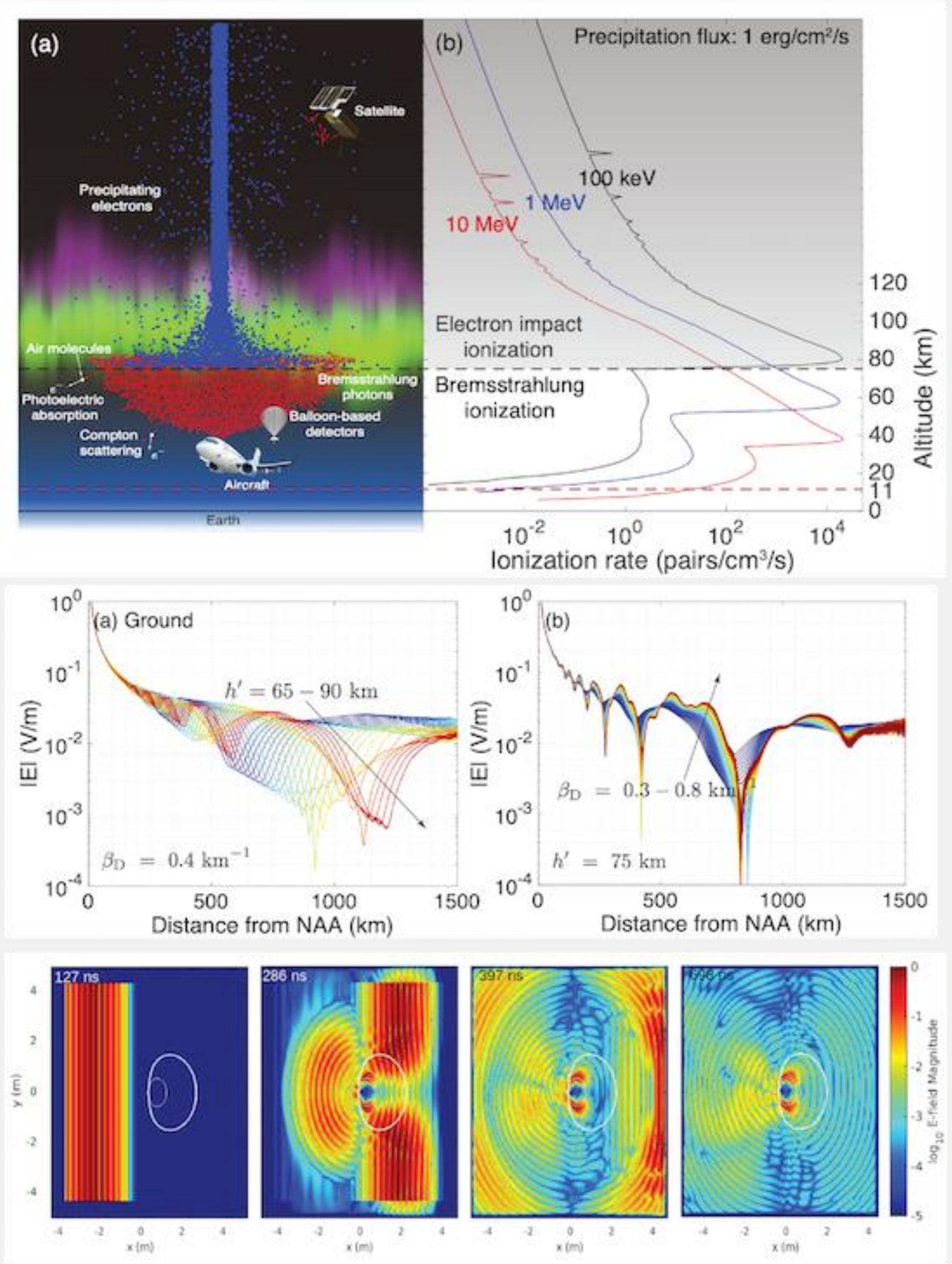
- 4 postdocs that have moved on
- 6 PhDs graduated
- 4 MS theses
- 20+ undergraduates

BOULDER AEROSPACE INSTRUMENTATION LABORATORY
BASIL
FREE WI-FI

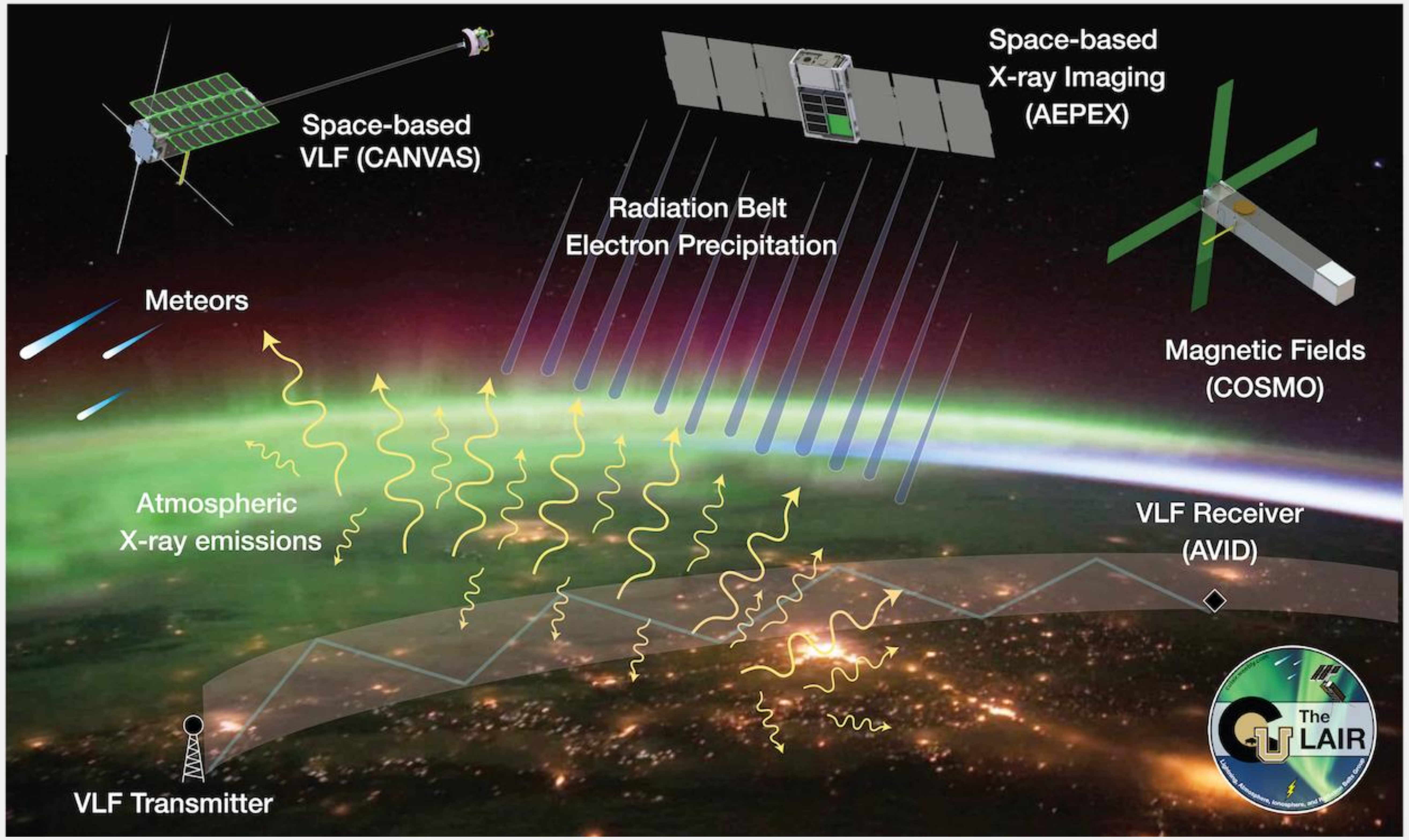
culair.weebly.com
The LAIR
Lightning, Atmosphere, Ionosphere, and Radiation Belts Group



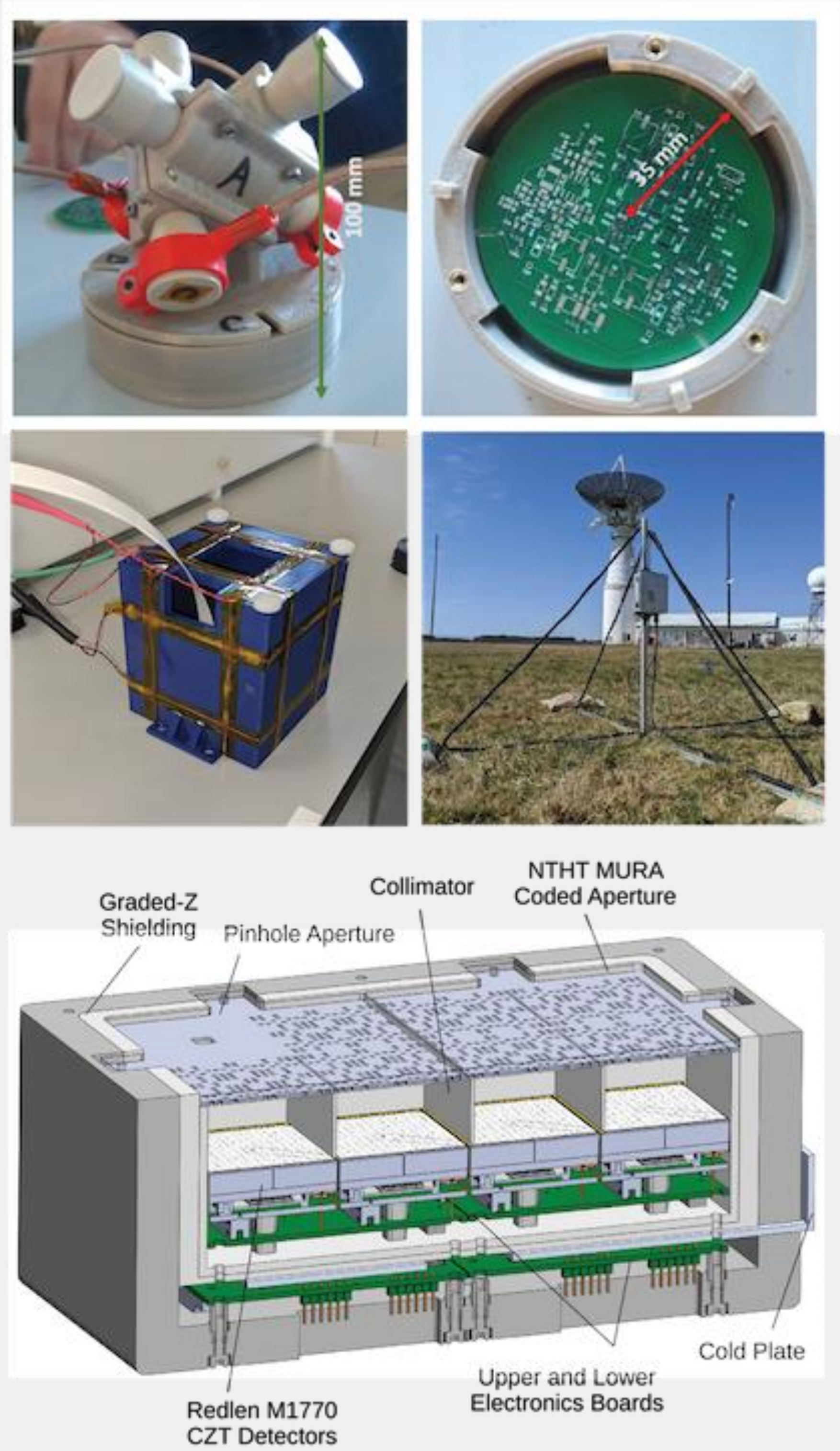
The LAIR Research Overview



Modeling, Simulation, and Data Analysis



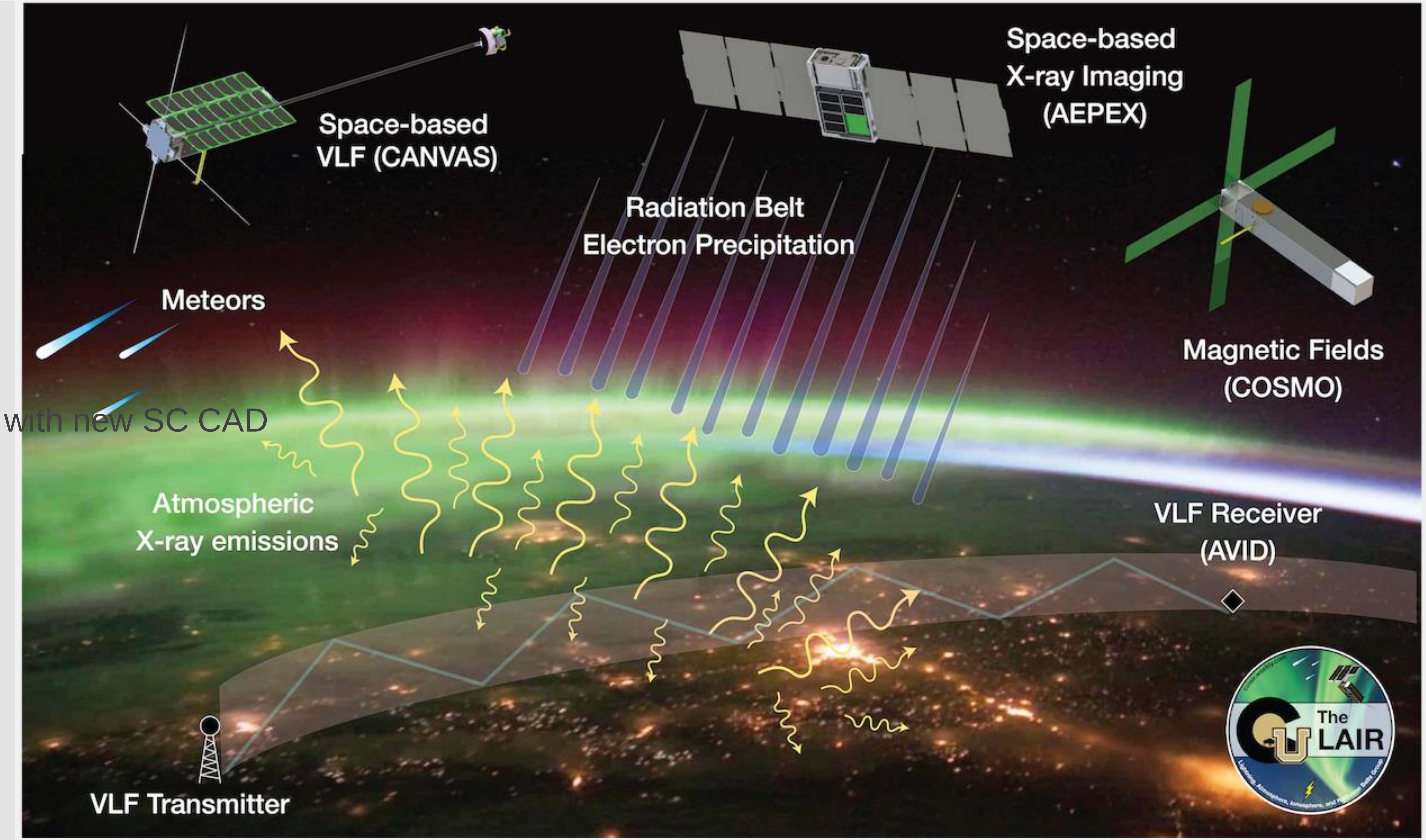
CubeSats for Space Science



Instrumentation

CubeSats for Space Science

- lder; update with new SC CAD

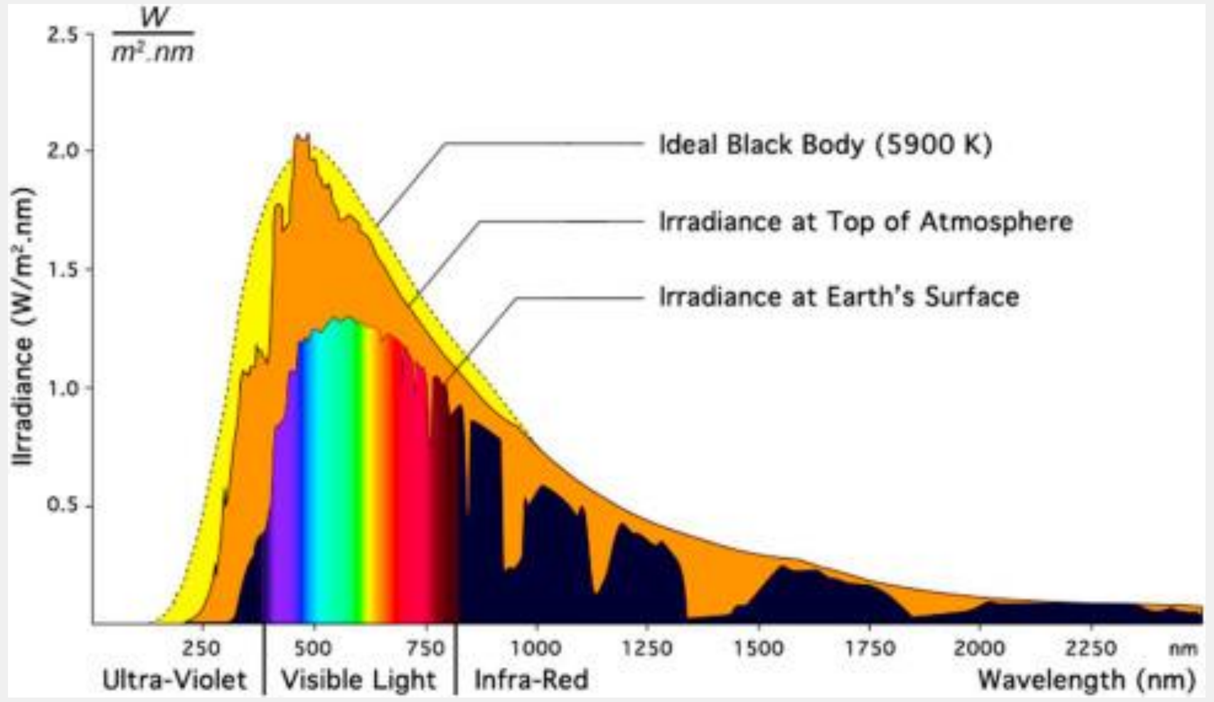


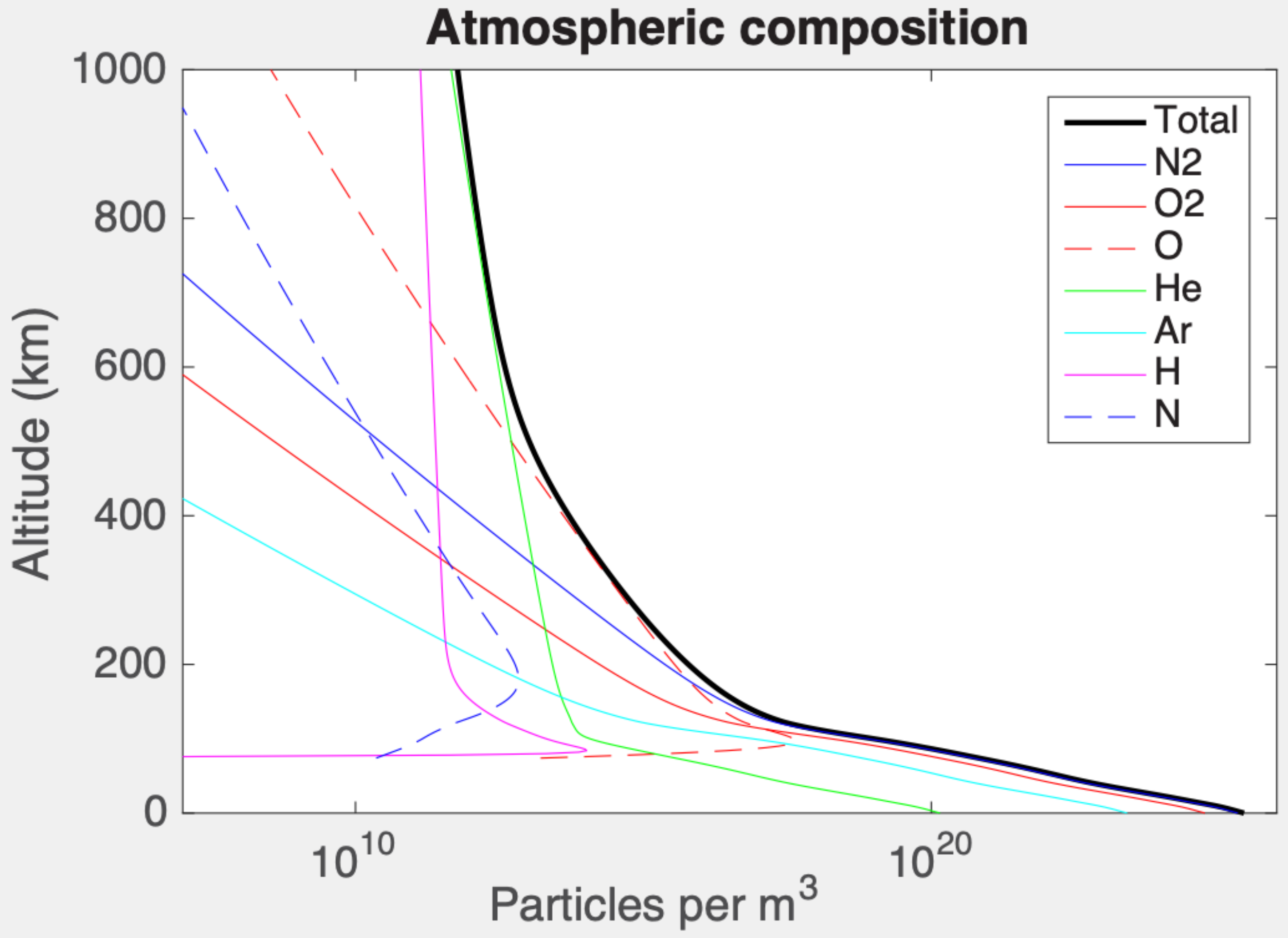
Ionosphere Lectures: Goals

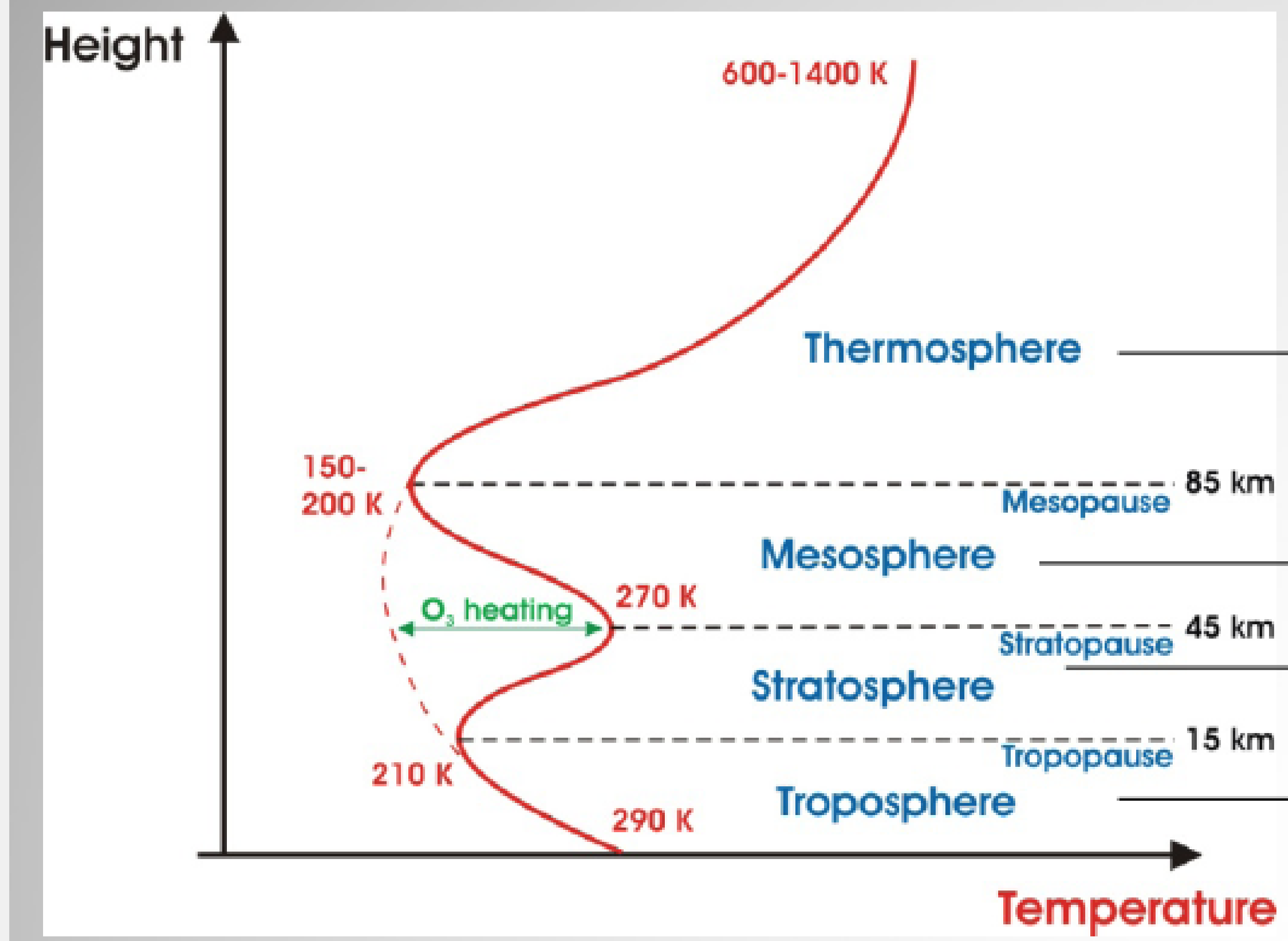
- **Understand basic physics of the Earth's ionosphere**
  - Origin, composition, layers
  - Variations: diurnal, seasonal, solar cycle, plus other anomalies
- **Effects of the Ionosphere on Spacecraft and technology**
  - Radio communications and GPS
- **Comparative Ionospheres: Jupiter and Mars**

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

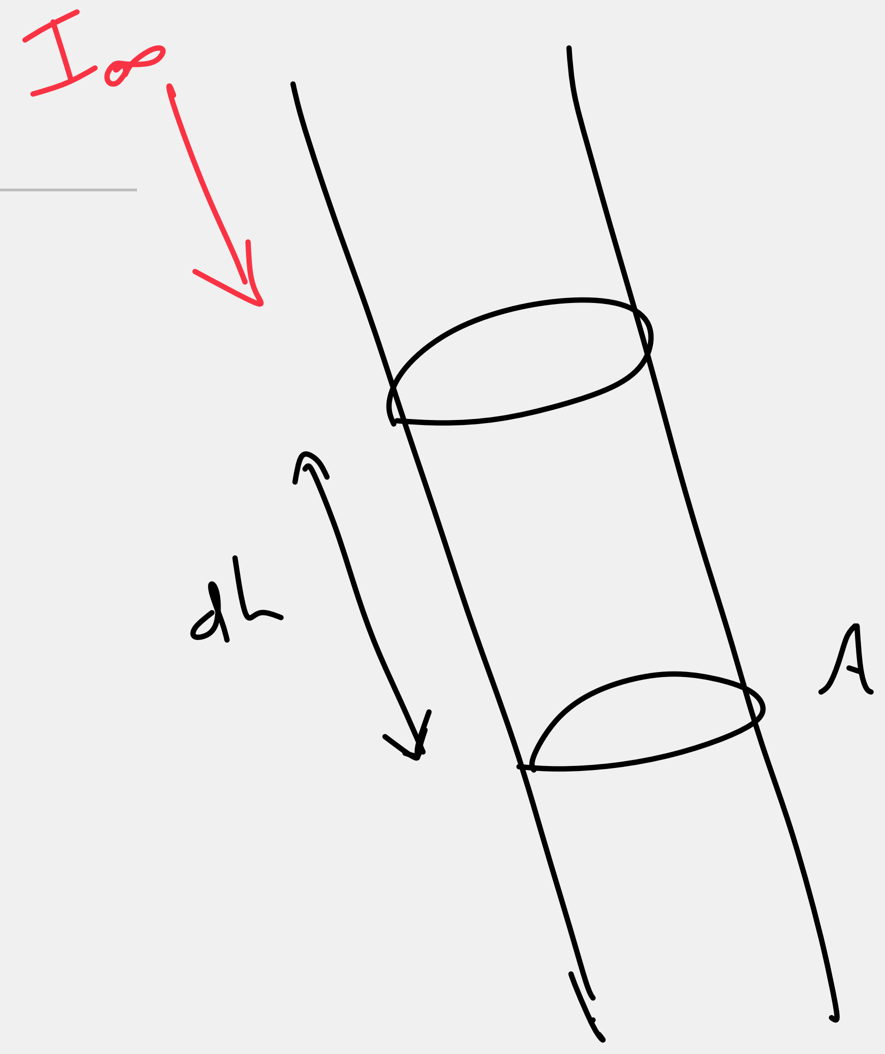
Mesosphere:
- Energy sources:
  - Some UV absorption by O_3 (lower heights)
  - Heat transport down from thermosphere (minor, upper heights only)
  - Chemical heating
- Energy sinks:
  - IR radiation by CO_2 H_2O, OH

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

Absorption in Earth's Atmosphere

$$I = \text{brightness} = \text{flux} = J/cm^2/sec = W/cm^2$$



$$-\ dI \sim I\, dh$$

$$dI = -\sigma n I\, dh$$

number density, cm^{-3}

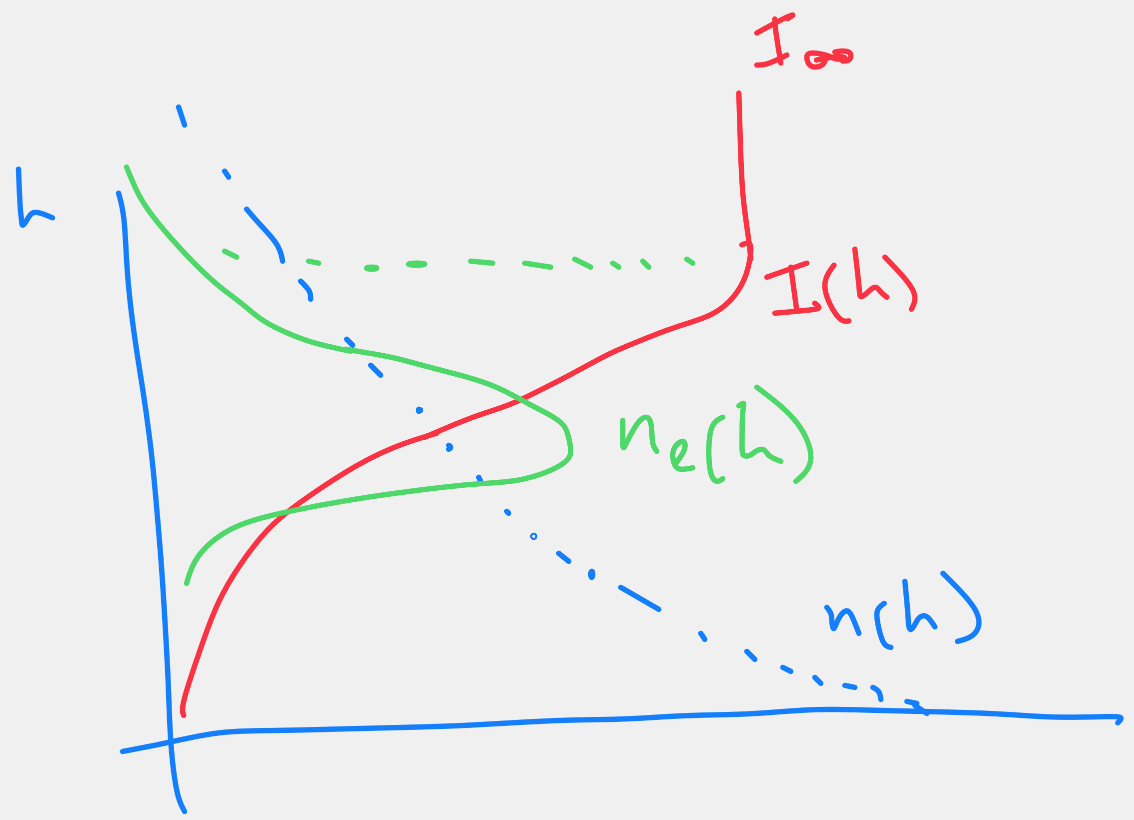
absorption cross section, cm^2

molecule, λ-dependent

$$\frac{dI}{I} = -\sigma n\, dh \longrightarrow \ln I \Big|_\infty^h = -\int_\infty^h \sigma(h)\, n(h)\, dh$$

$$I(h) = I_\infty e^{-\tau}$$

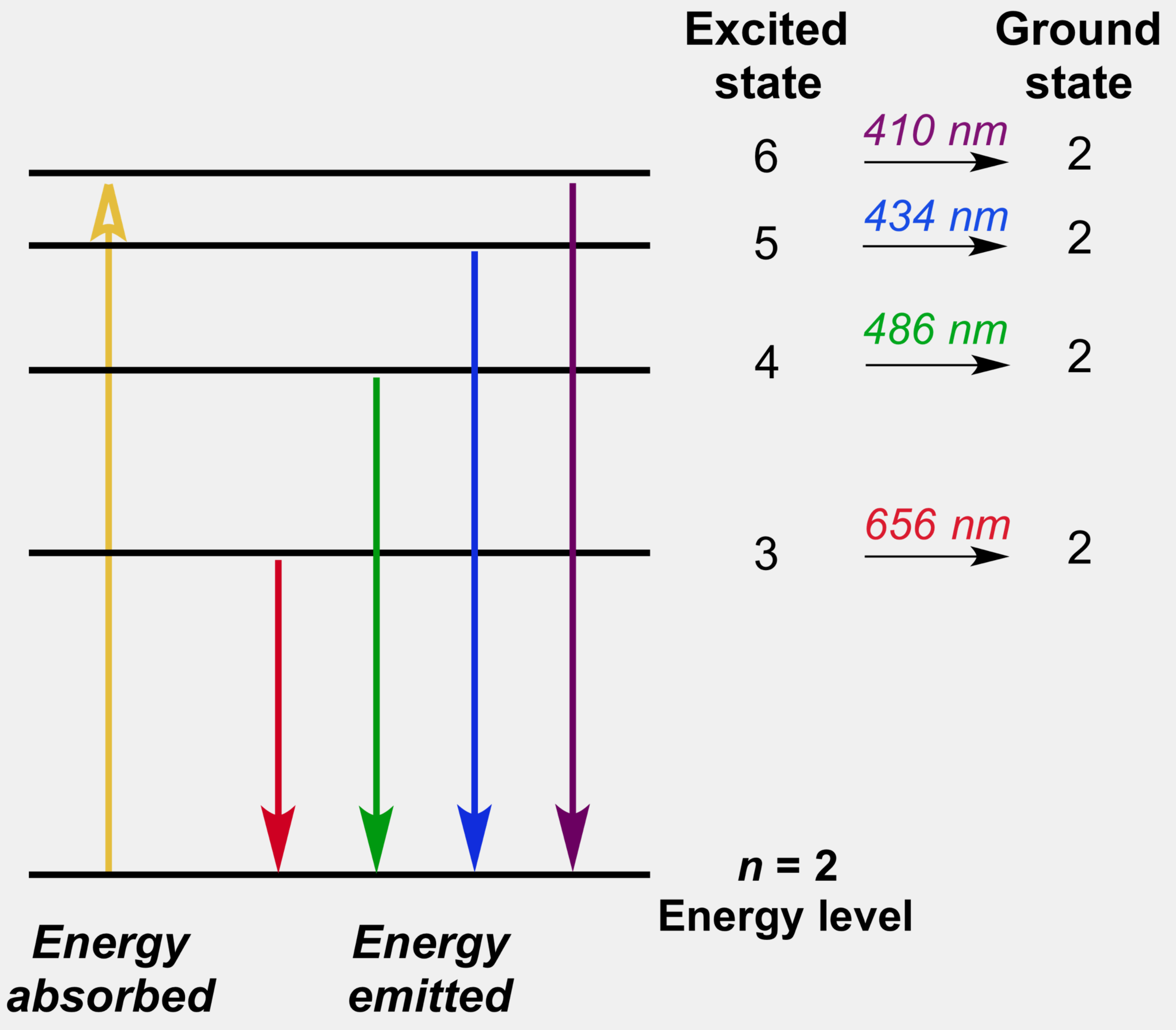
$\tau \rightarrow$ optical dept



Atmospheric Heating

free electron

- Though less that 1.5% of TSI, wavelengths < 300 nm are primary source of atmospheric heating from 15—500 km.
  - Excitation; dissociation; ionization
  - Relaxation, association, recombination —> heat



$h\nu$

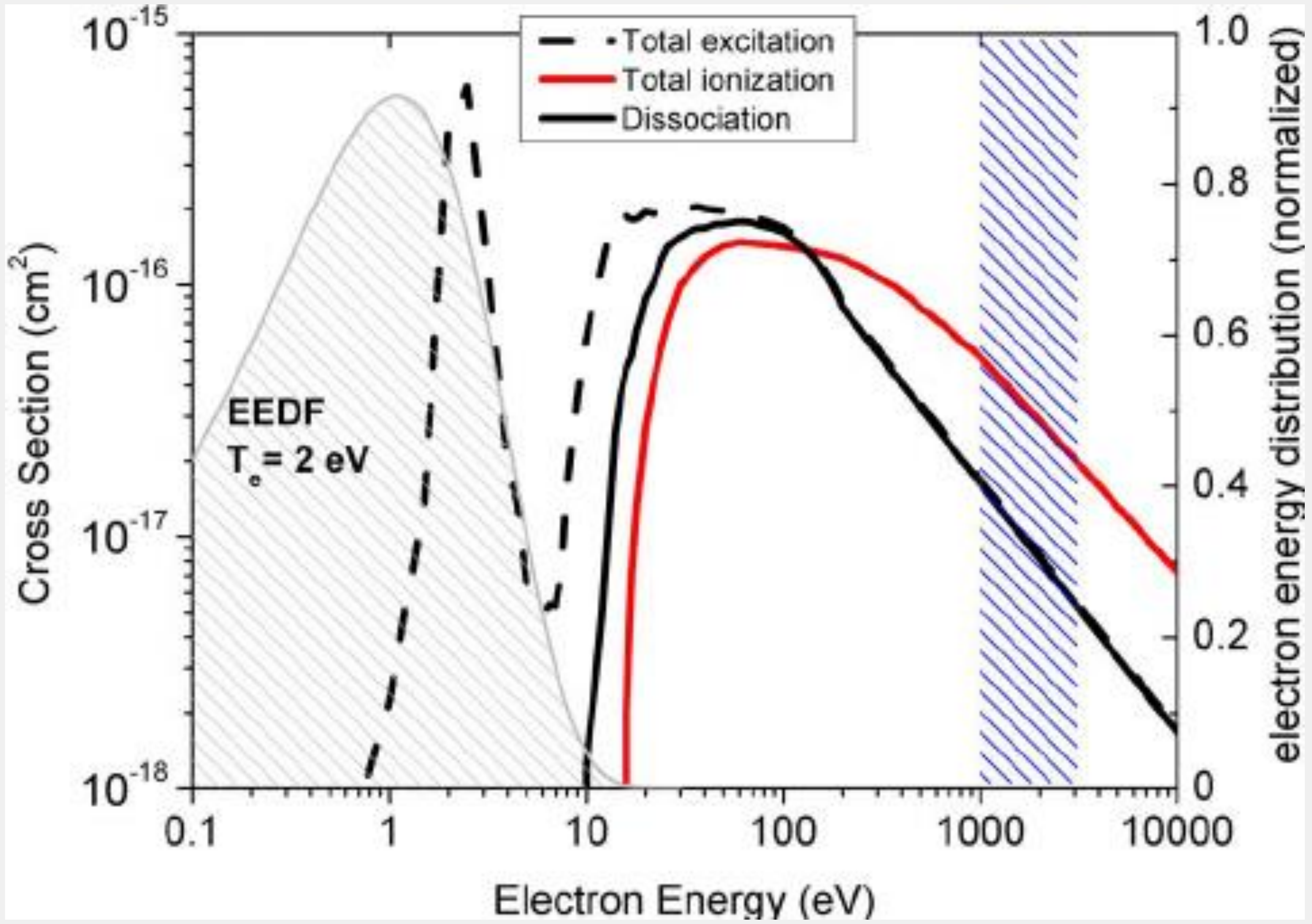
excitation $N_2 + \gamma \rightarrow N_2^*$

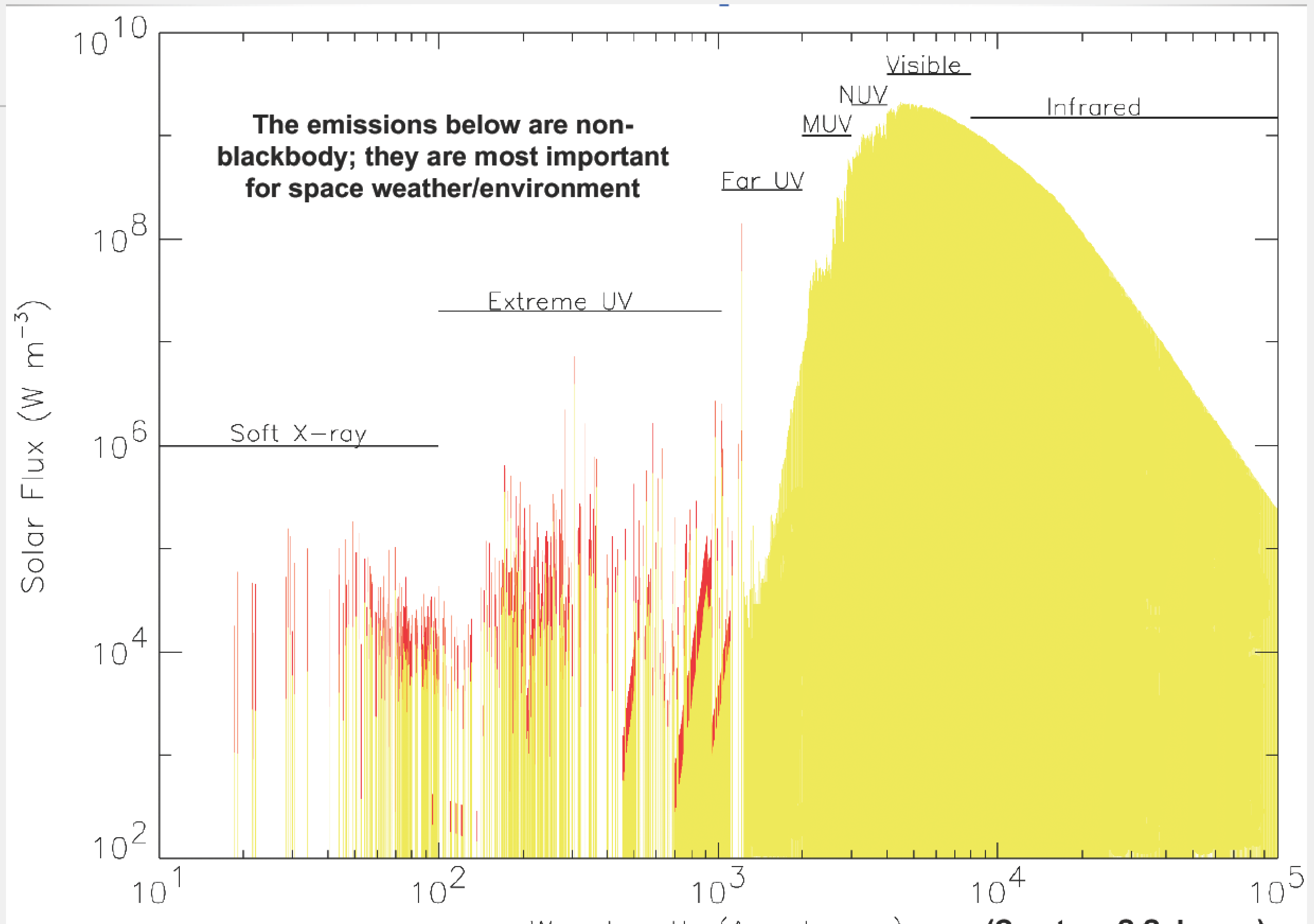
dissociation $N_2 + \gamma \rightarrow N + N$

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

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



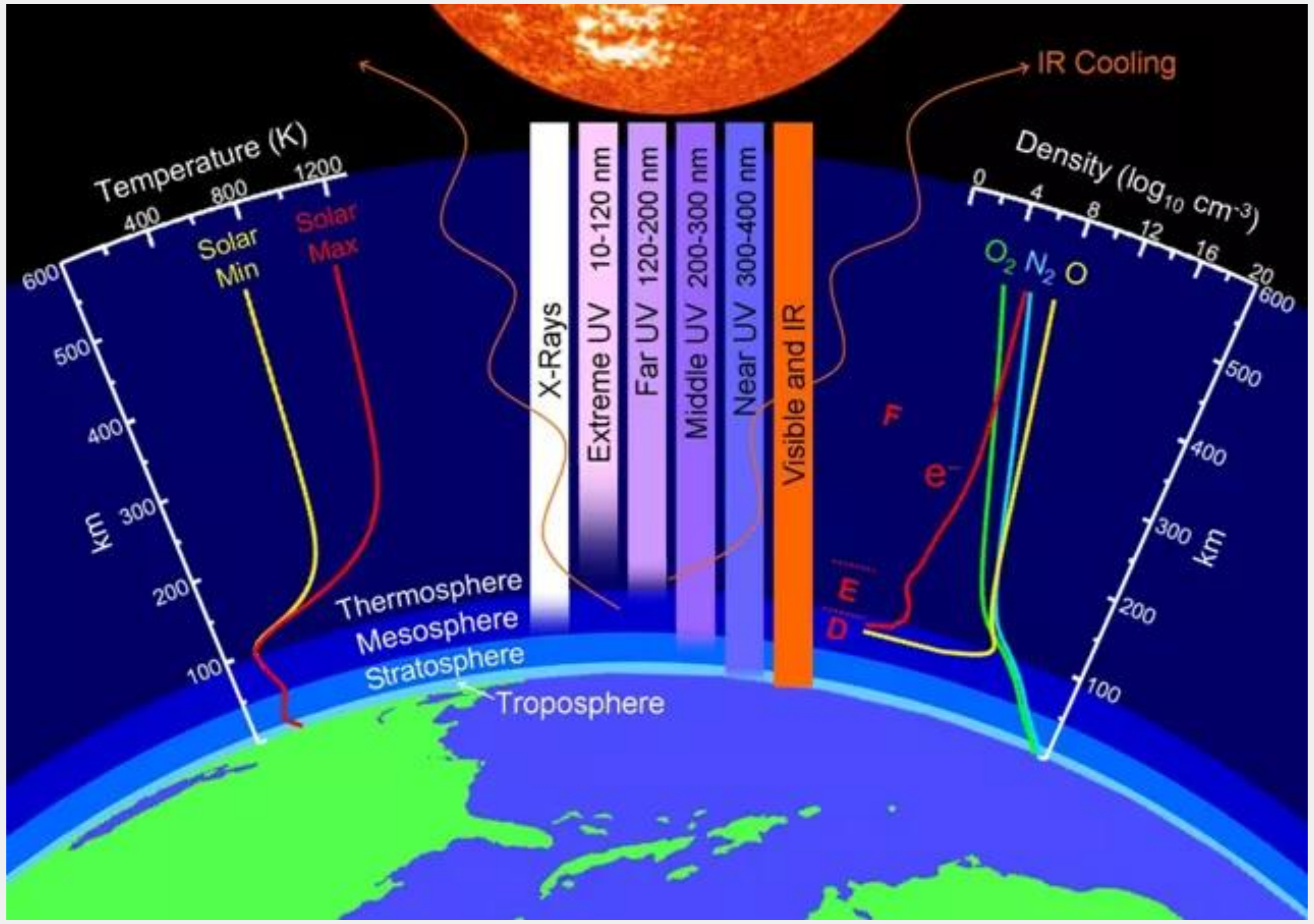


Compare to USW Fig 2-20

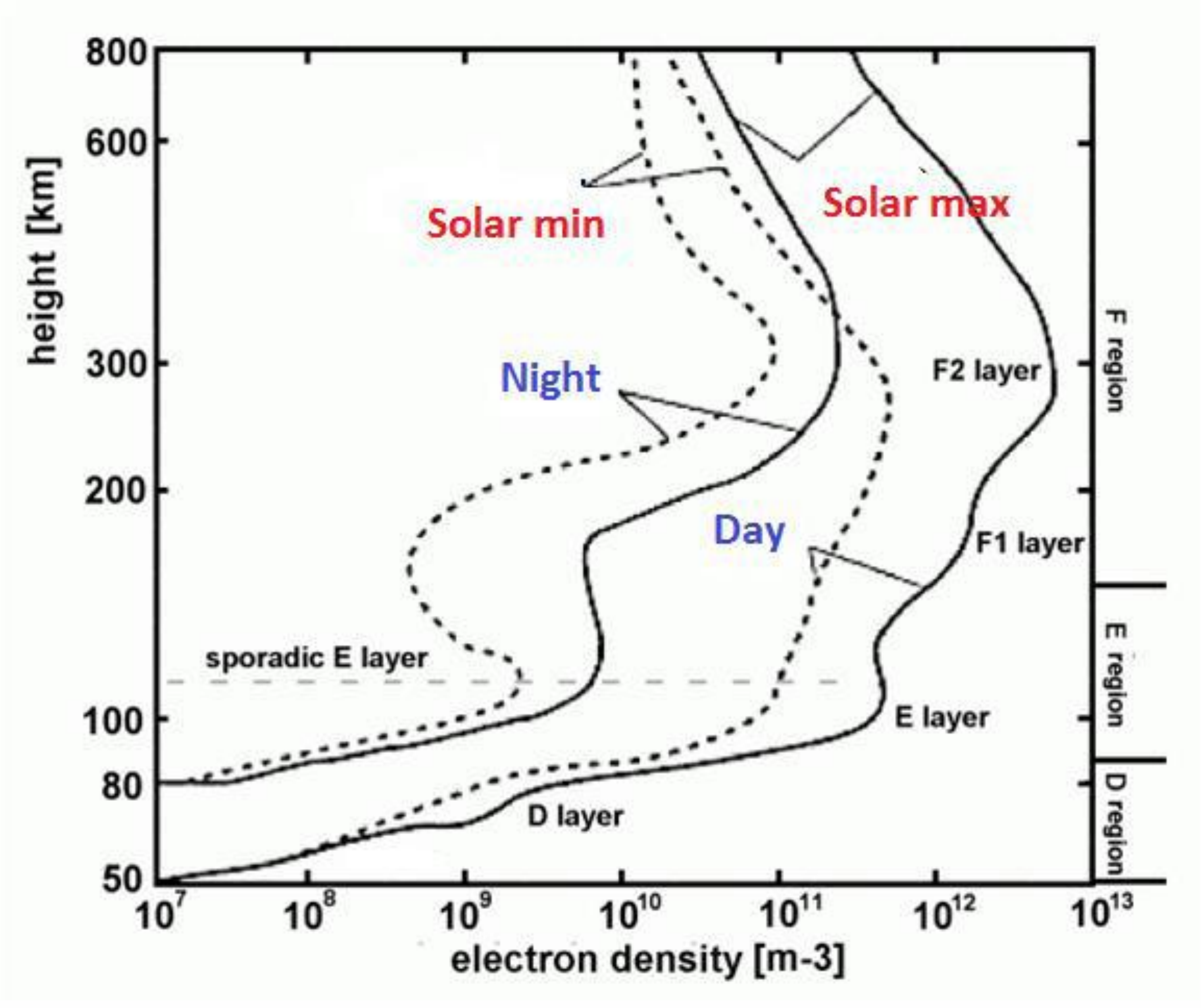
(Courtesy S Solomon)

	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

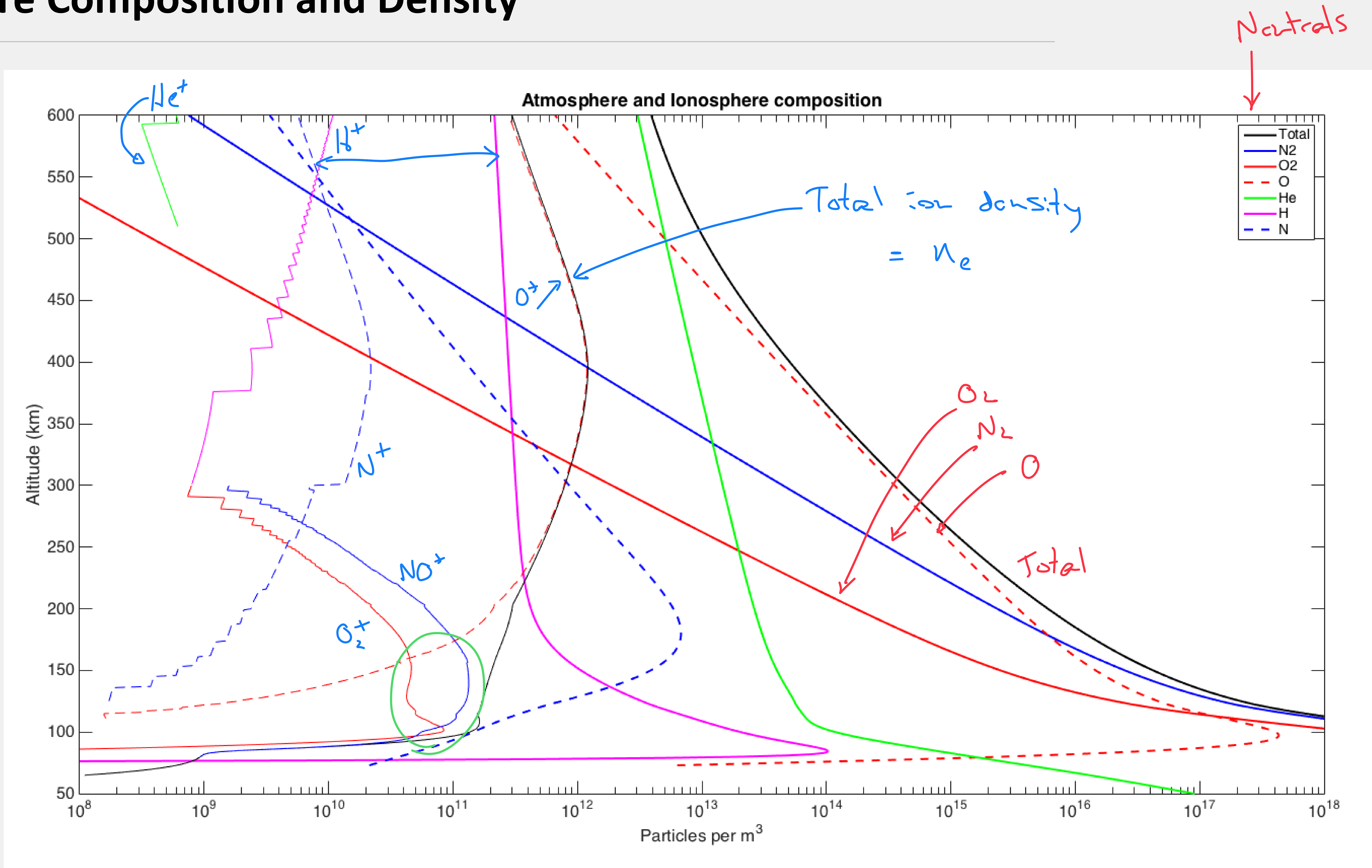


- Ionosphere altitudes and layers have a lot to do with where solar radiation is absorbed!



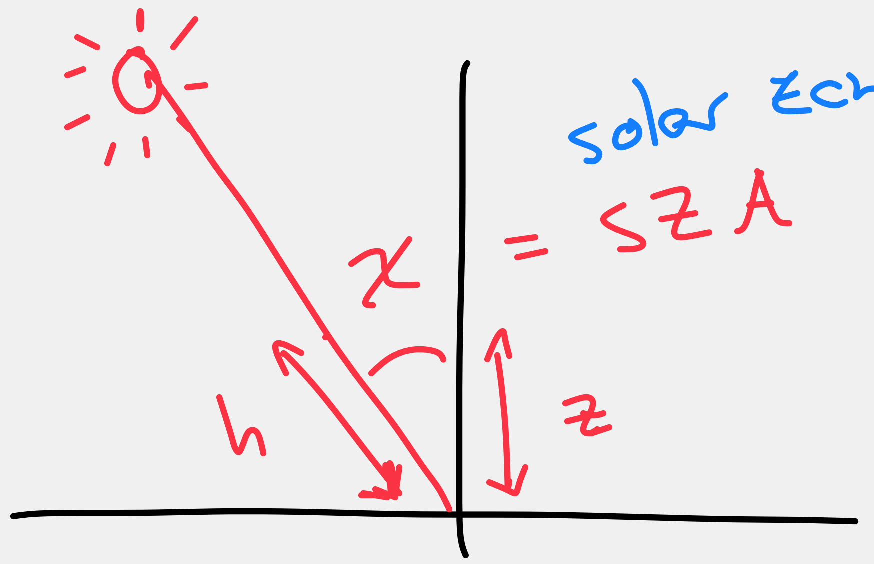
- Right: ionization density changes by 100x day vs night, and 10x or more with solar cycle

Ionosphere Composition and Density



Why is the Ionosphere finite in altitude?

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



solar zenith angle

χ = SZA

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

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

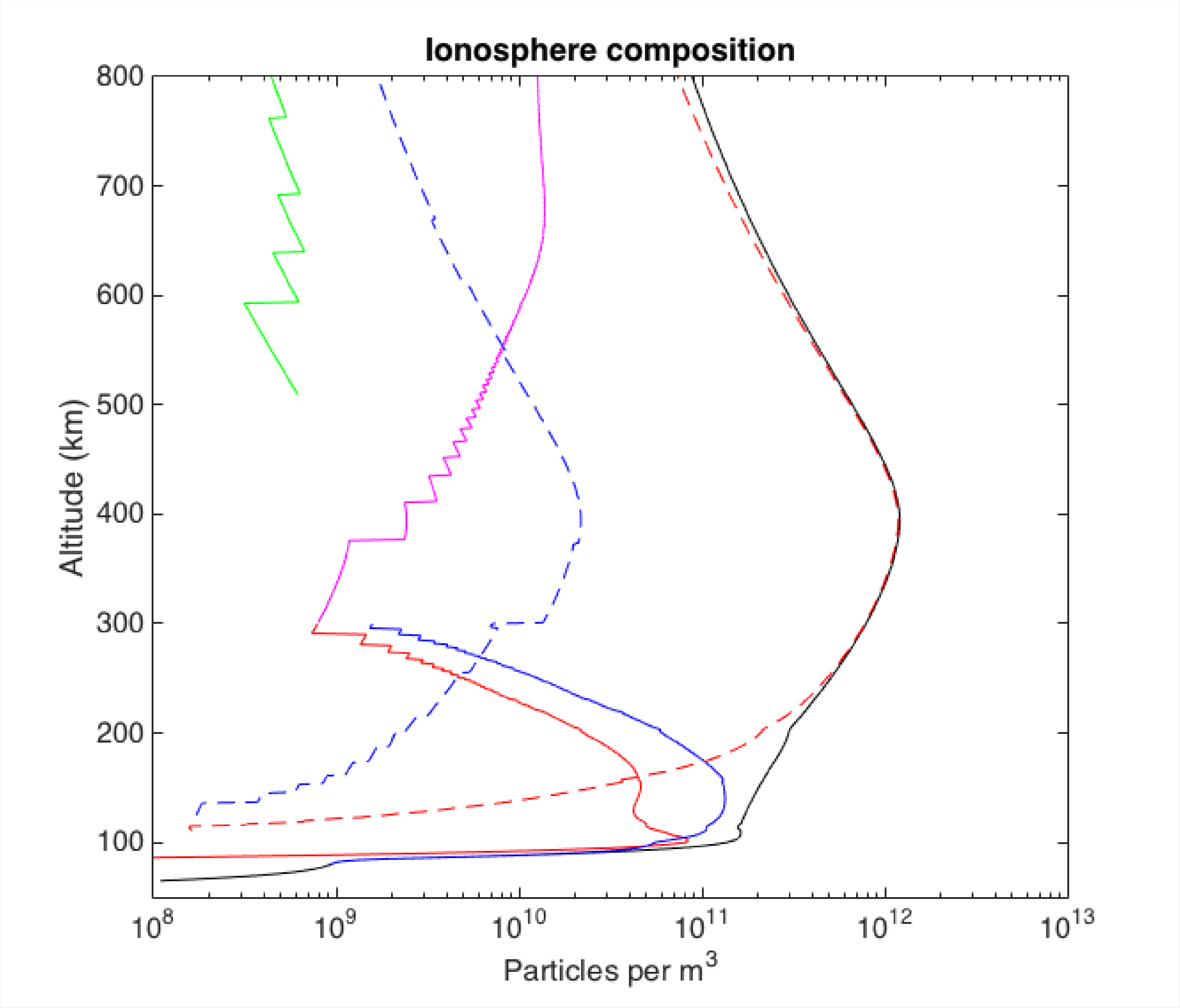
$$I(z) = I_\infty e^{-\int_\infty^z n(z) \sigma \sec \chi \, dz}$$

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

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

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

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



Chapman Layer

Ionization Production Rate, P (Q), pairs/m^3/sec

$$P = I(z, \lambda, \chi) \cdot n(z) \cdot \underbrace{\sigma \cdot \eta_i}_{\sigma_i\ (\mathrm{cm}^2),\ \text{ioniz. cross section}}$$

η_i: ionization efficiency, 0 – 1

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

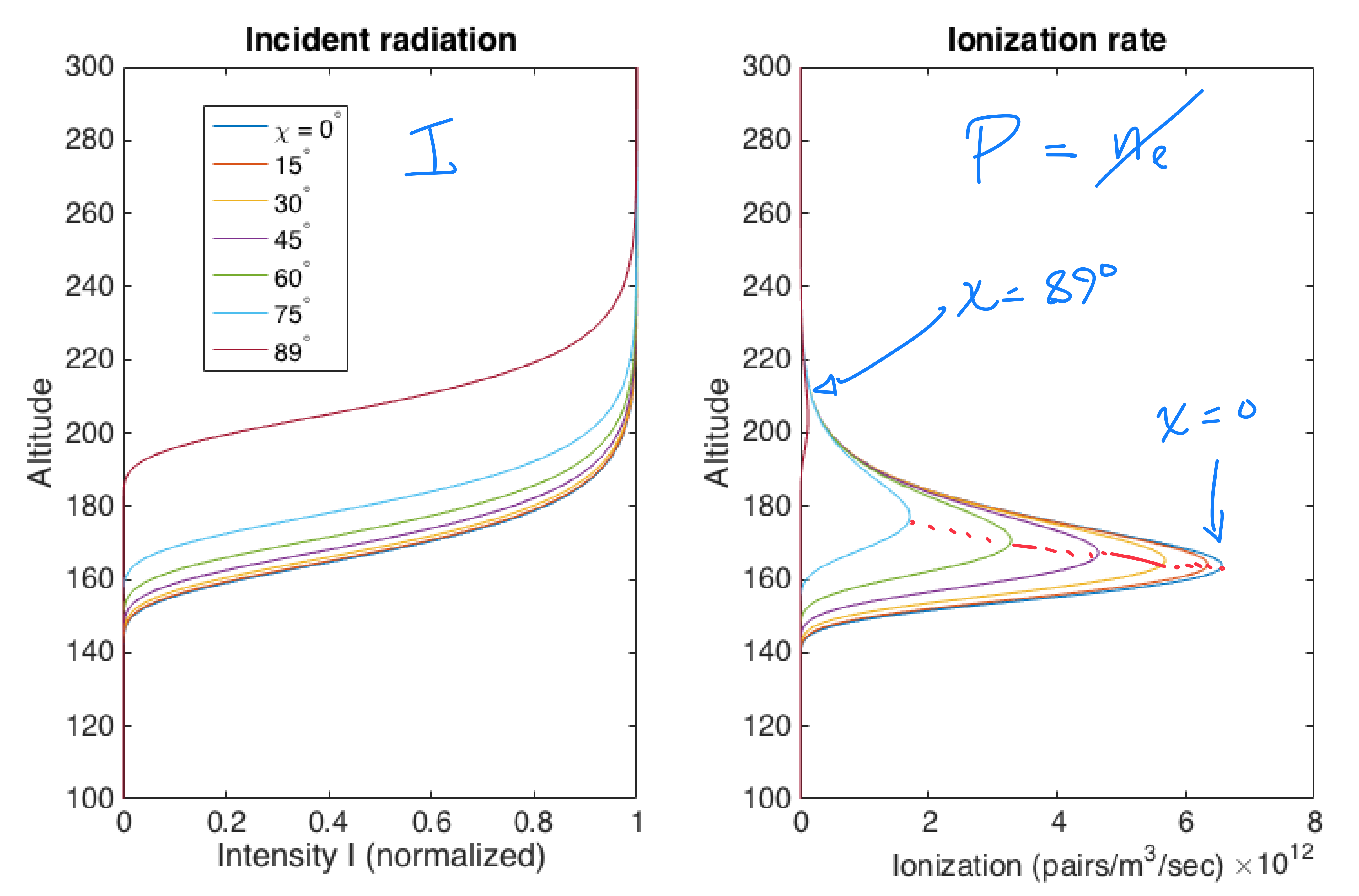
$n(z) = n_0 e^{-z/H}$

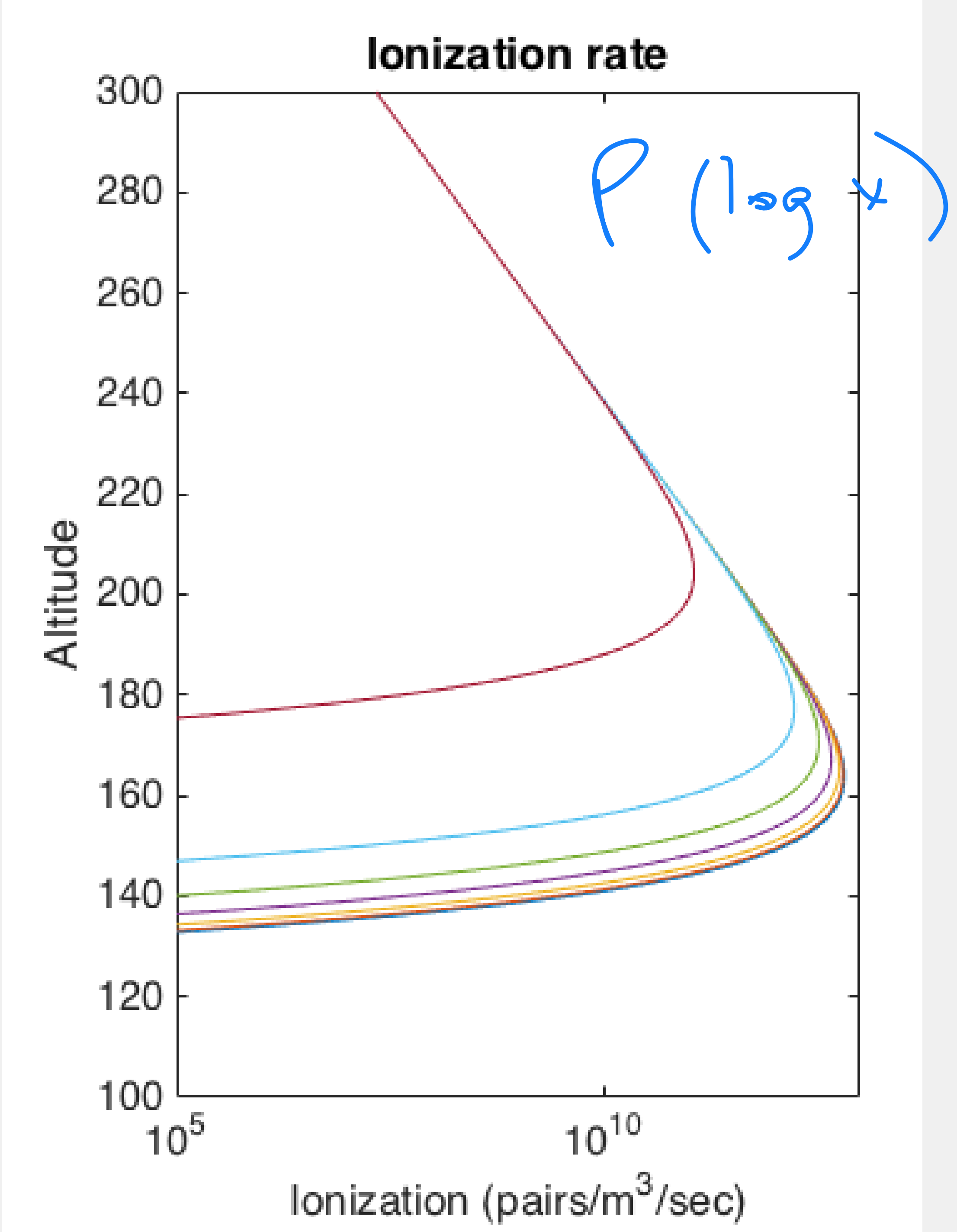
$$P = I_\infty \sigma \eta_i n_0 e^{-z/H} \exp\left(-H\sigma \sec\chi\, n_0 e^{-z/H}\right)$$

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

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





Ionization Chemistry

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

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

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

P: $O + \gamma \rightarrow O^+ + e^-$ (UV)

L: $O^+ + e^- \xrightarrow{\alpha} O + \gamma$ (IR)

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

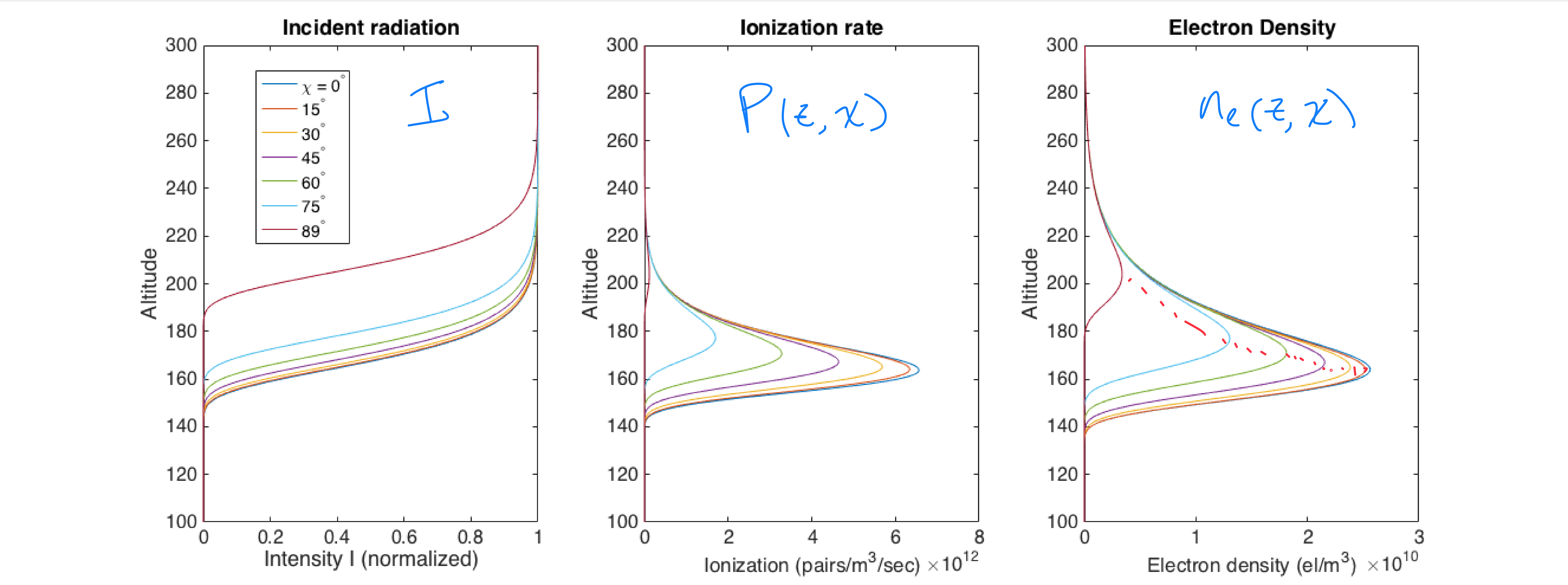
$$P = L \Rightarrow P = \alpha n_e^2 \Rightarrow \boxed{n_e = \sqrt{\frac{P}{\alpha}}}$$

Electron Density Profile

- Balancing production (ionization) with loss (recombination), we get an equilibrium electron (or ion) density below
- Higher, less dense for increasing zenith angle
  - Reminder: this is for a single species, and single photon wavelength!

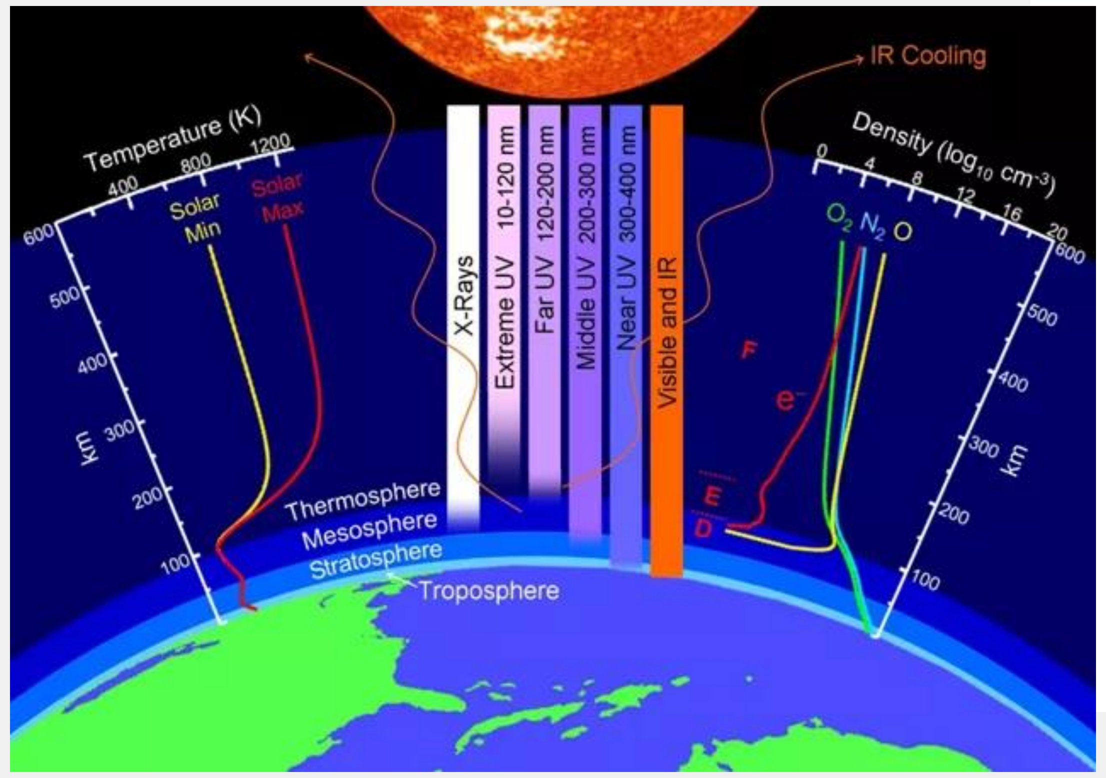
$$n_e = \sqrt{\frac{P}{\alpha}} = \sqrt{\frac{P_{max}}{\alpha}} \exp\left(0.5\left(1 - z_1 - e^{-z_1}\right)\right)$$

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

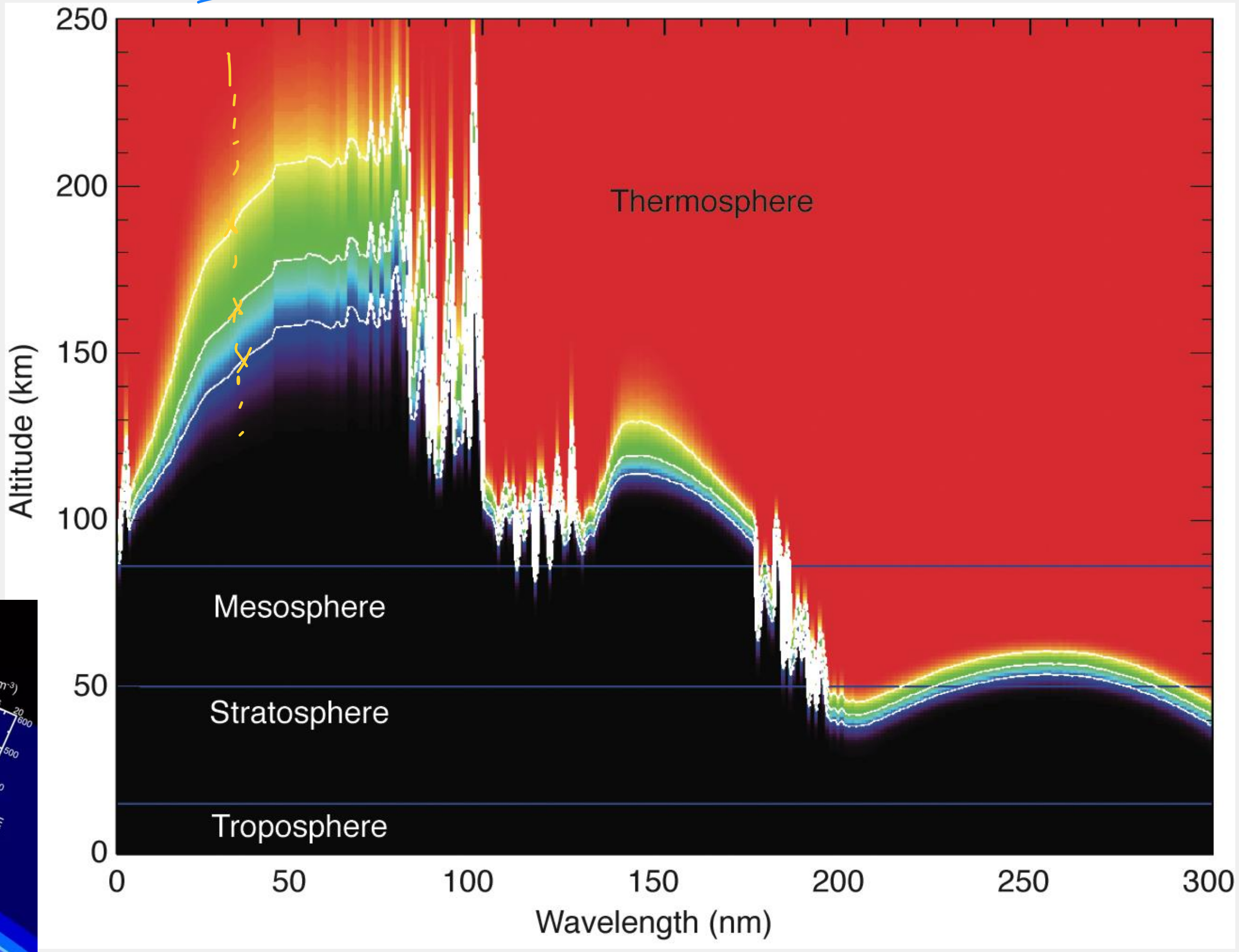


Ionosphere Layers

- 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

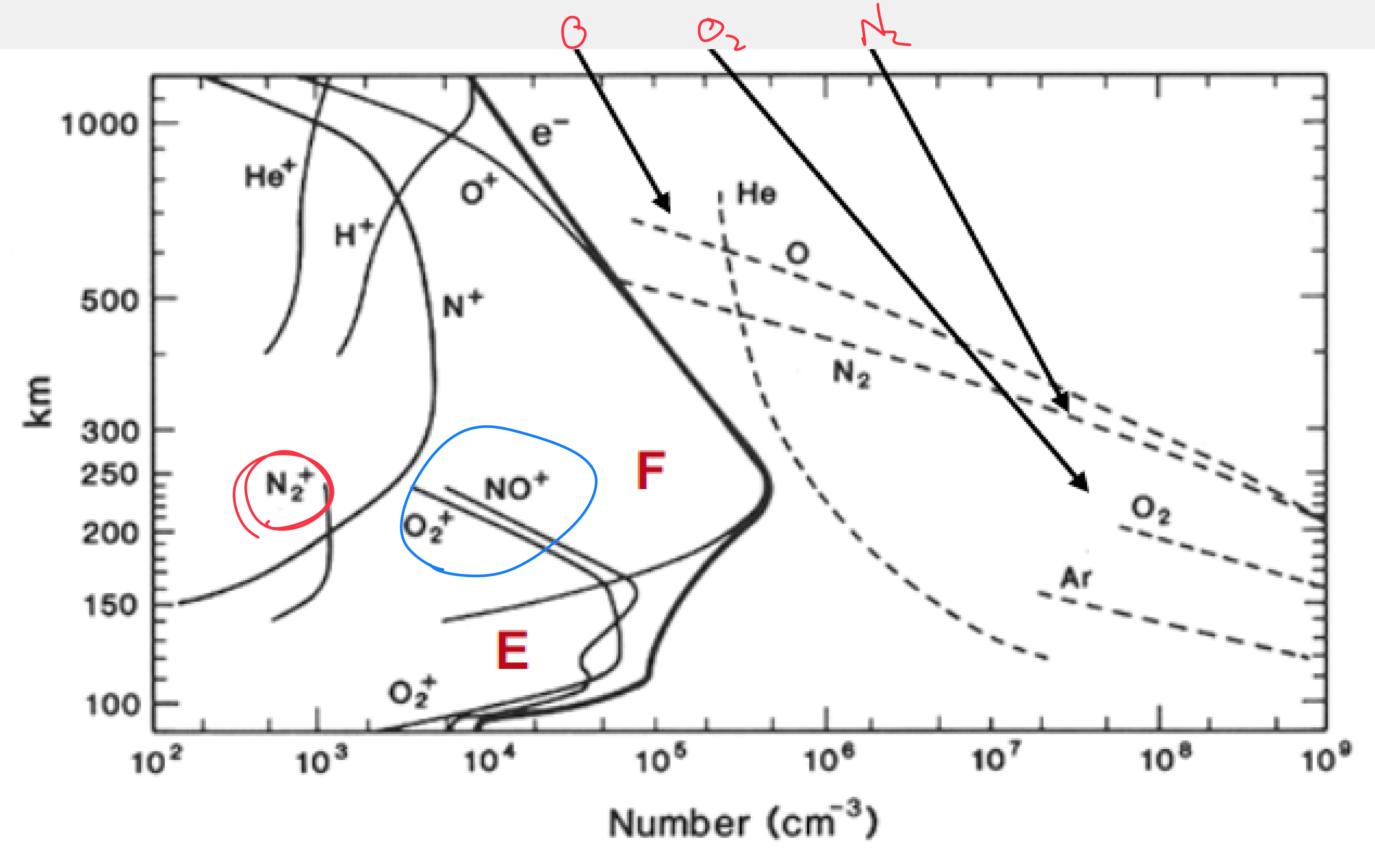


I(z)



Another way of looking at it

- Ionosphere layers depend on composition (atmosphere) and radiation (solar spectrum and flux)
- D, E, and F regions are dominated by different ions, depending on the neutral species



Primary Production / Loss channels

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

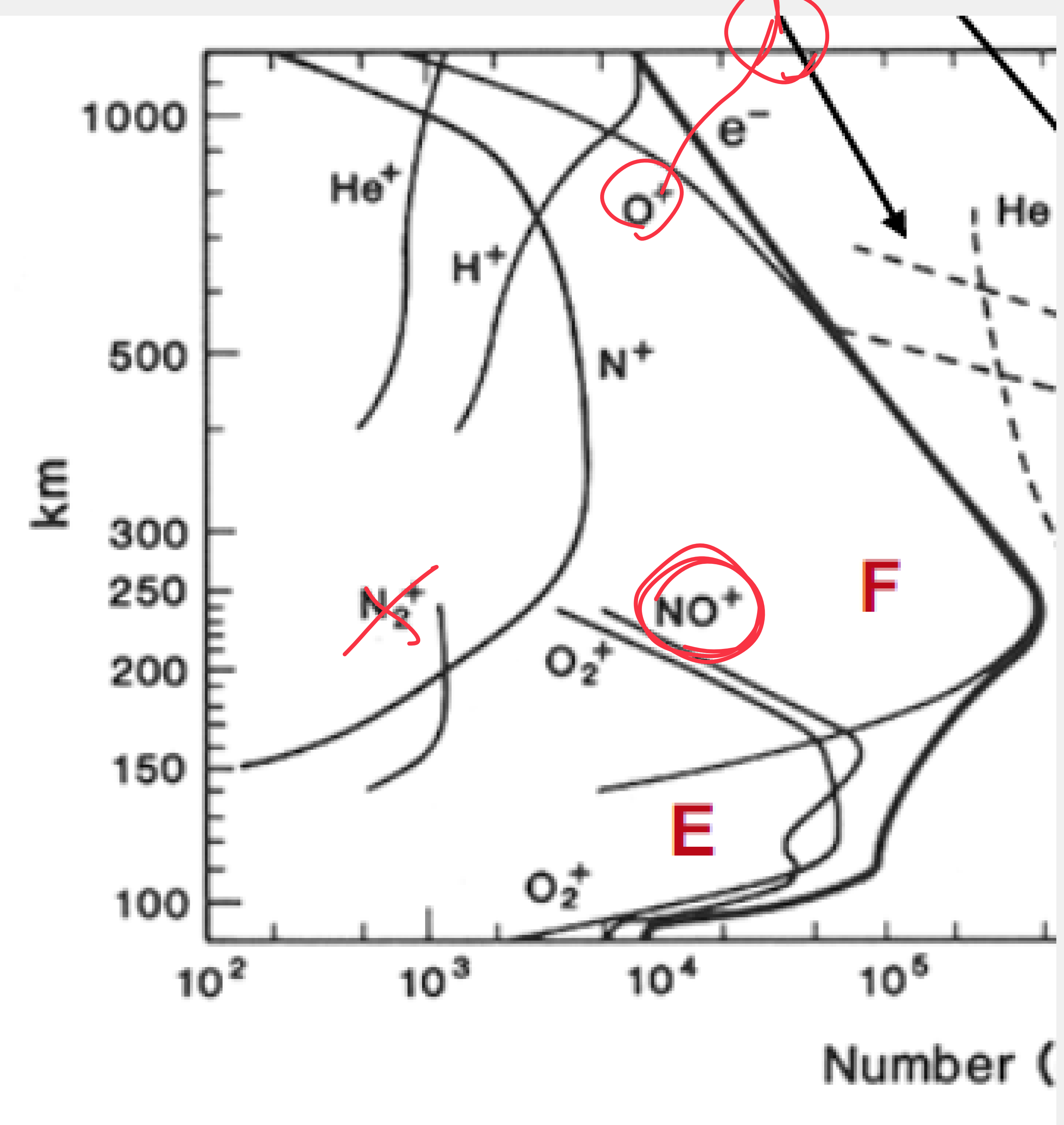
$O_2 + \gamma \rightarrow O_2^+ + e^-$

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

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

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

↓protons



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

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

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

meta-stable

630 nm
577.7 nm

E-region

→ chapman

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

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

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

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

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

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

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

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

F-region : F1

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

(some N_2 ionization)

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

instead

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

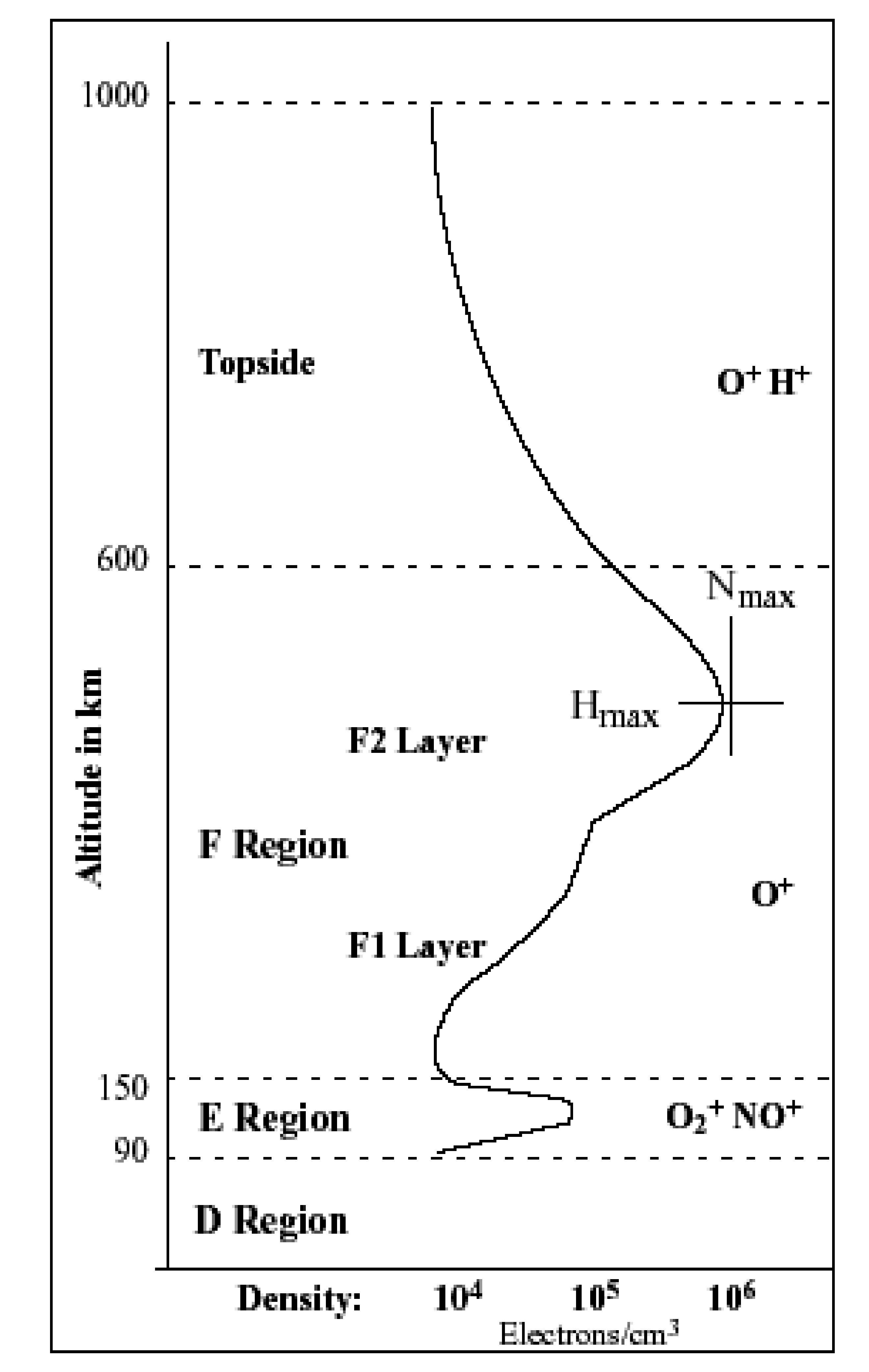
$$O^+ + N_2 \rightarrow \cancel{N_2^+ + O}\ NO^+ + N$$

then:

$$\star \quad \boxed{O_2^+ + e^- \xrightarrow{\alpha'}} O + O$$

$$NO^+\ \cancel{N_2^+} + e^- \xrightarrow{\alpha_2} N + O$$

$$L = \alpha' n_{O_2^+} n_e + \alpha_2 n_{NO^+} n_e \simeq \alpha n_e^2, \quad \text{chapman!}$$



F-region

: F2

3 chapmans

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

charge exchange

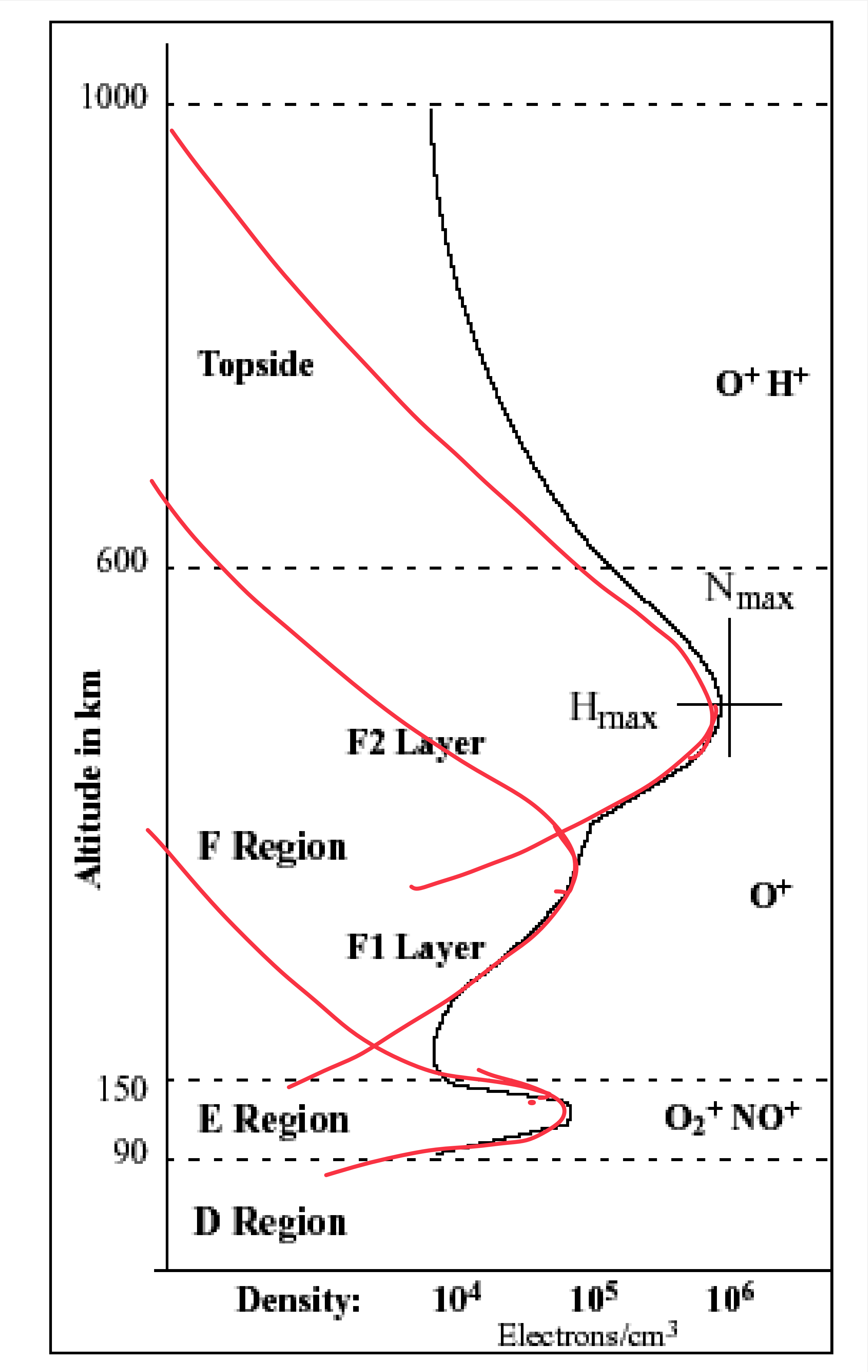
$$\boxed{O^+ + O_2 \xrightarrow{\alpha'}} O_2^+ + O$$

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

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

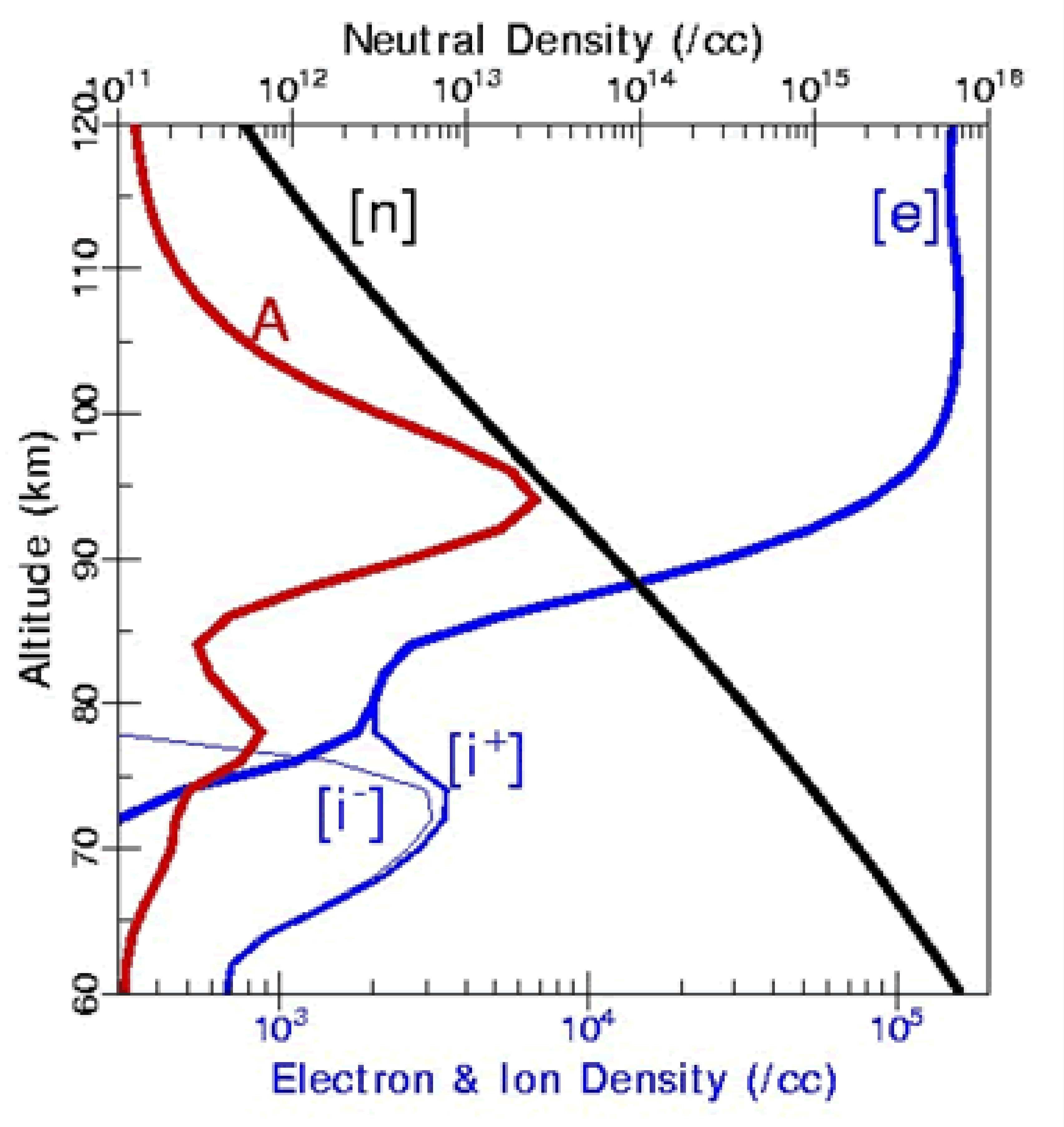
other factors

* dynamics : vertical transport
  - diffusion
* electrostatic forces



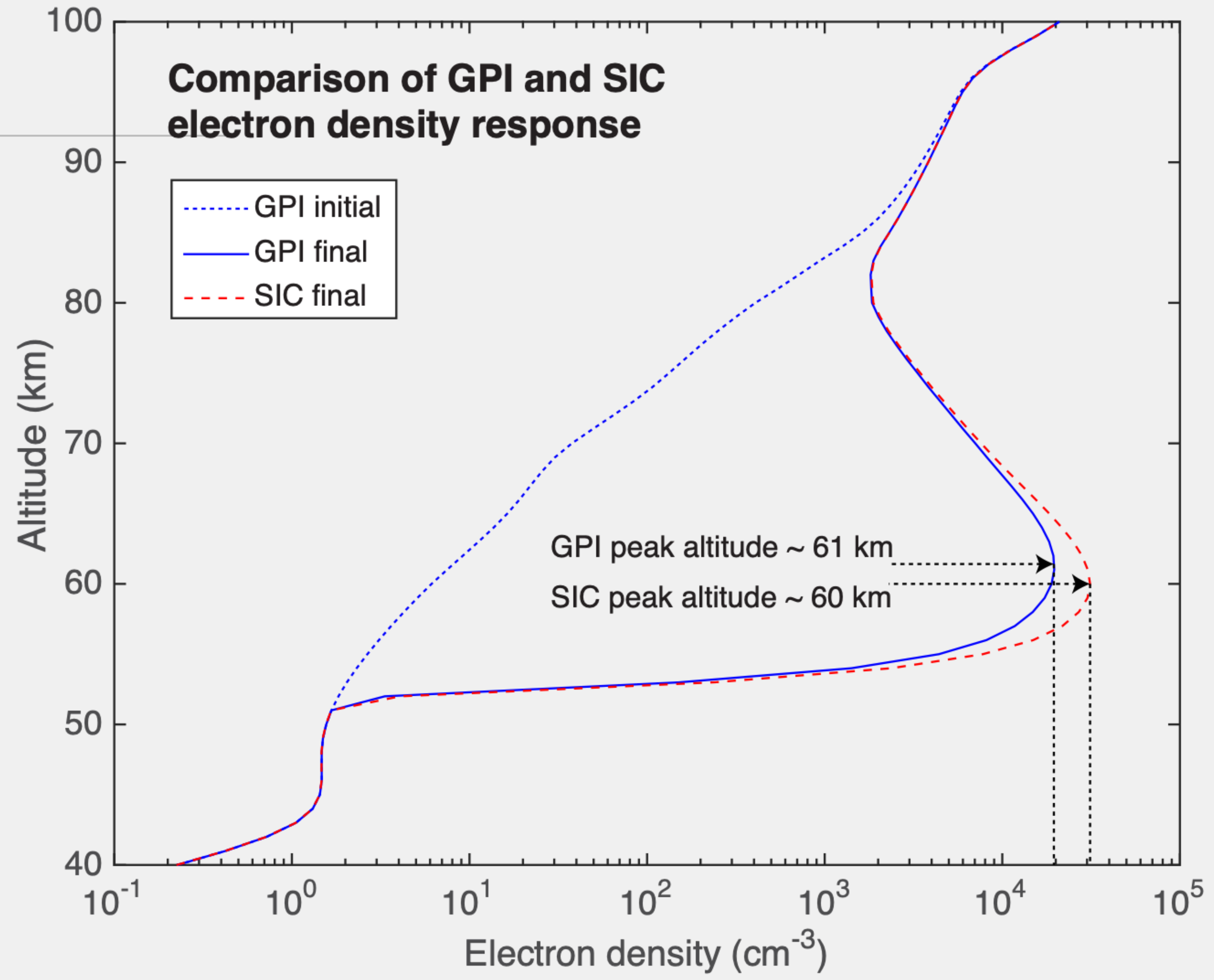
D-region

- 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



$\frac{dn_e}{dt} = P - L$ $\quad P - \alpha n_e^2$

Glukhov Pasko Inan (GPI) 2009 model:

$$\frac{dN_e}{dt} = Q - \beta N_e + \gamma N^- + \gamma_x N_x^- - (\alpha_d N^+ + \alpha_d^c N_x^+) N_e$$

$$\frac{dN^-}{dt} = \beta N_e - \gamma N^- - \alpha_i (N^+ + N_x^+) N^- - A N^-$$

$$\frac{dN_x^-}{dt} = -\gamma_x N_x^- - \alpha_i (N^+ + N_x^+) N_x^- + A N^-$$

$$\frac{dN^+}{dt} = Q - \alpha_d N_e N^+ - \alpha_i (N^- + N_x^-) N^+ - B N^+$$

$$\frac{dN_x^+}{dt} = \alpha_d^c N_e N_x^+ - \alpha_i (N^- + N_x^-) N_x^+ + B N^+$$

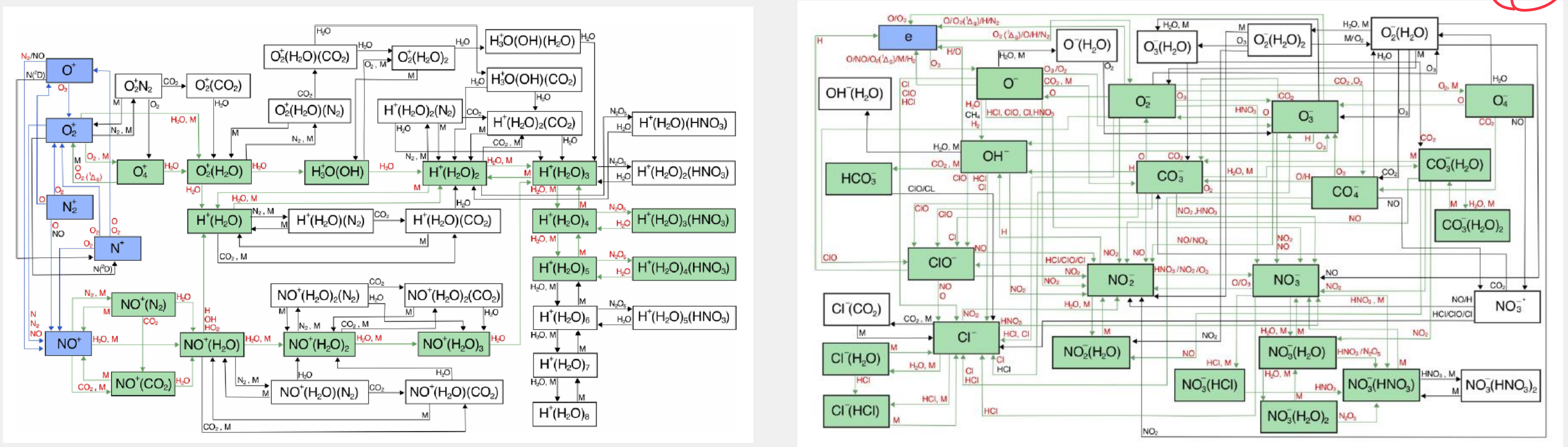
P

P

+

Sodankyla Ion and Neutral Chemistry (SIC) model:

−

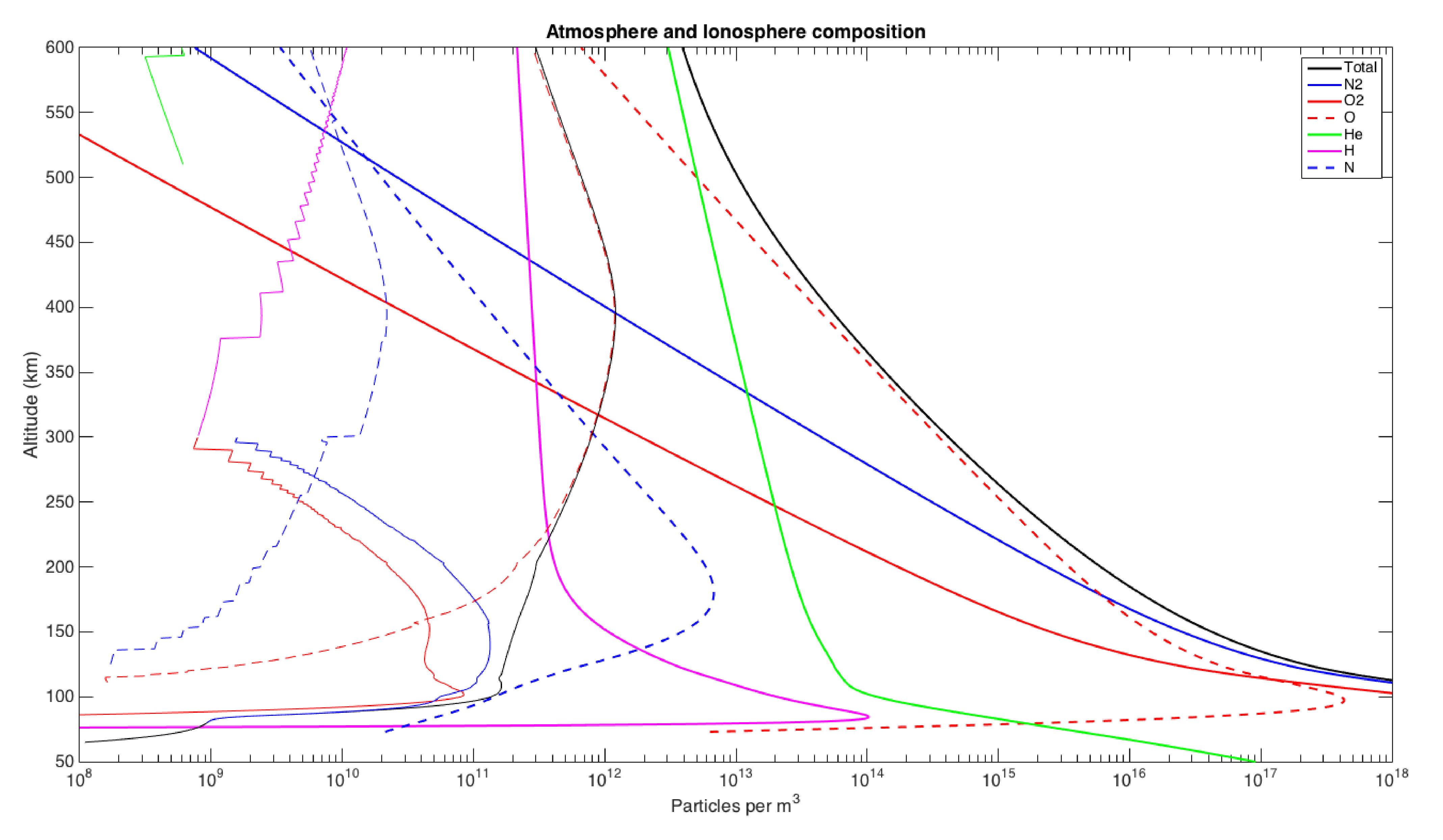


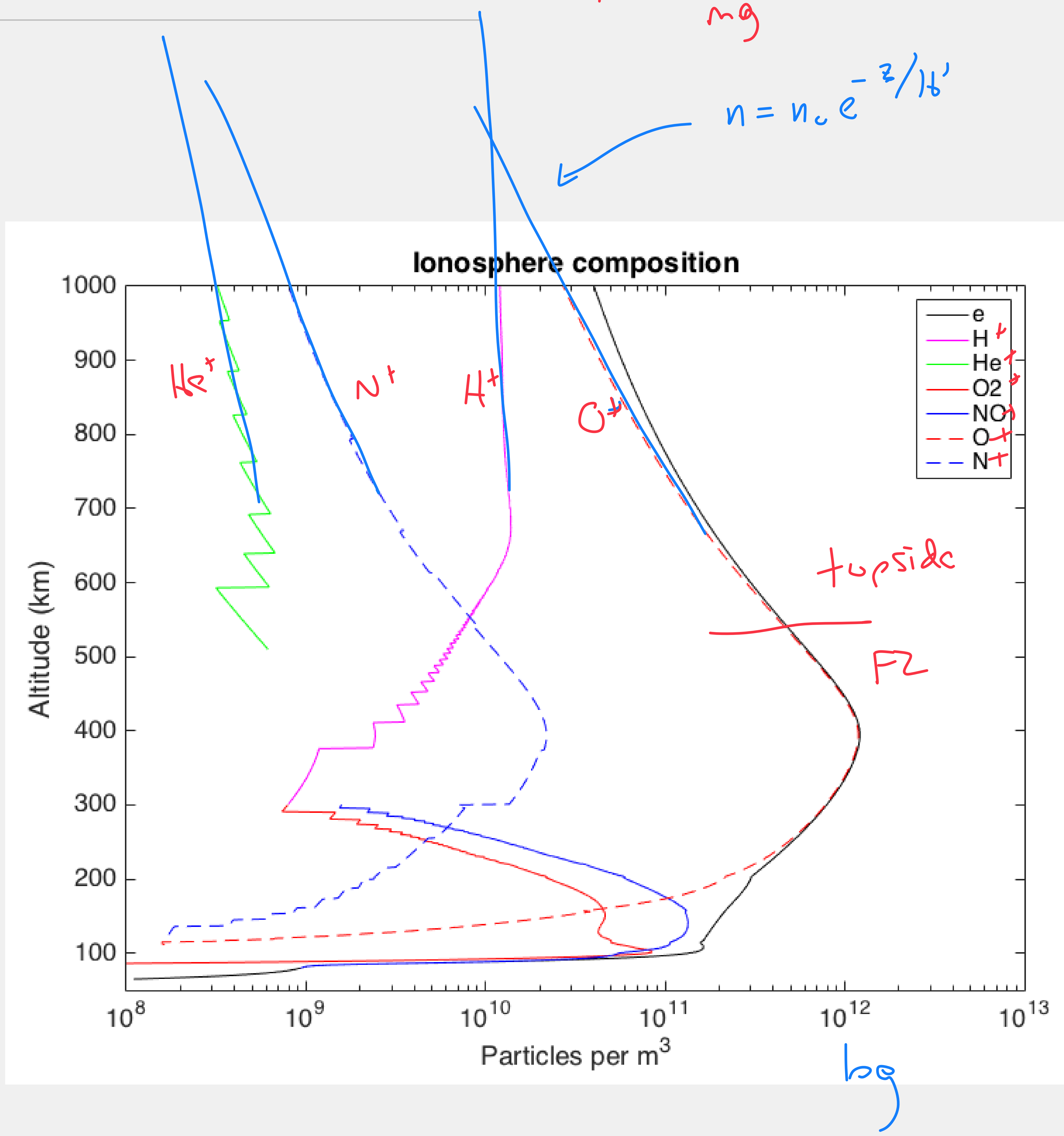
Topside Ionosphere

$H \sim \frac{kT}{mg}$

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

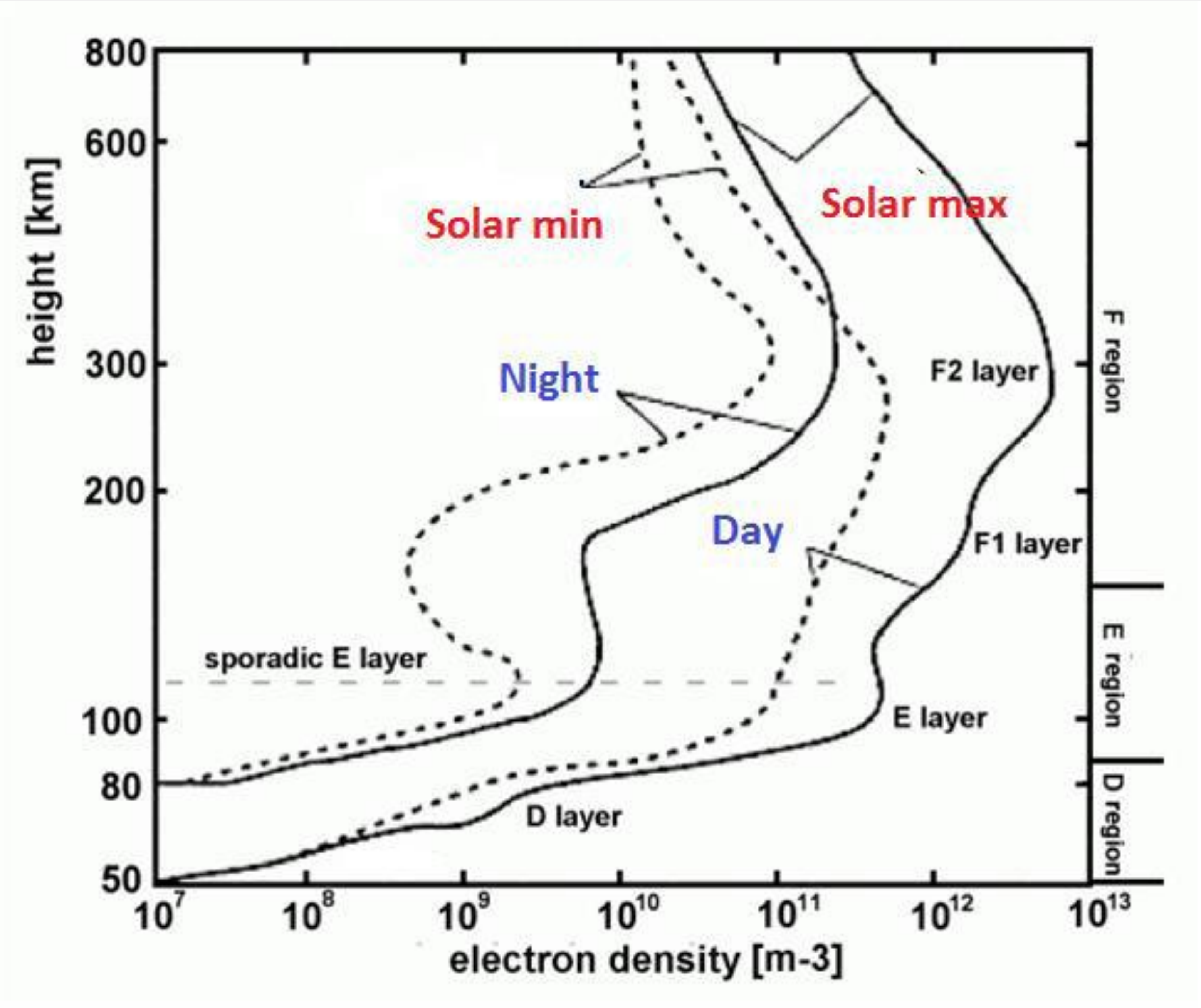
- Above ~350 km, densities are so low that ions are not dominated by chemistry, but **diffusive equilibrium**





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.

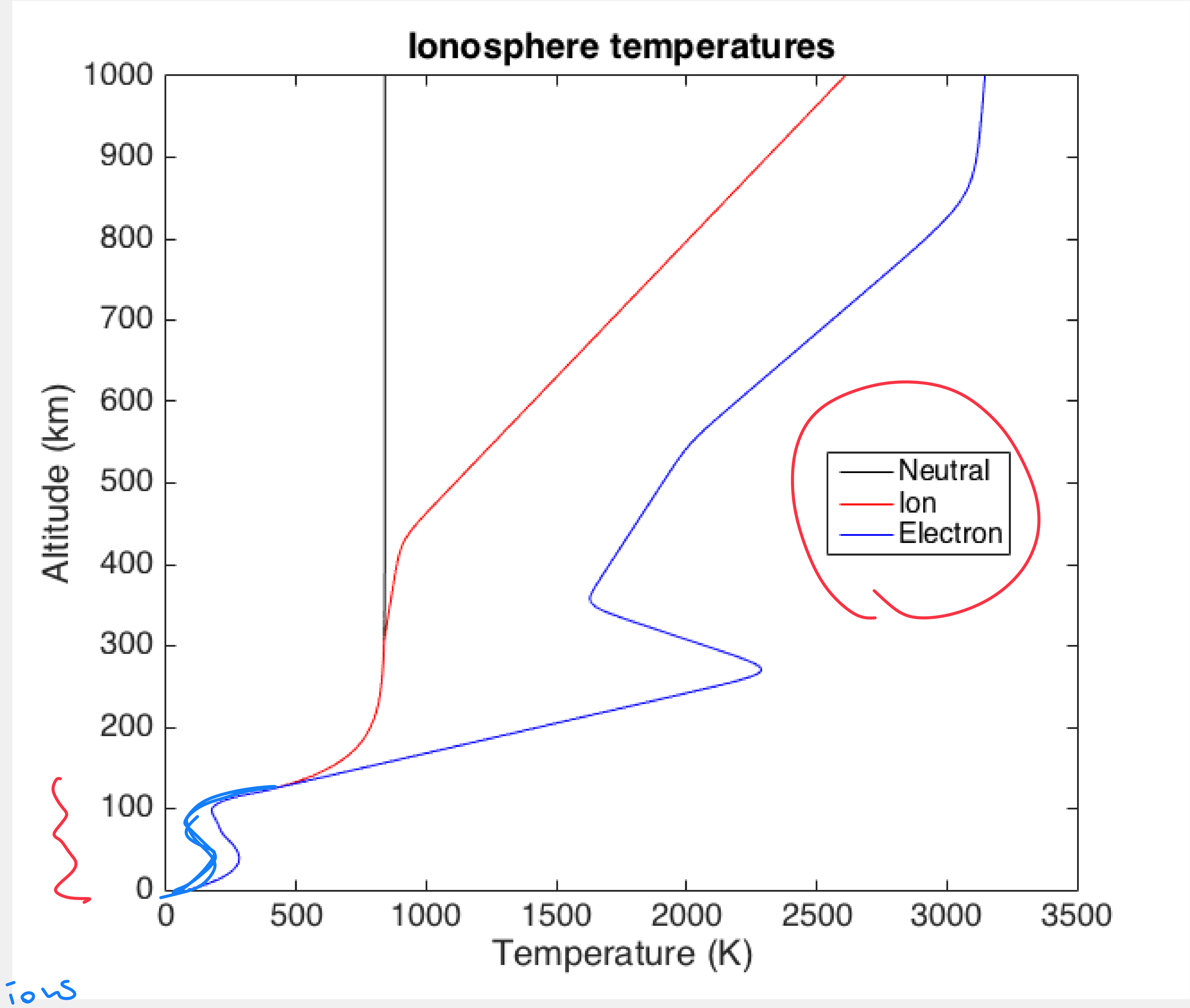
Ionosphere Temperatures

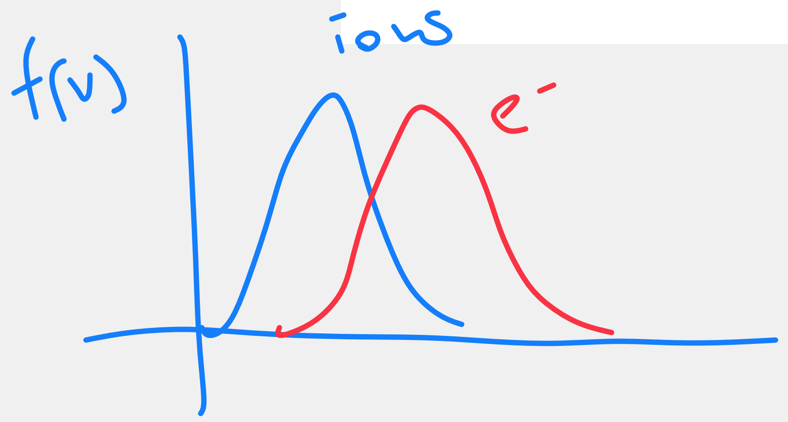
collisions
(nu)

B-field

$\nu \leftrightarrow B$

- 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

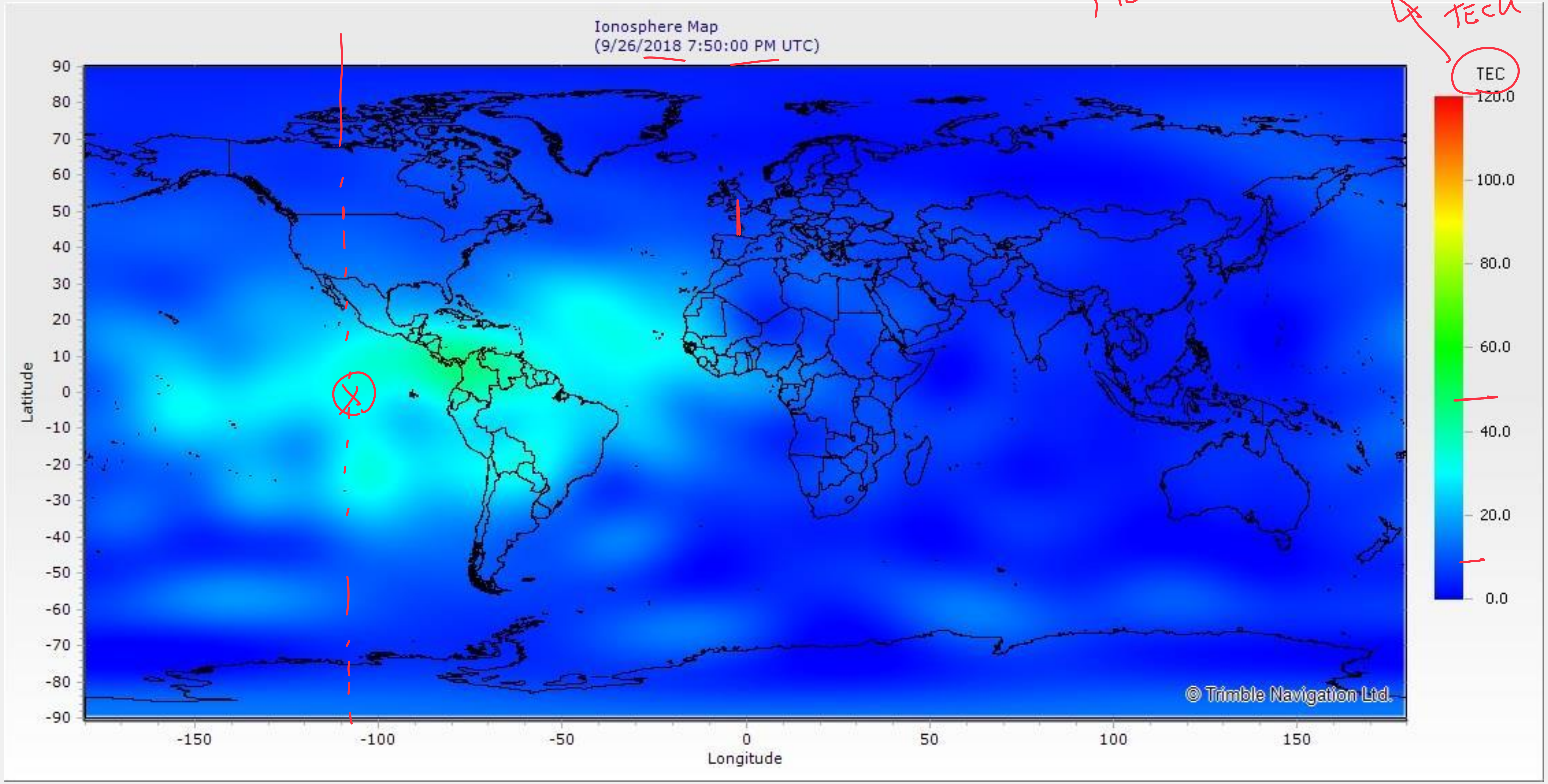
- Variety of processes move plasma in the ionosphere:
  - **Winds**: neutral winds drag ions along with them, if collision frequency is high enough
  - **Drifts**: various forces cause plasma to “drift”: electric and magnetic fields; gravity; pressure; etc.
- **These contribute to complex spatial and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

Global variation: Snapshots

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

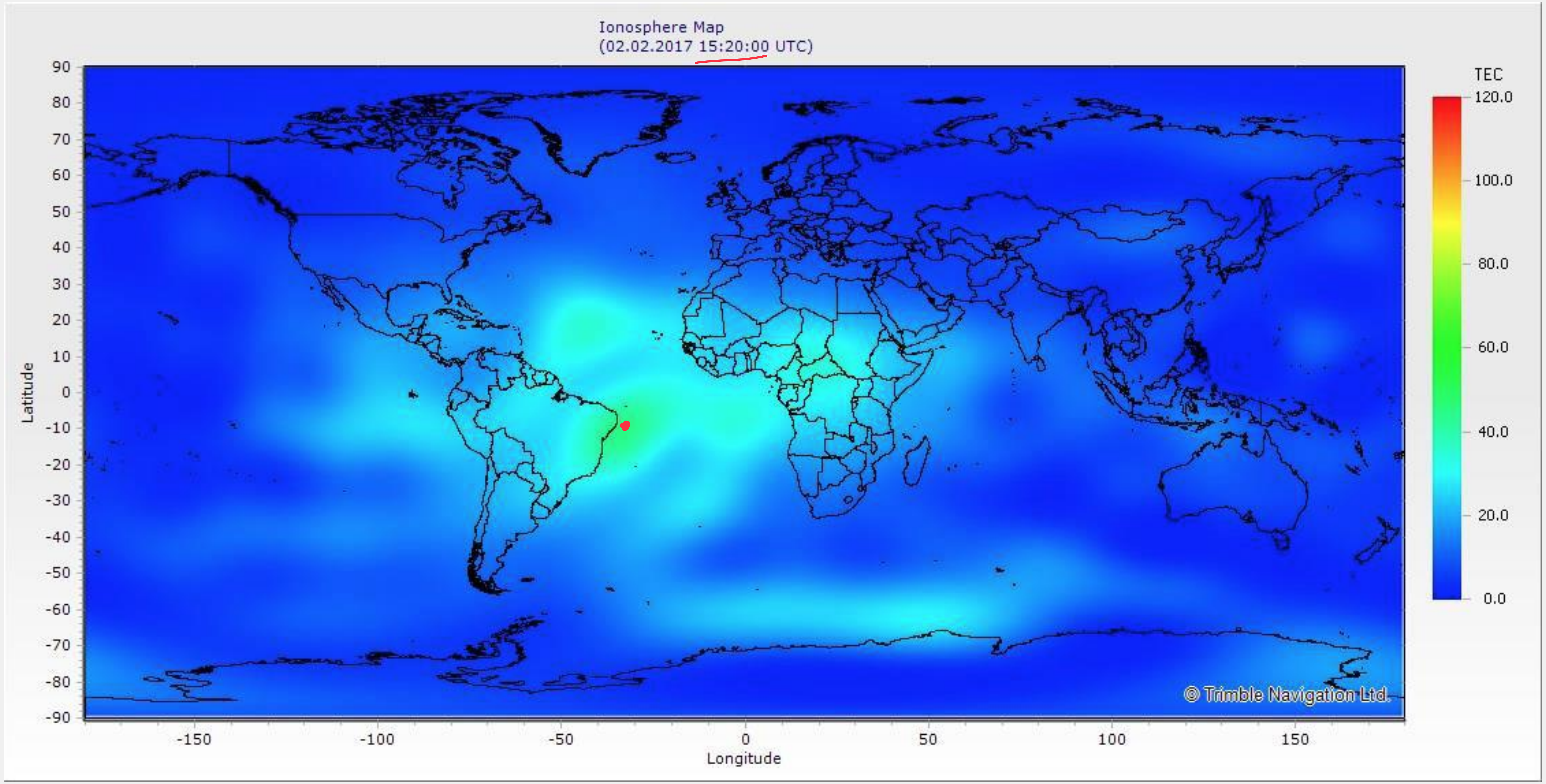
1 TECU = 10^{16} e^-/m^2

TECU



Global variation: Snapshots

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



foF2 and hmF2

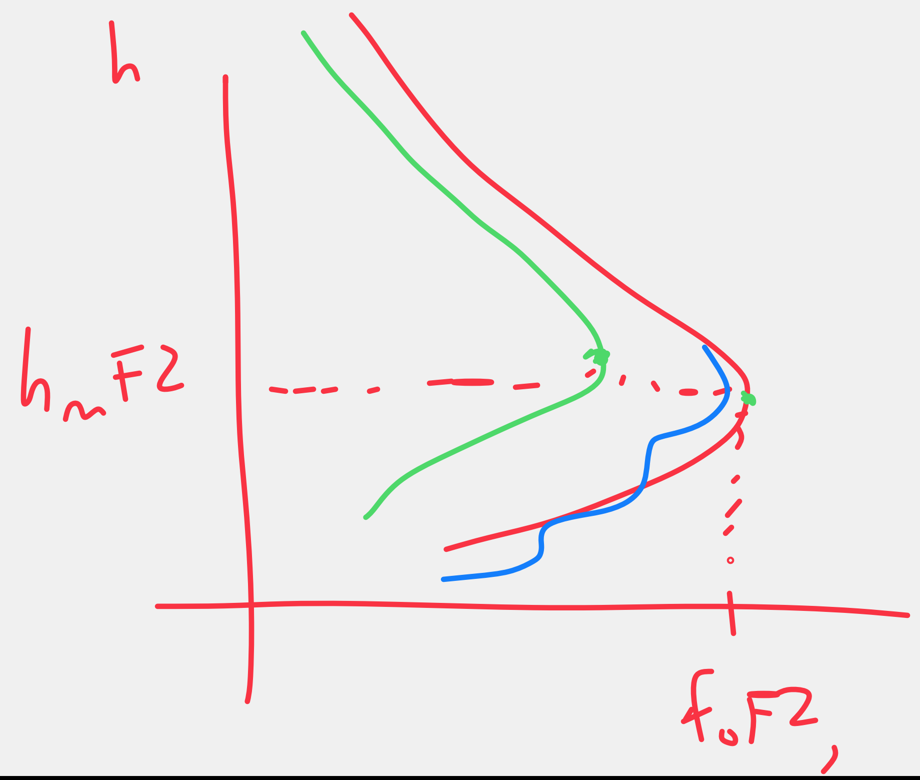
- We often characterize the ionosphere by its peak density, foF2, and the altitude where that occurs, hmF2
- foF2 is a frequency in MHz. related to electron density:

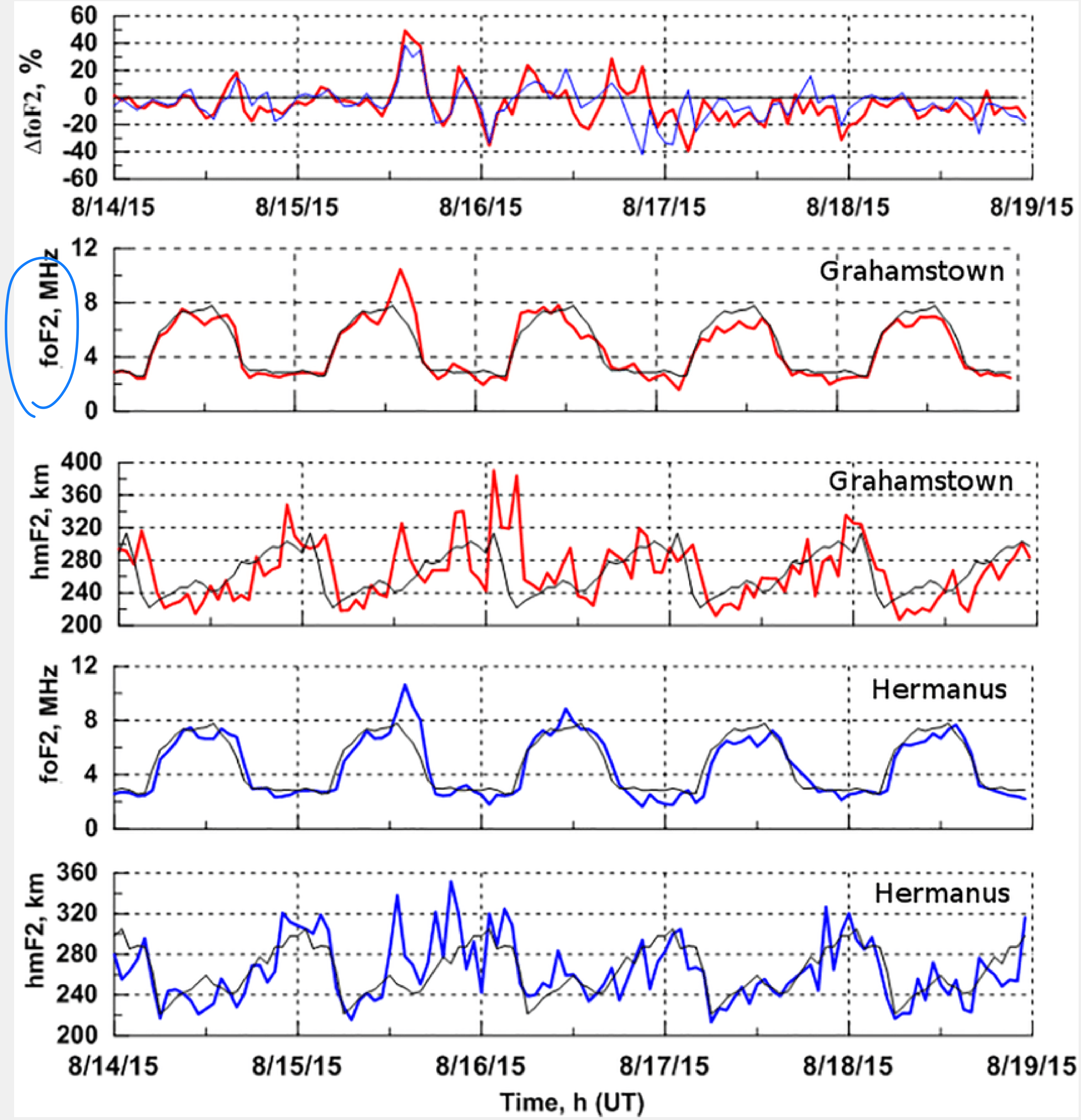
$$\omega_{pe} = \sqrt{\frac{n_e q_e^2}{m_e \epsilon_0}} \sim \sqrt{n_e}$$

(kHz)

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

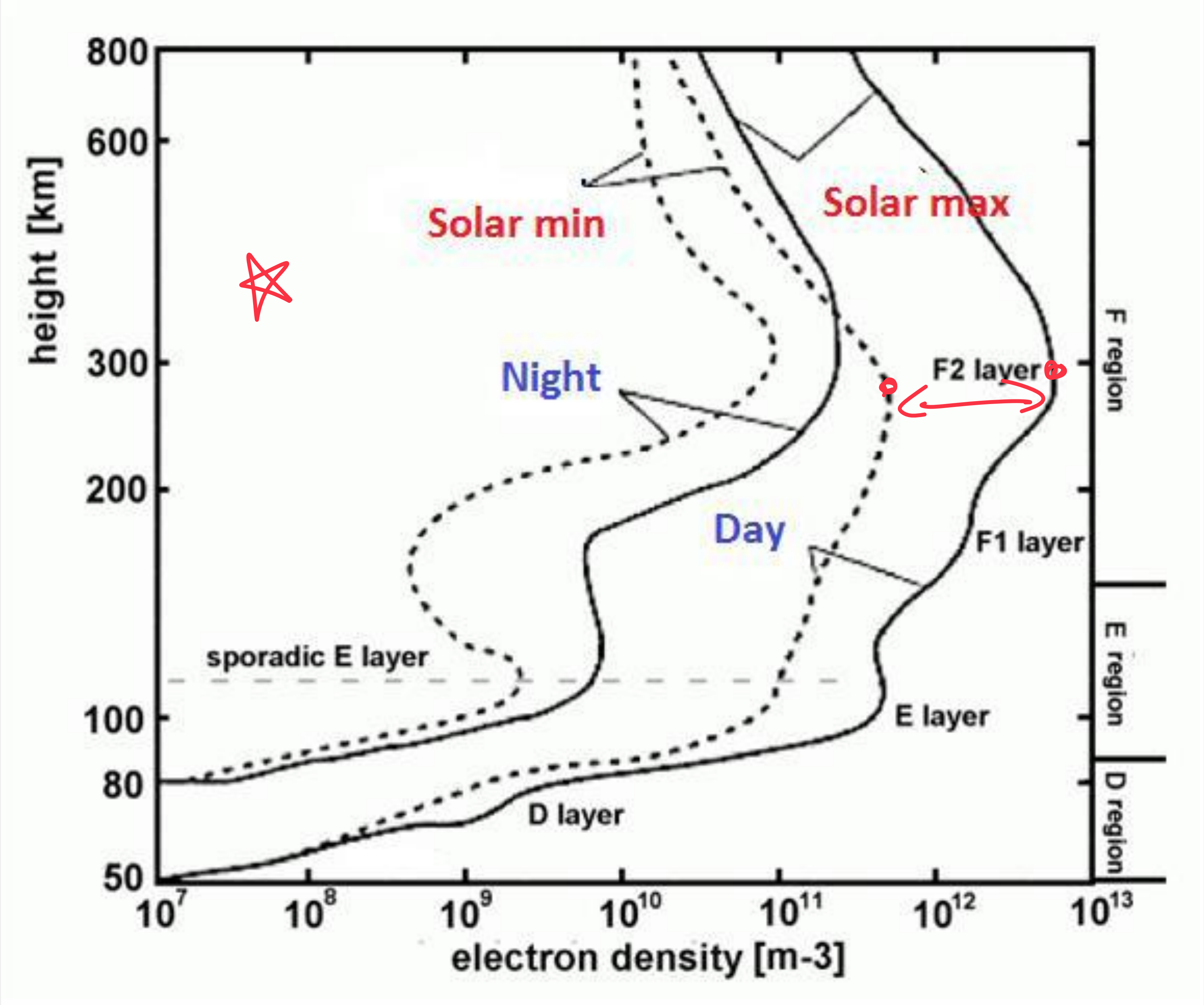
- hmF2 is simply altitude in km

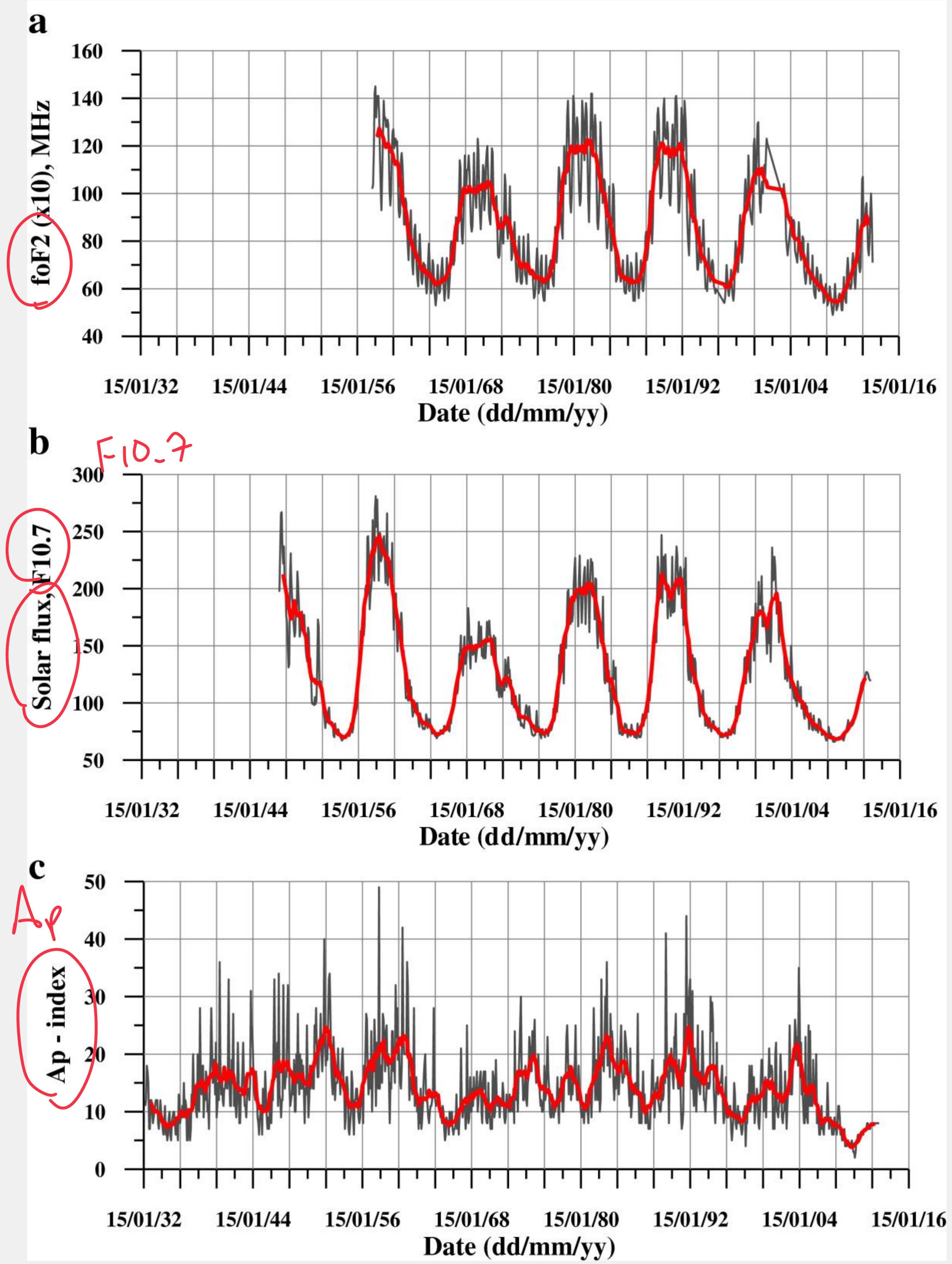




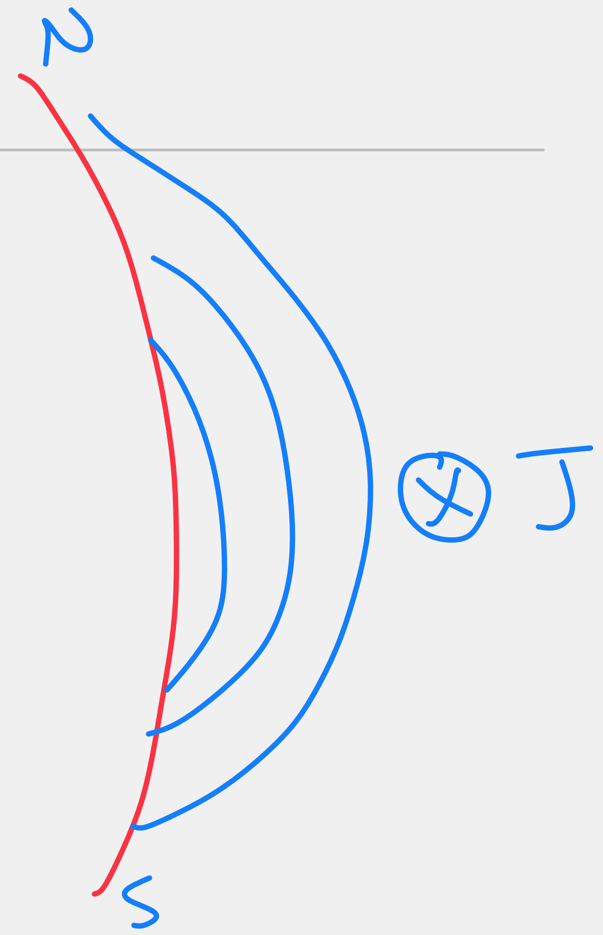
Solar Cycle Variation

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



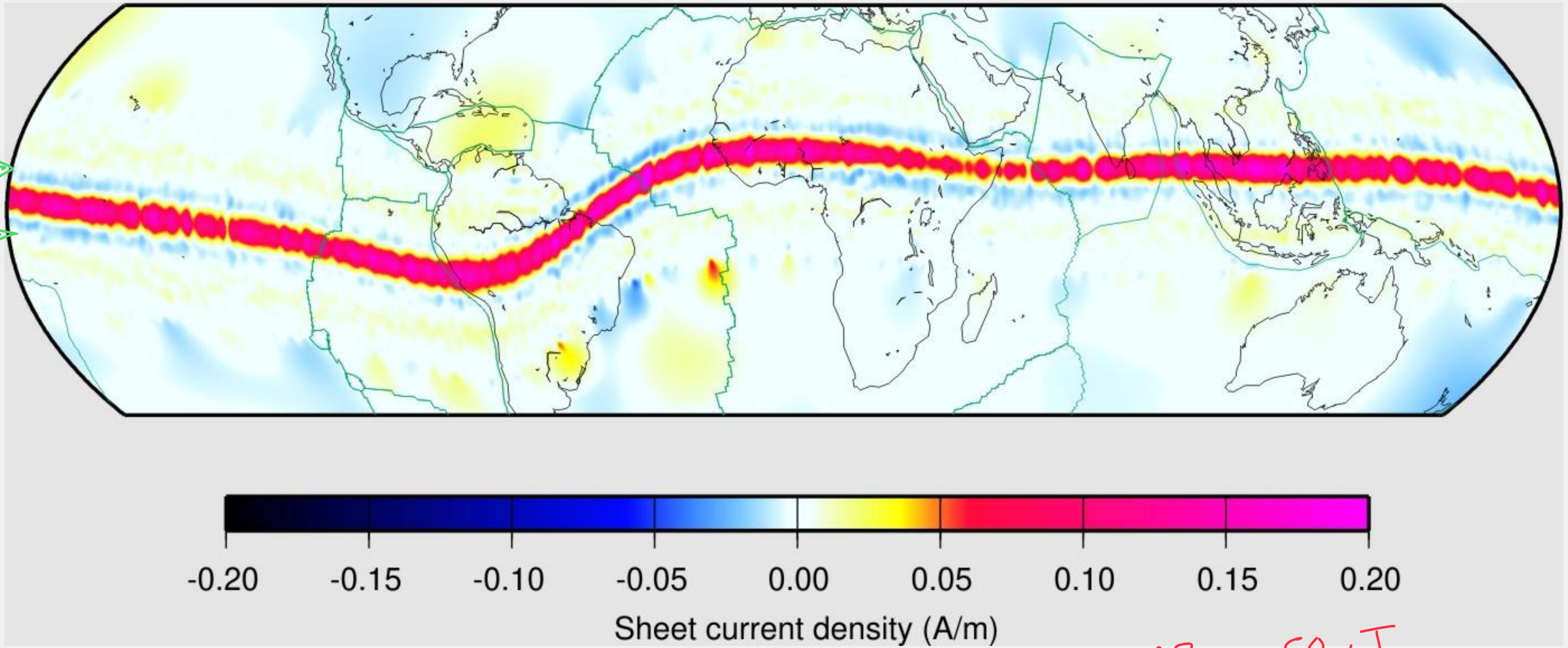


Equatorial Electrojet



$J = \sigma E$

- 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

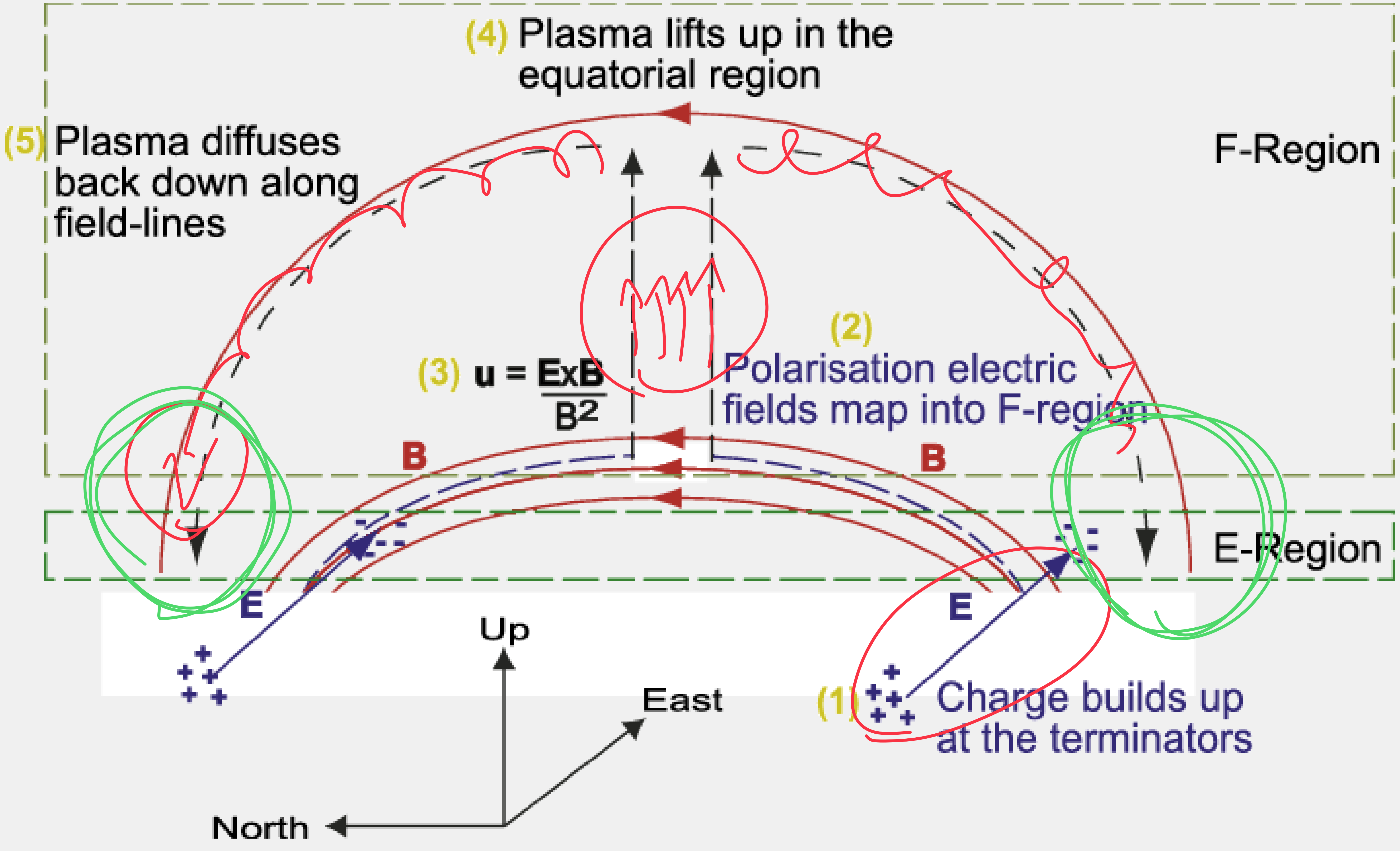
E

$\Delta B \sim 50$ nT

~ 100 kA

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"

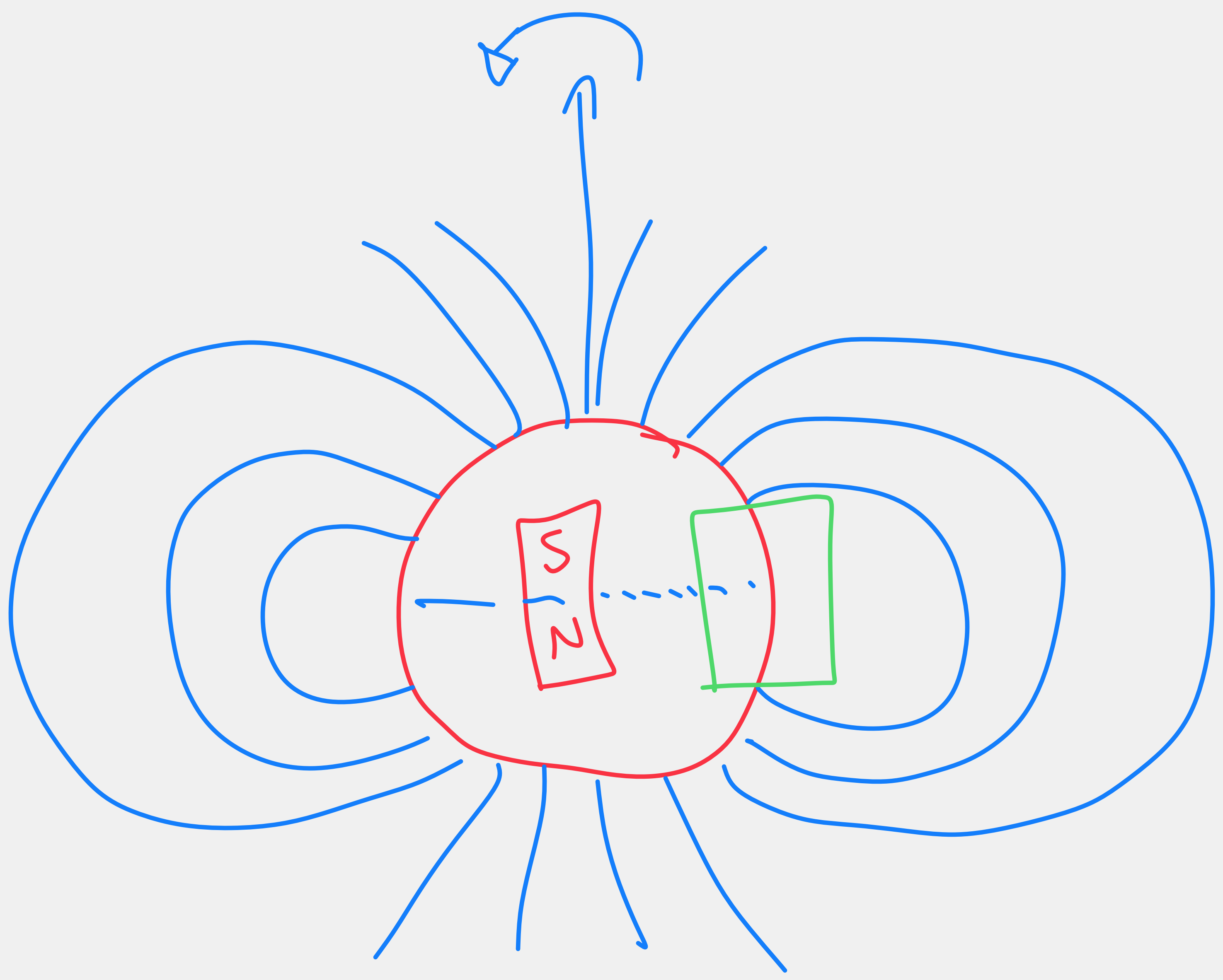


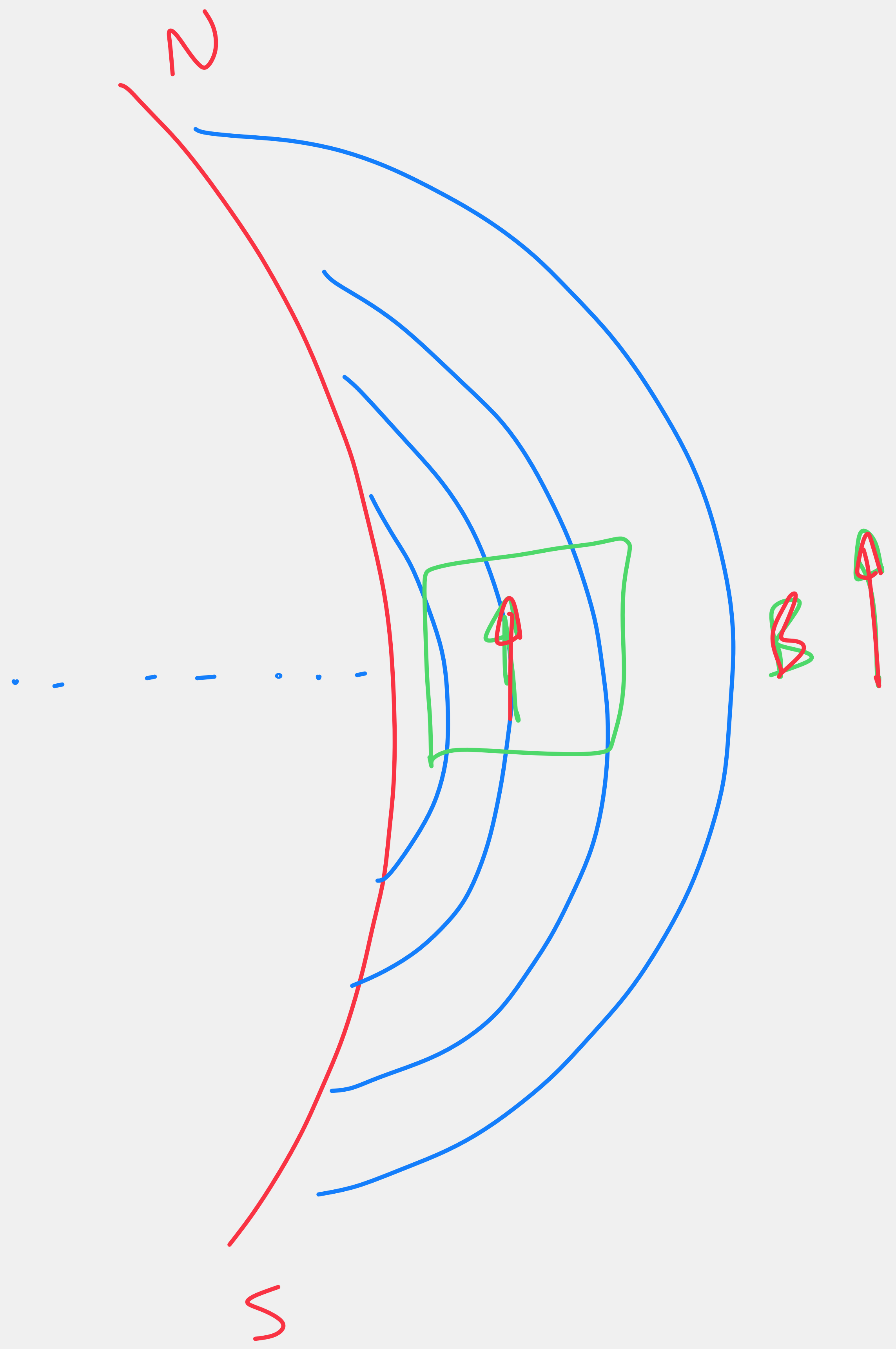
$$\bar{V}_d = \frac{\bar{F} \times \bar{B}}{qB^2}$$

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

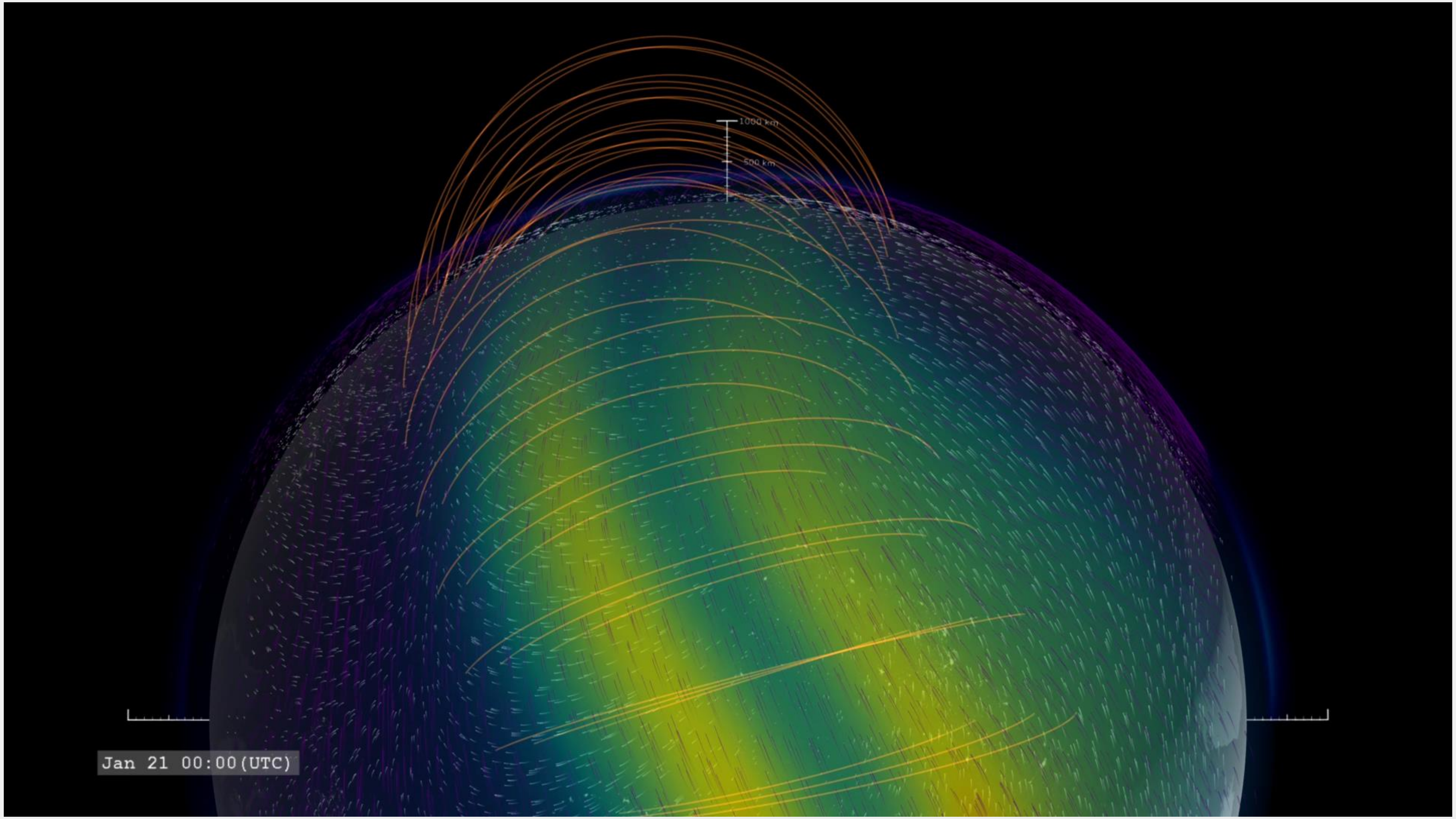
$$\bar{V}_d = \frac{\bar{E} \times \bar{B}}{B^2}$$

Magnetic field



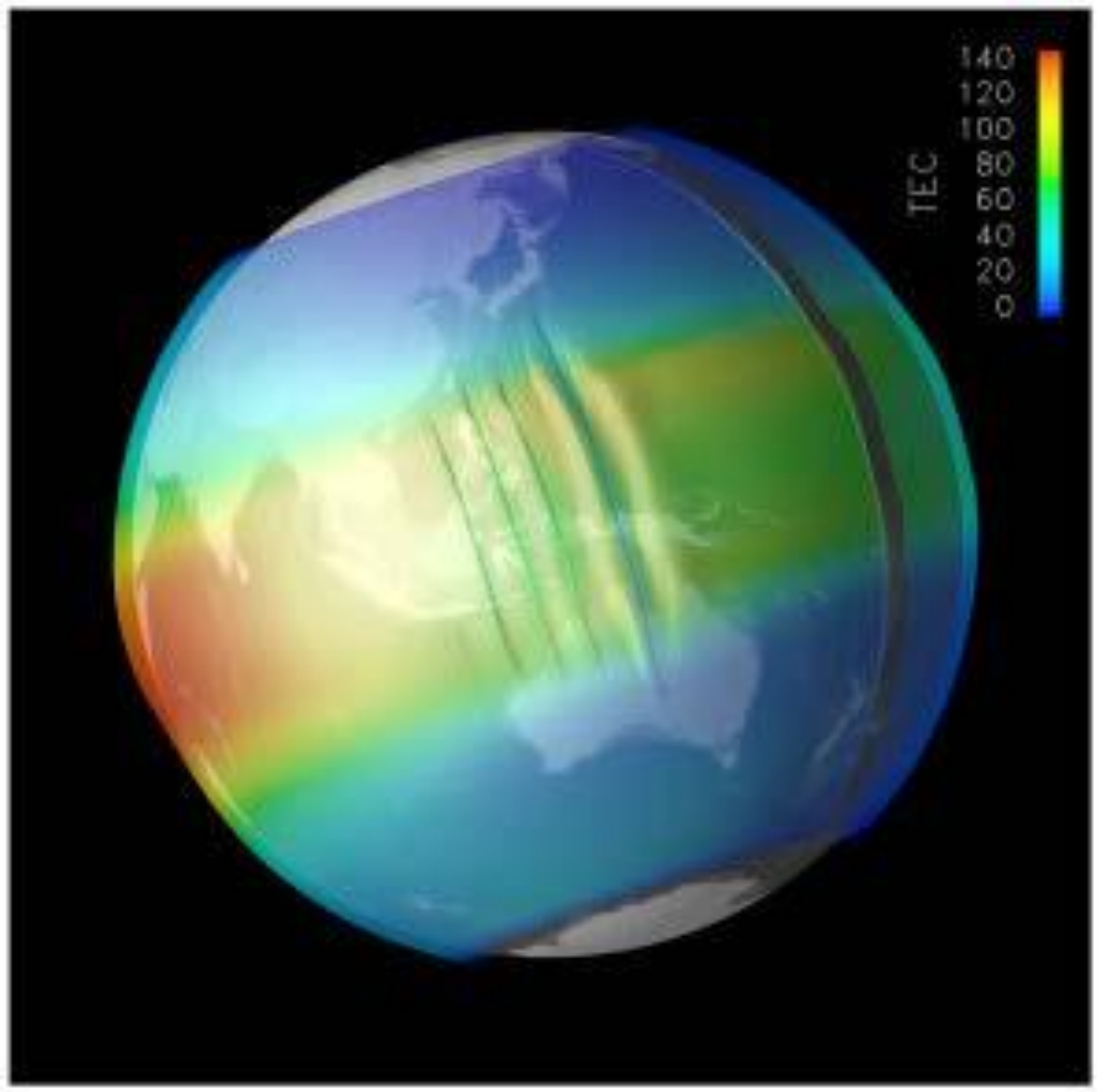


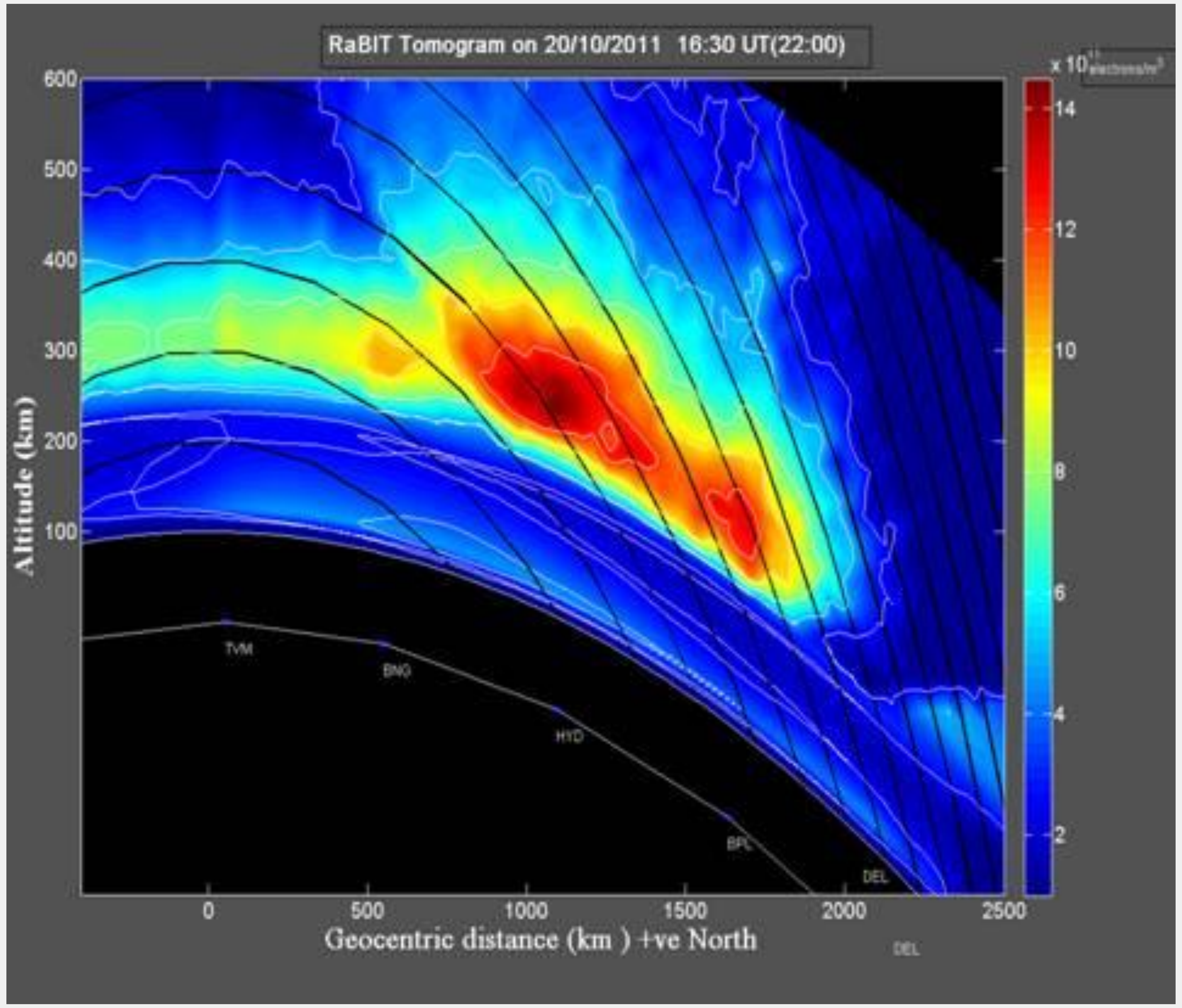
Equatorial Anomaly



Equatorial Spread-F

- Plasma instabilities that occur right after sunset cause the F-region to take on an array of structures
  - Times scales from seconds to hours
  - Spatial scales from cm to tens of km



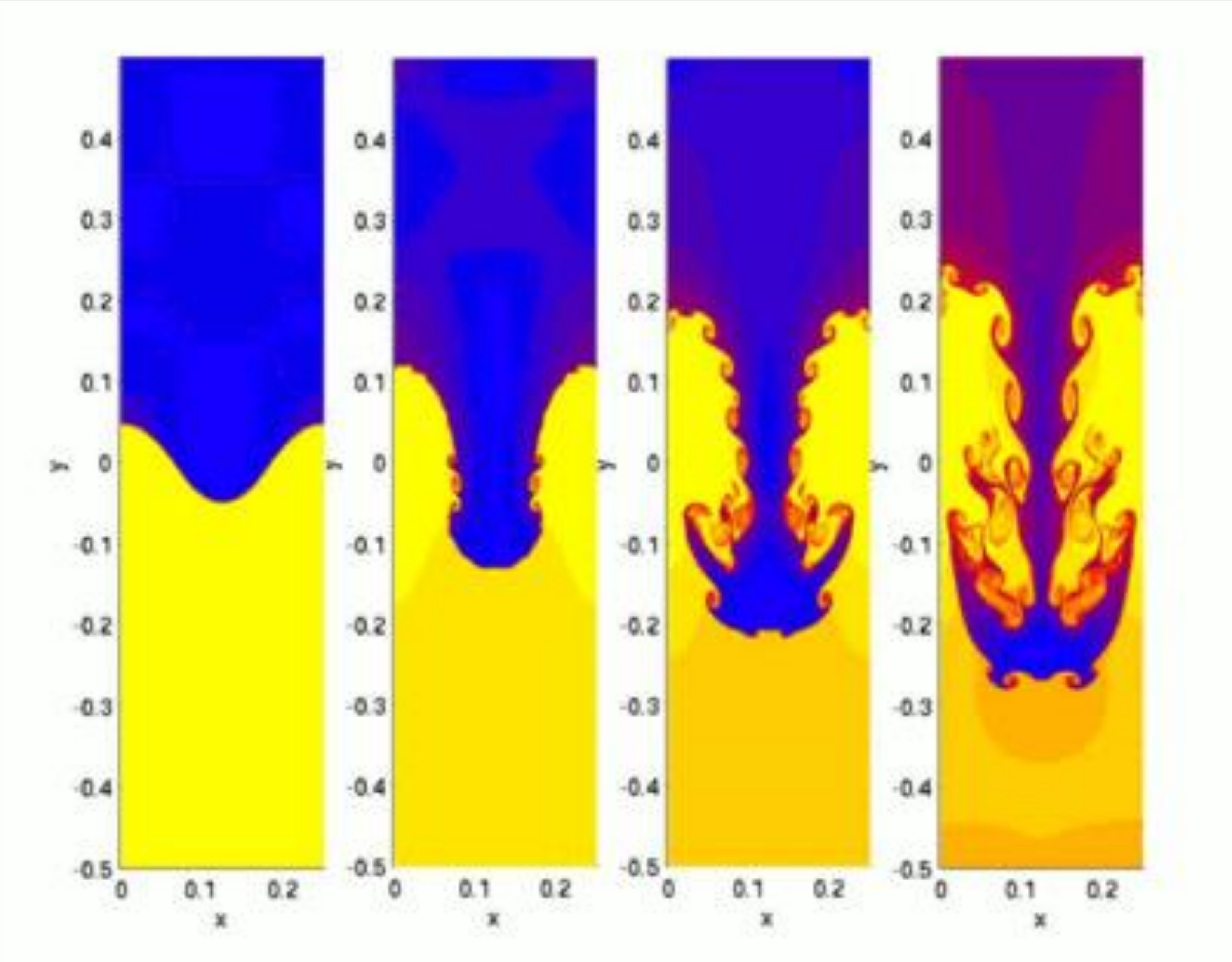


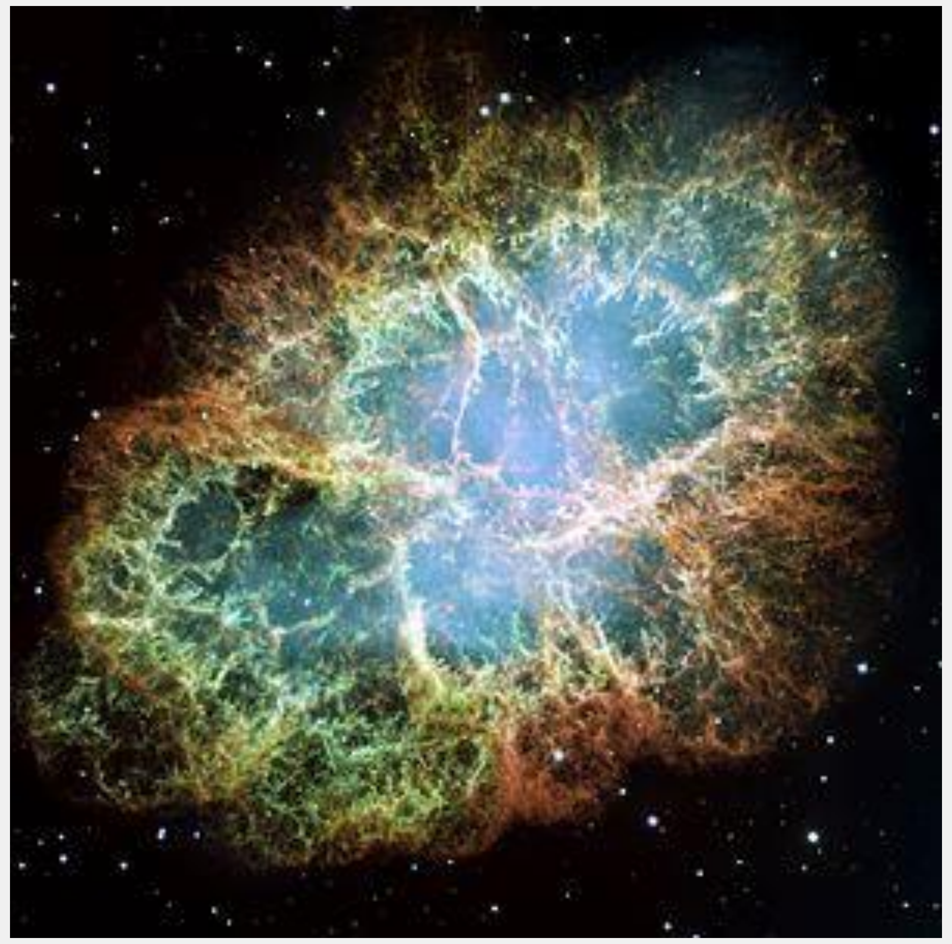
Equatorial Plasma Bubbles

- Instability due to heavier fluid on top of lighter fluid:

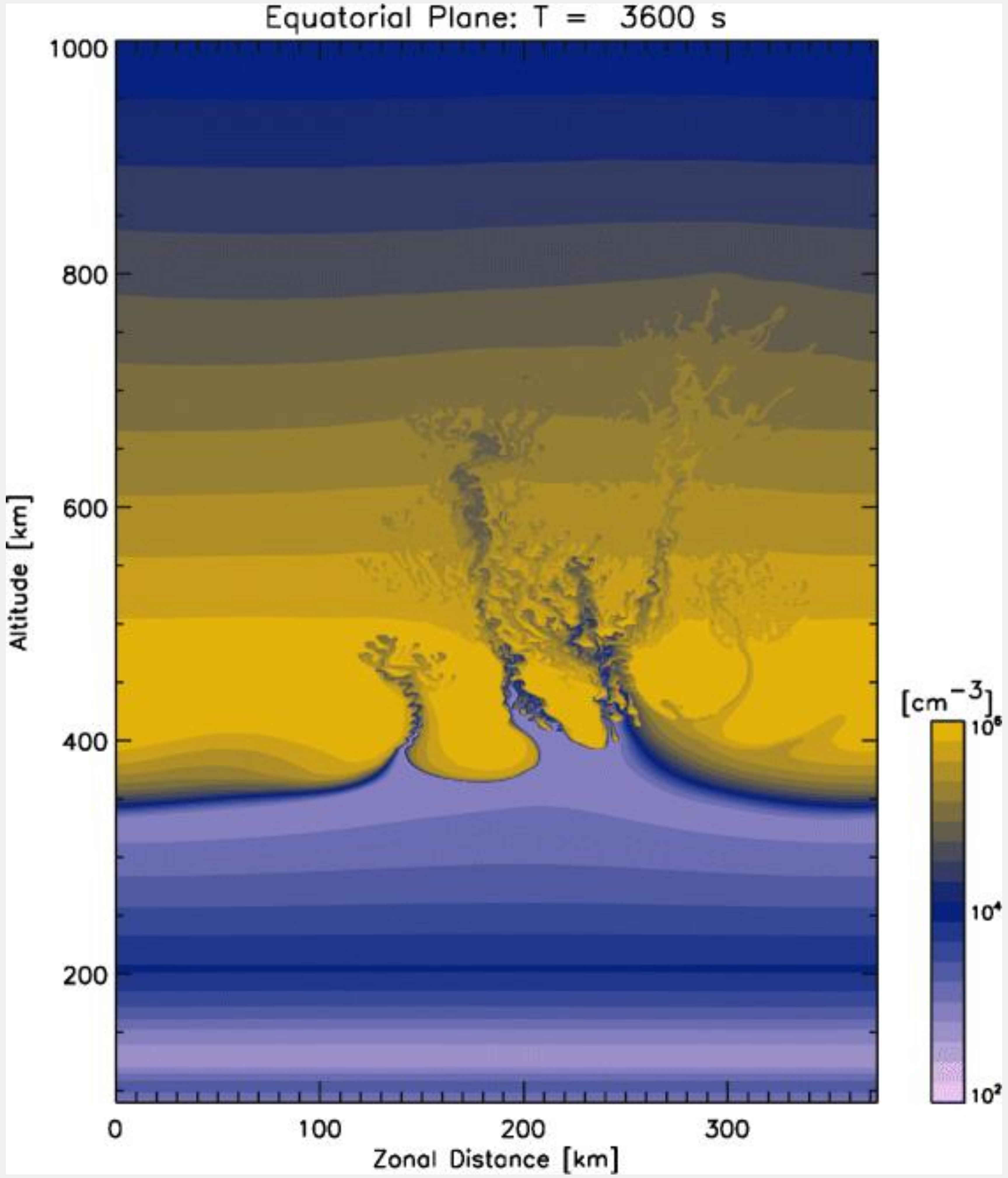
  Rayleigh-Taylor Instability

- Leads to rising bubbles with detailed structure and wide range of spatial scales, and large density variation

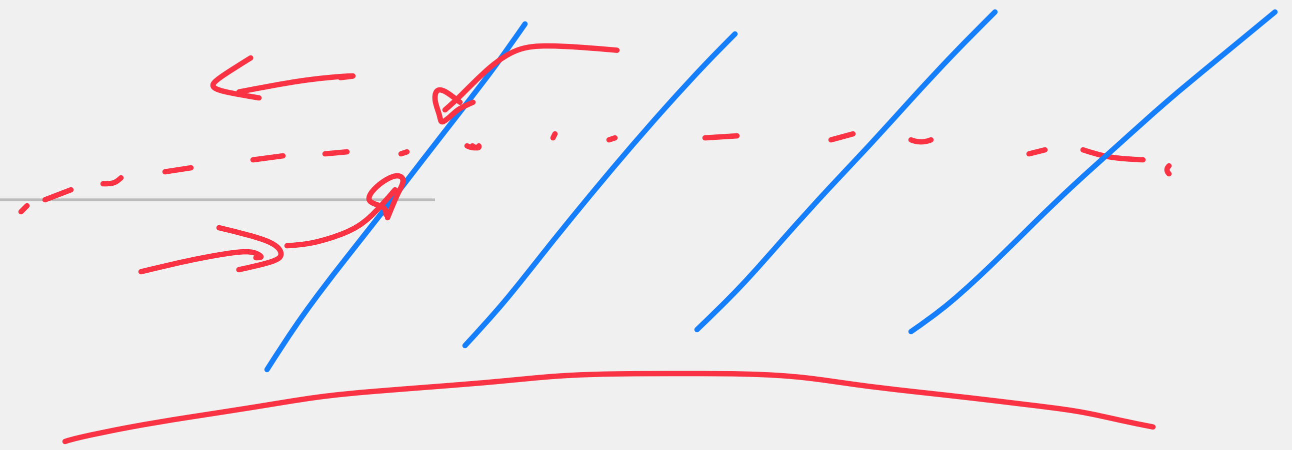




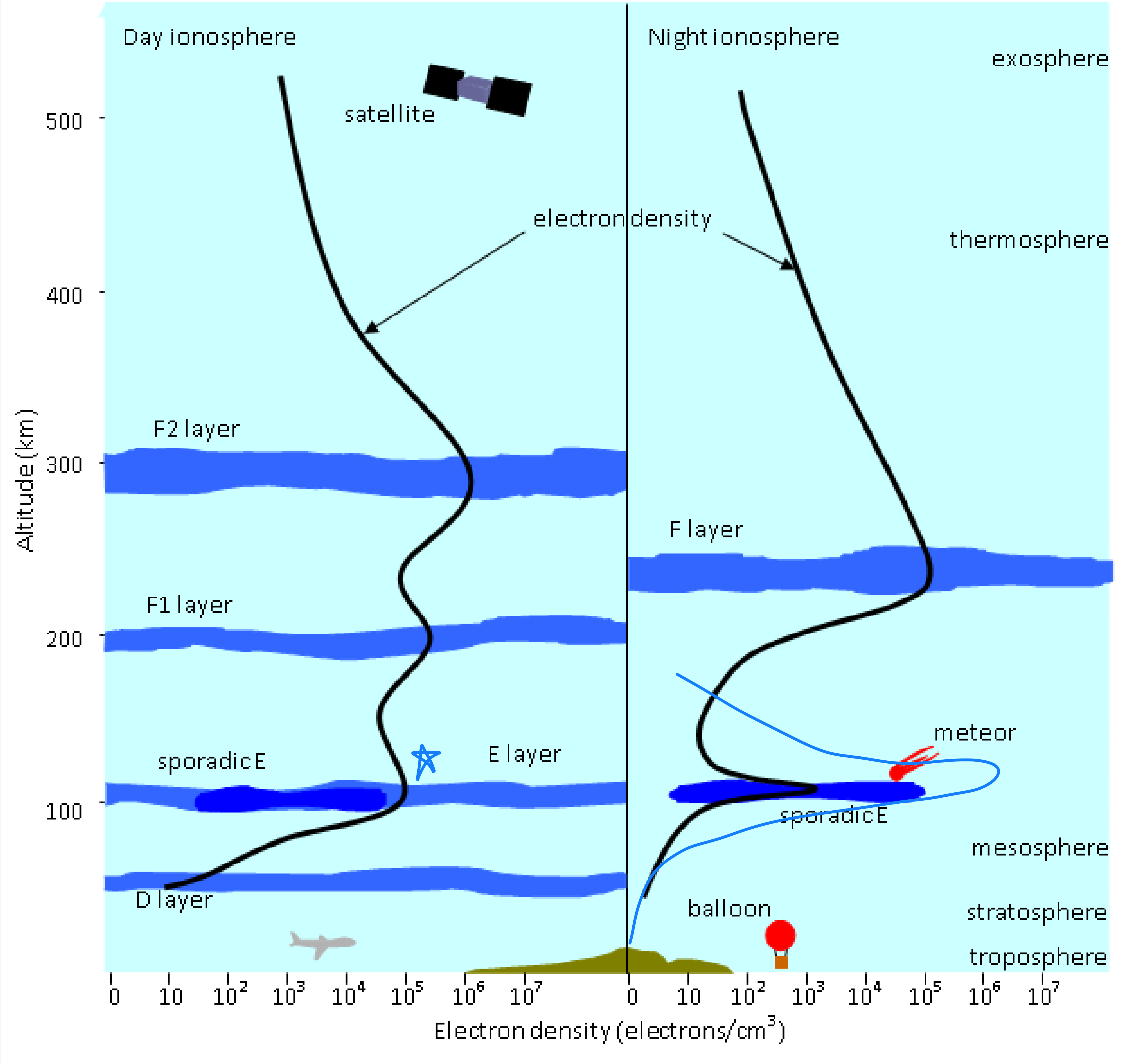
Crab Nebula



Mid-latitudes: Sporadic E

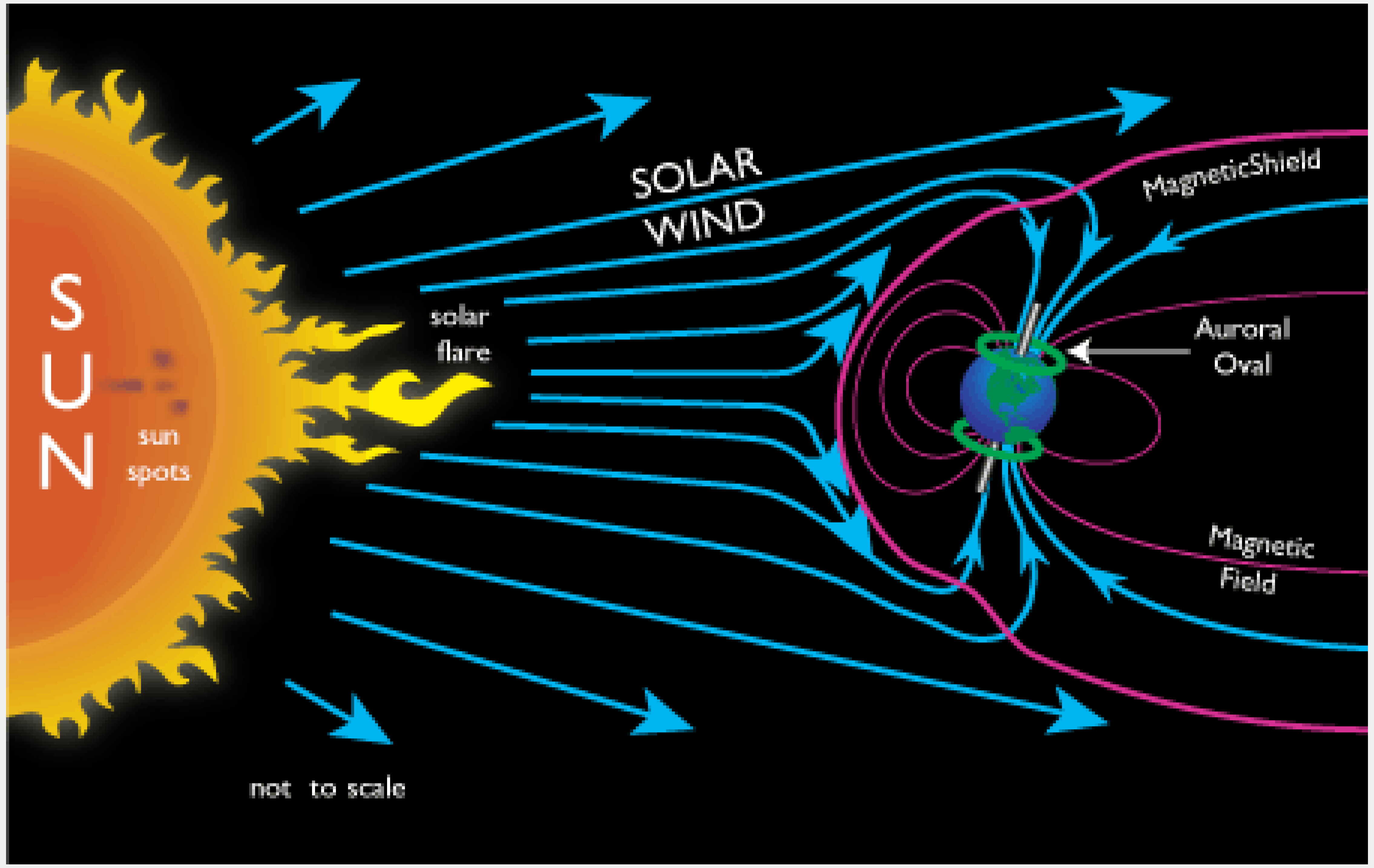


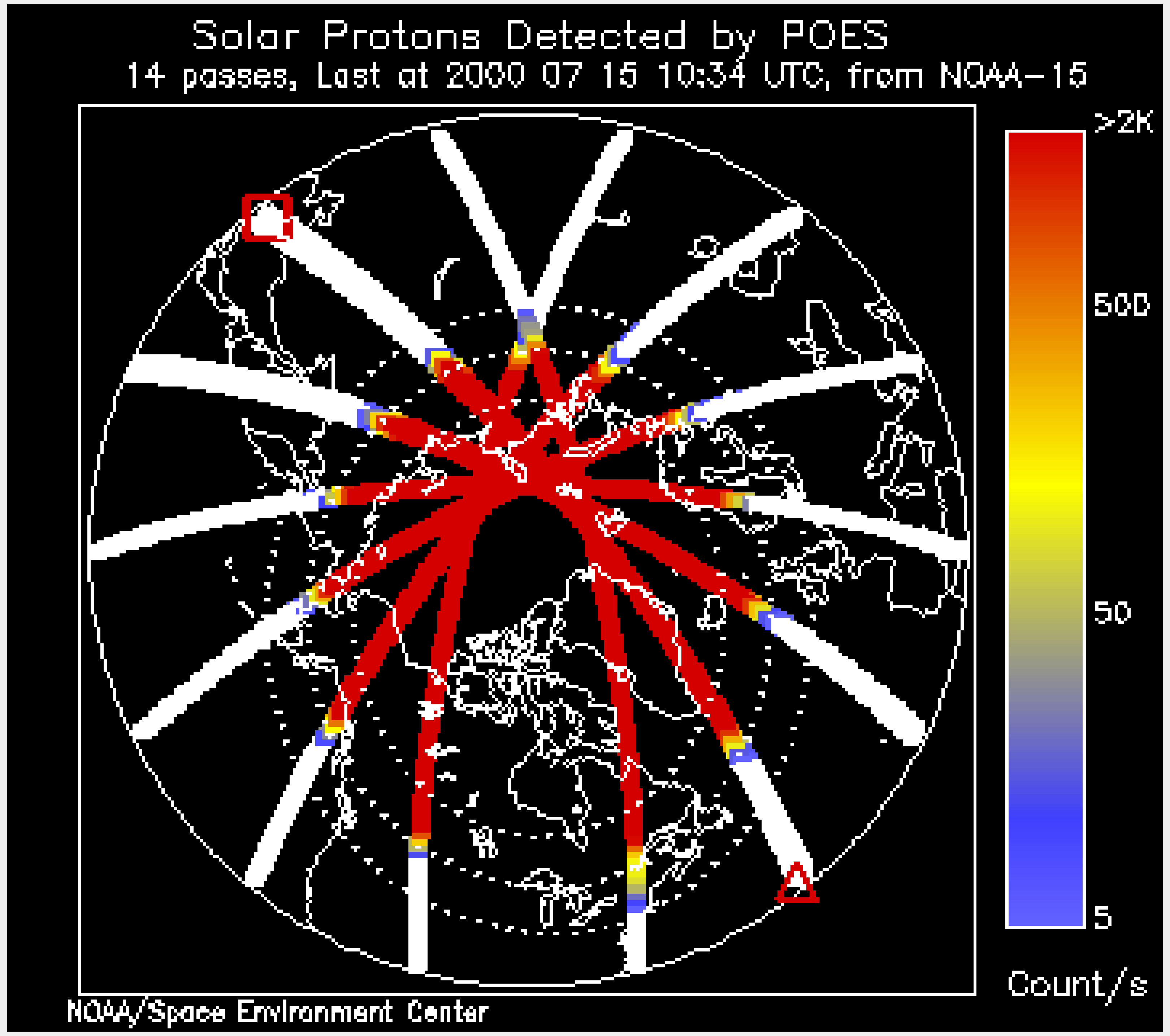
- Sporadic increase in E-region electron density, primarily at night, by orders of magnitude
- "Patch" of increased ionization
- Still not clear what the spatial scale is
- Observed by radio wave scattering
- Effect is most likely due to shear winds driving metal ions (from meteors) into thin layer



High-Latitudes: Polar Cap Absorption

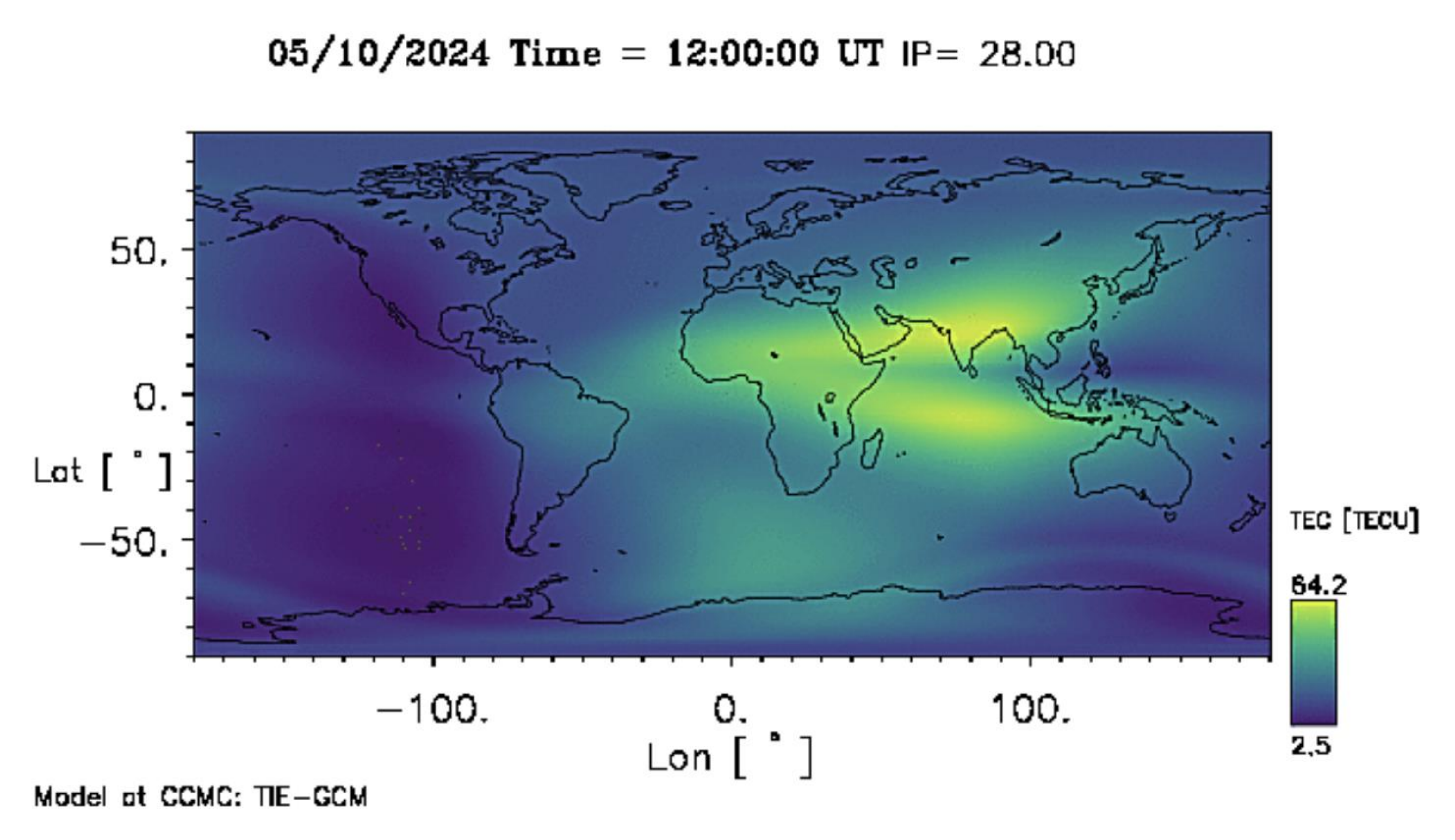
- Solar Energetic Protons (SEPs) deposit their energy in the D-region of the ionosphere
  - Flow along open magnetic field lines
- Increased D-region density adds to absorption of radio waves (discussed a bit later)

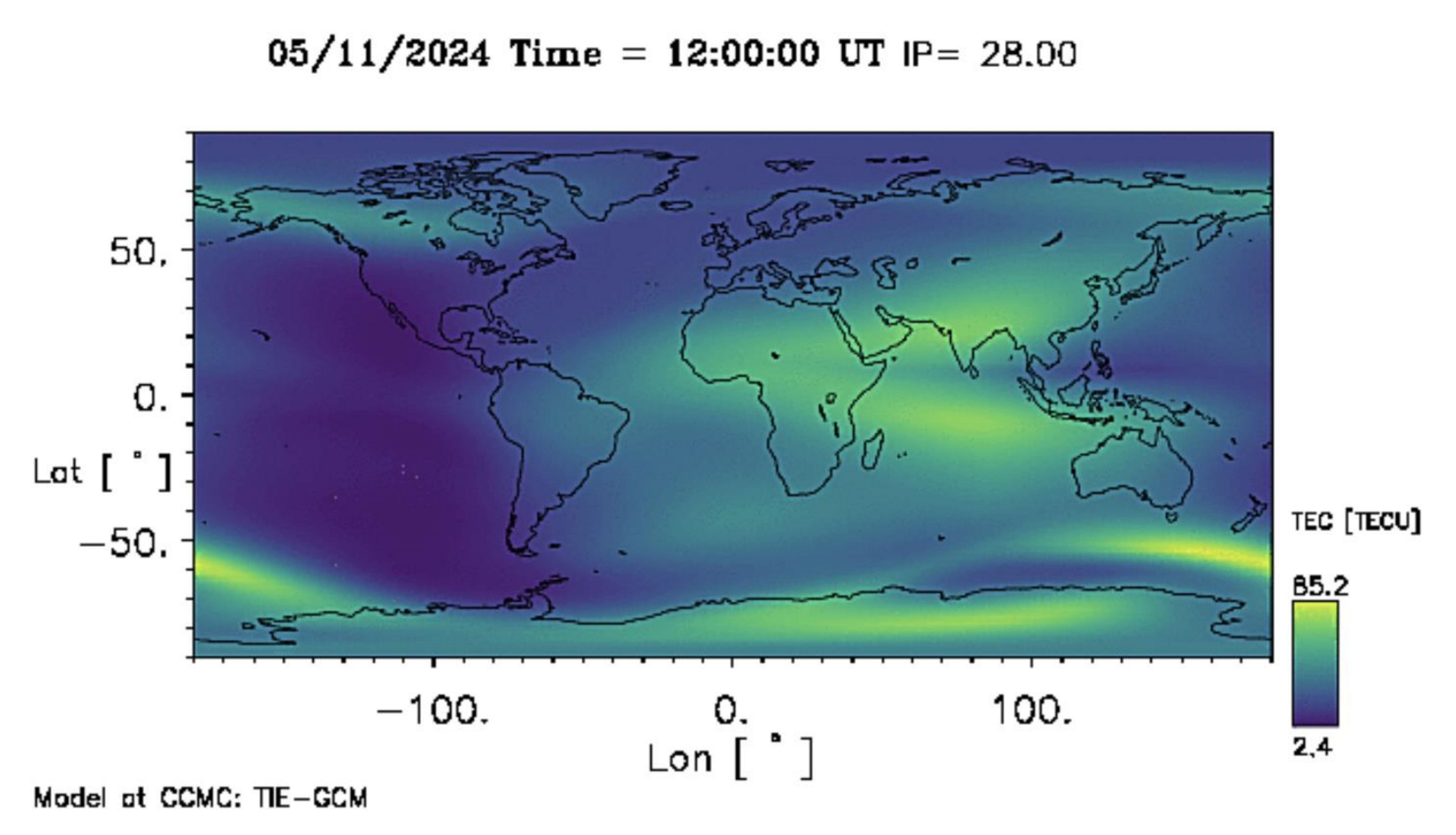




Storm-time variability: Gannon Storm 2024

- **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

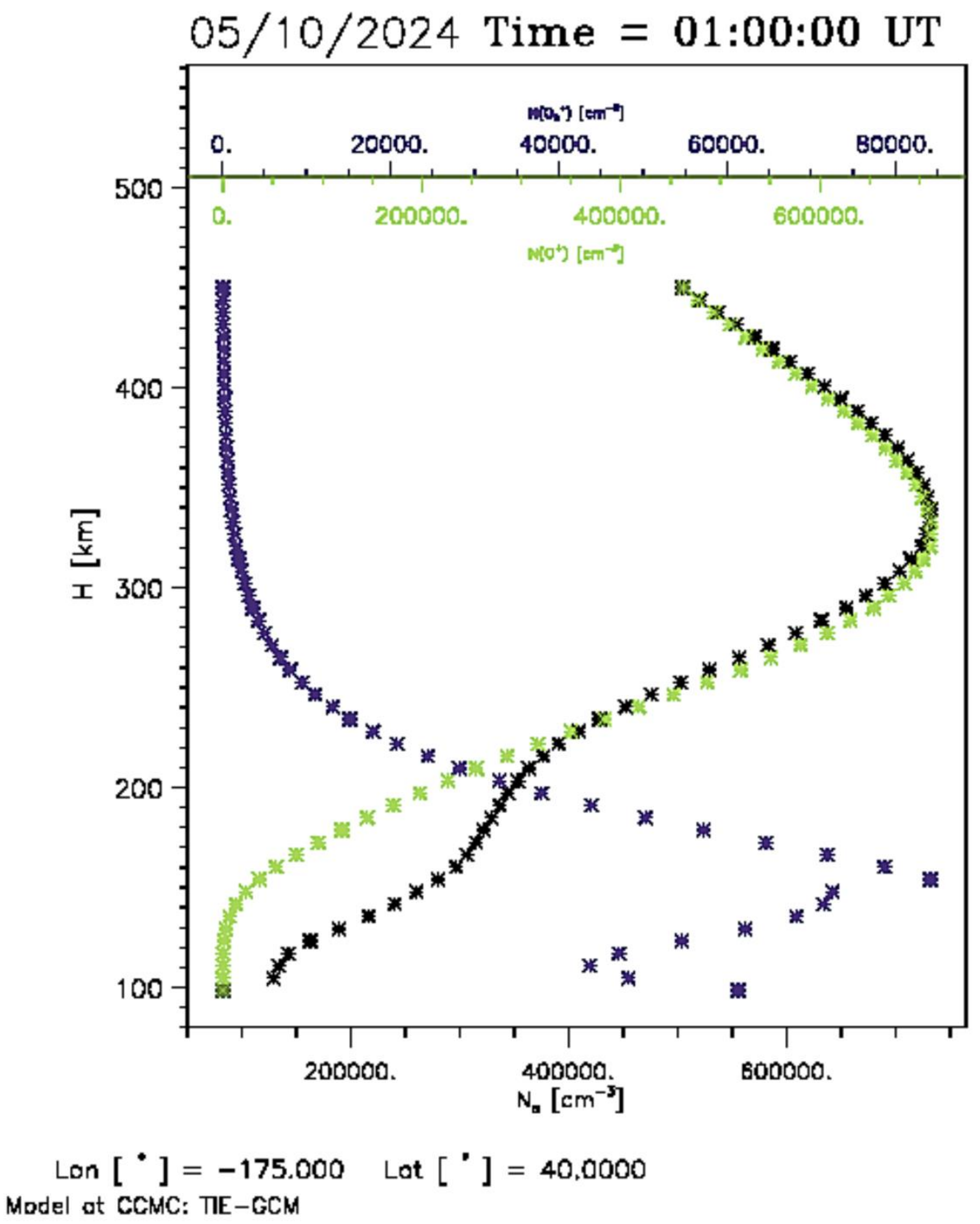


Figure: Simulation of the ionosphere/thermosphere of the Earth.
EPS image (684.44 KB)

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

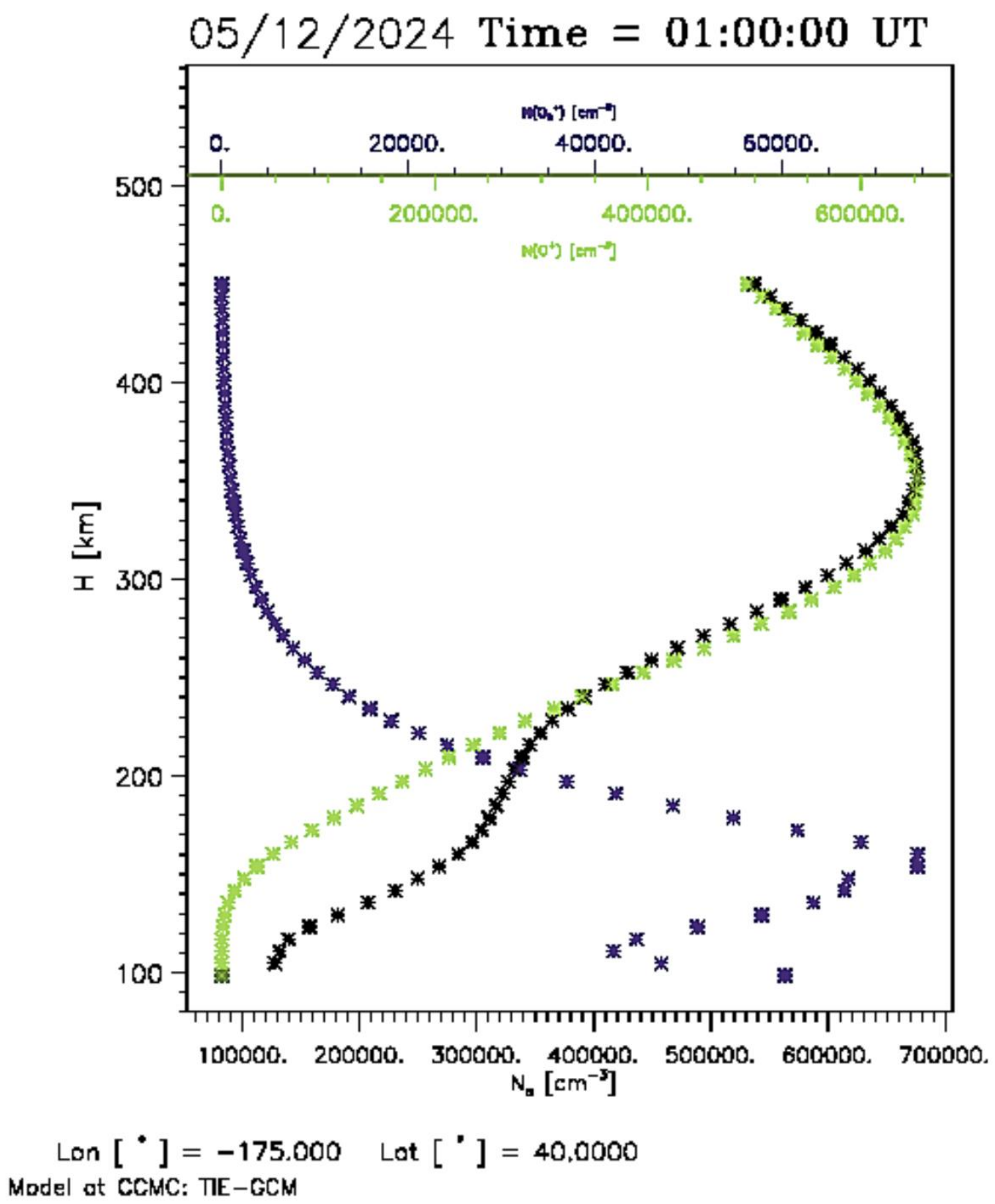
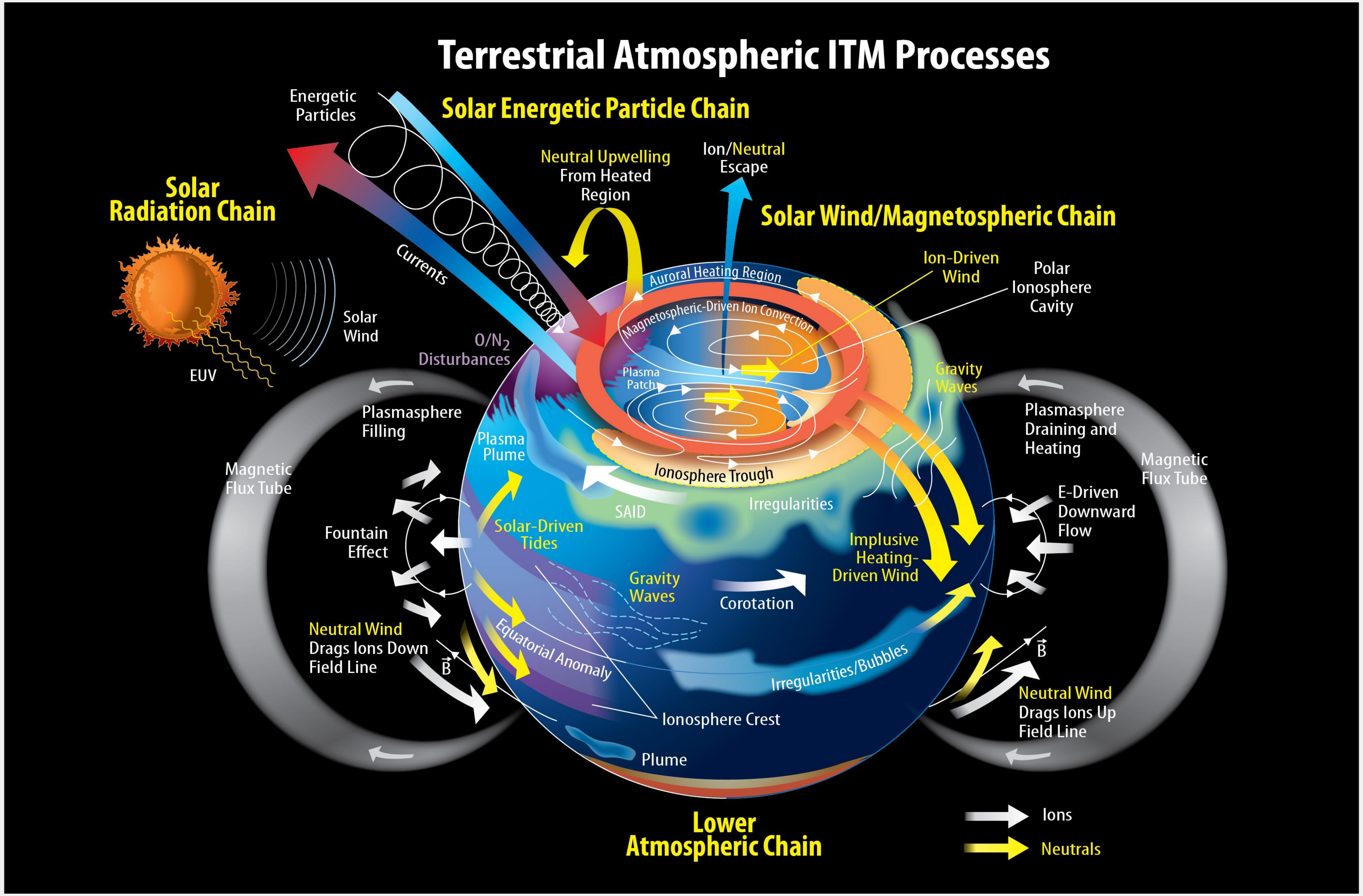


Figure: Simulation of the ionosphere/thermosphere of the Earth.
EPS image (688.14 KB)

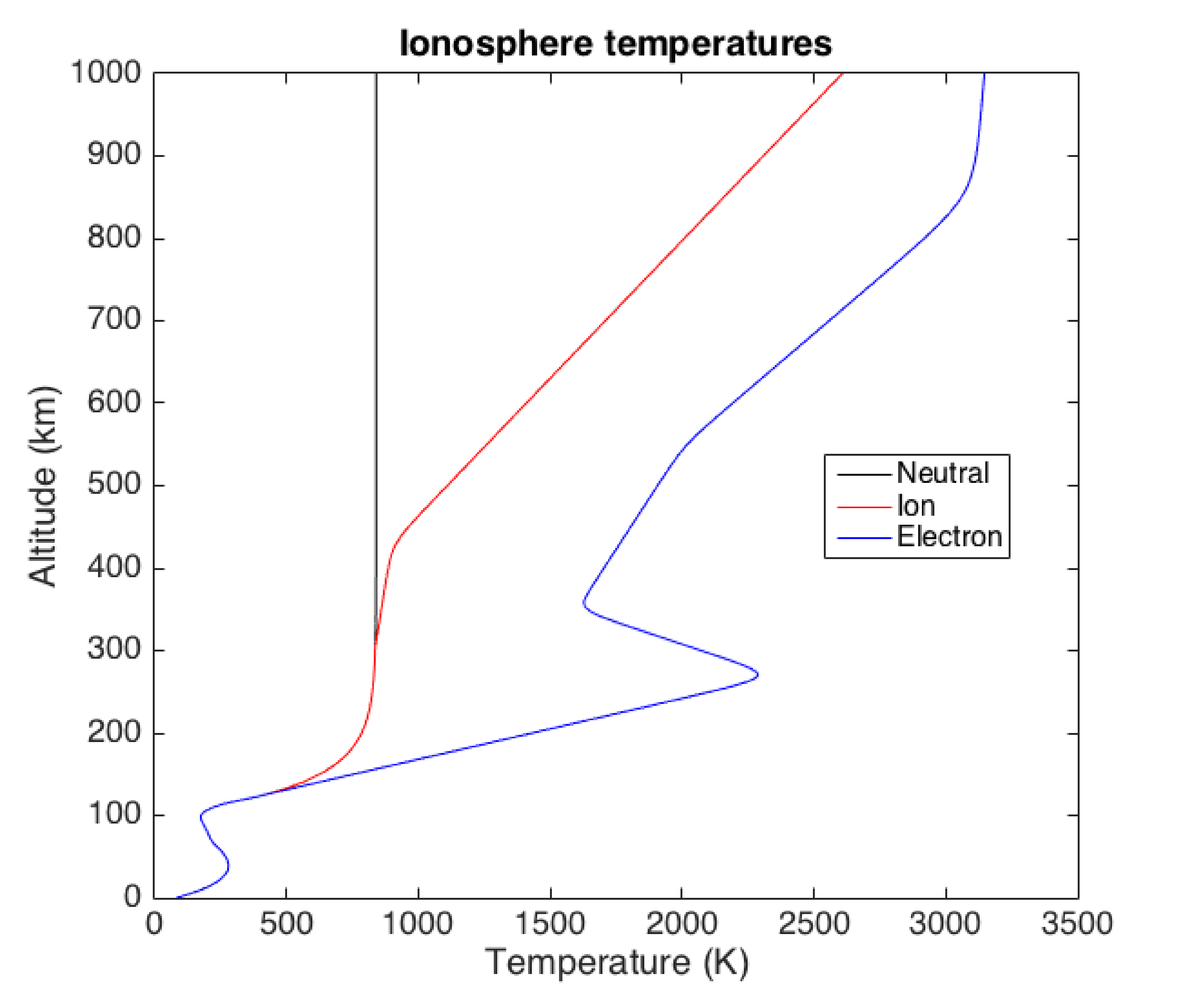
Model: TIE-GCM
Run: TIEGCM-Heelis-01_2024-05-TP-02_071624_IT_1

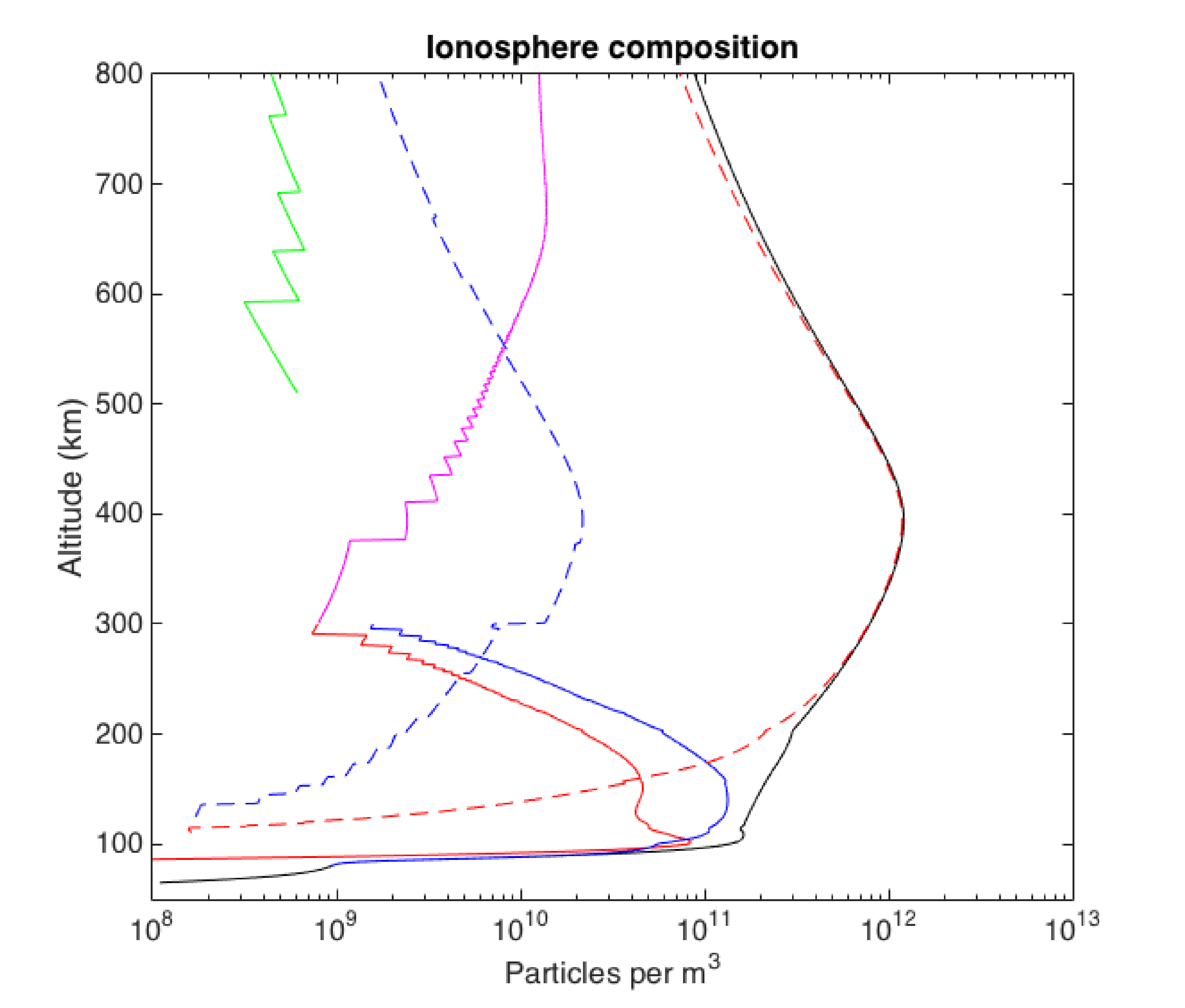
Lots more to the Ionosphere / Atmosphere system…



IRI model

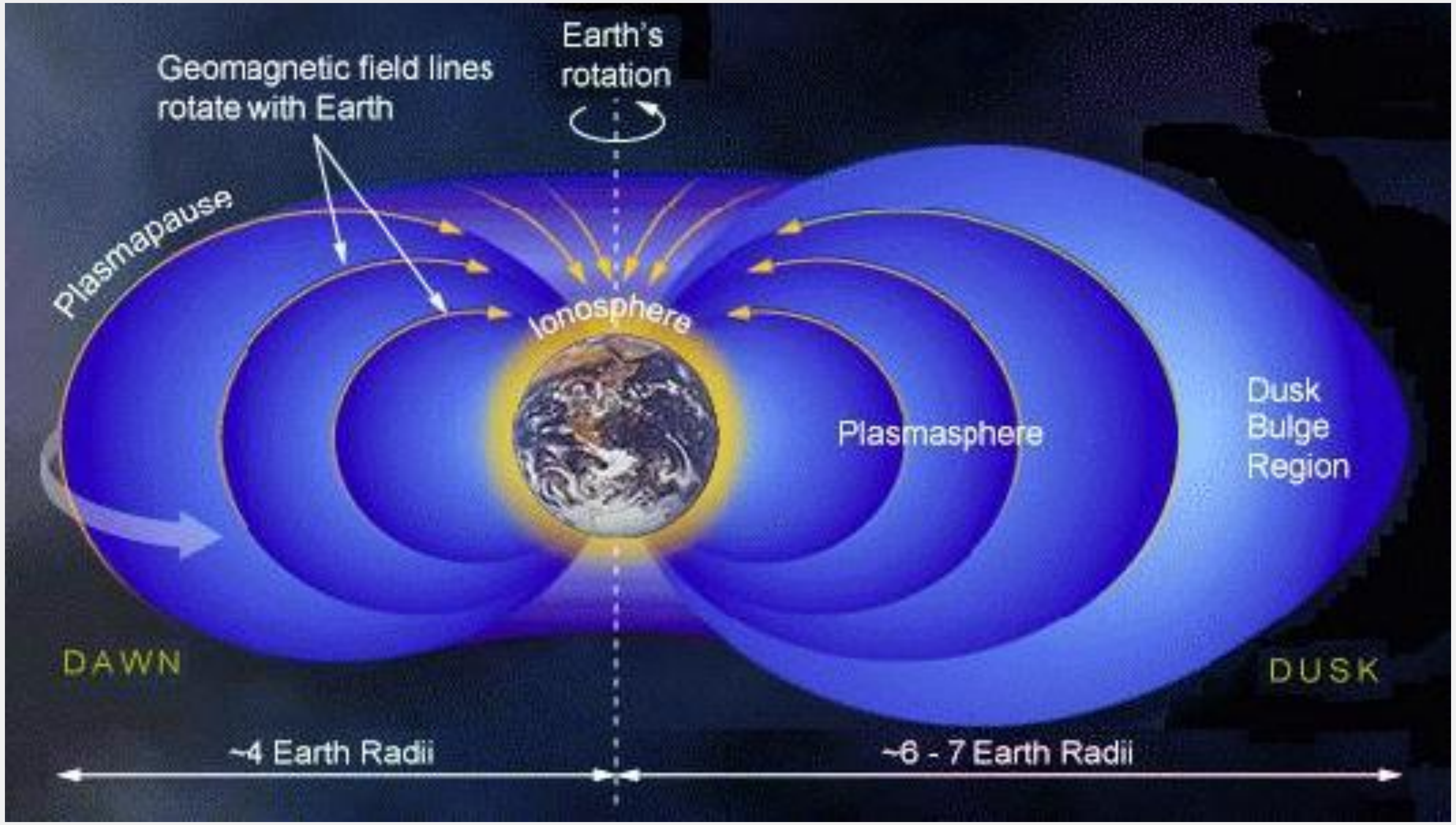
- International Reference Ionosphere: IRI
- https://ccmc.gsfc.nasa.gov/modelweb/models/iri2012_vitmo.php
- IRI is ionosphere equivalent to MSIS
- Empirical model; major data sources are the worldwide network of ionosondes, powerful incoherent scatter radars (Jicamarca, Arecibo, Millstone Hill, Malvern, St. Santin), ISIS and Alouette topside sounders (spacecraft), in situ instruments flown on many satellites and rockets.
- IRI is updated yearly during special IRI Workshops at COSPAR and URSI meetings





Plasmasphere

- Boundary between Topside ionosphere and Plasmasphere: where thermal pressure and magnetic pressure are equal
  - Plasma becomes confined by B-field
- Sometimes defined by altitude where H+ (protons) become dominant ion



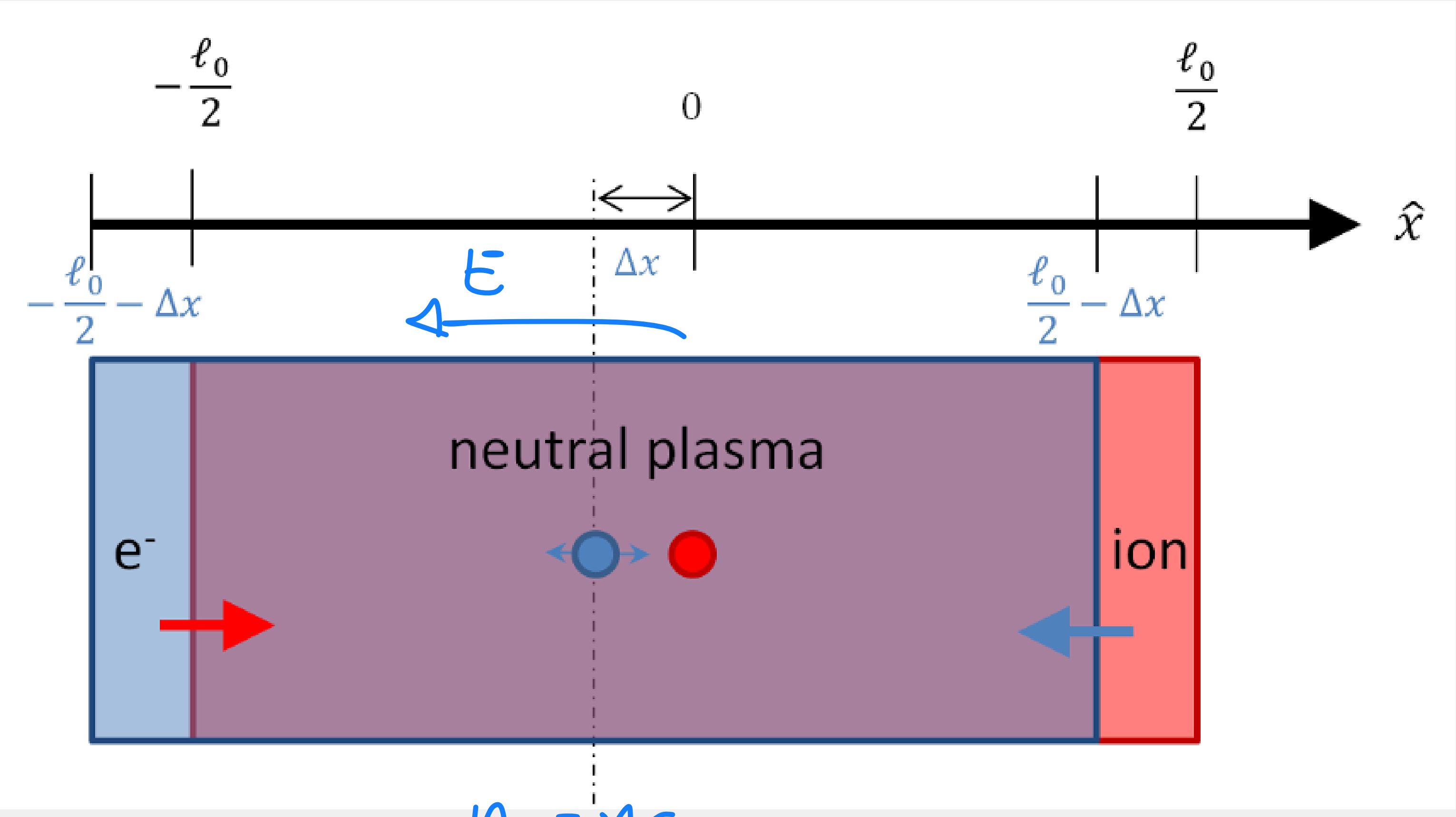
Ionosphere Effects:
Radio Wave Propagation

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



$n_e = n_i$

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

$$ma = F = q_e E$$

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

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

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

$$V_p = \frac{c}{n} = \frac{c}{\sqrt{\epsilon_r}} \qquad \epsilon\,(\text{permittivity}) = \epsilon_0 \epsilon_r$$

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

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

if $\omega < \omega_p$

n = complex

$n = \alpha + j\beta$

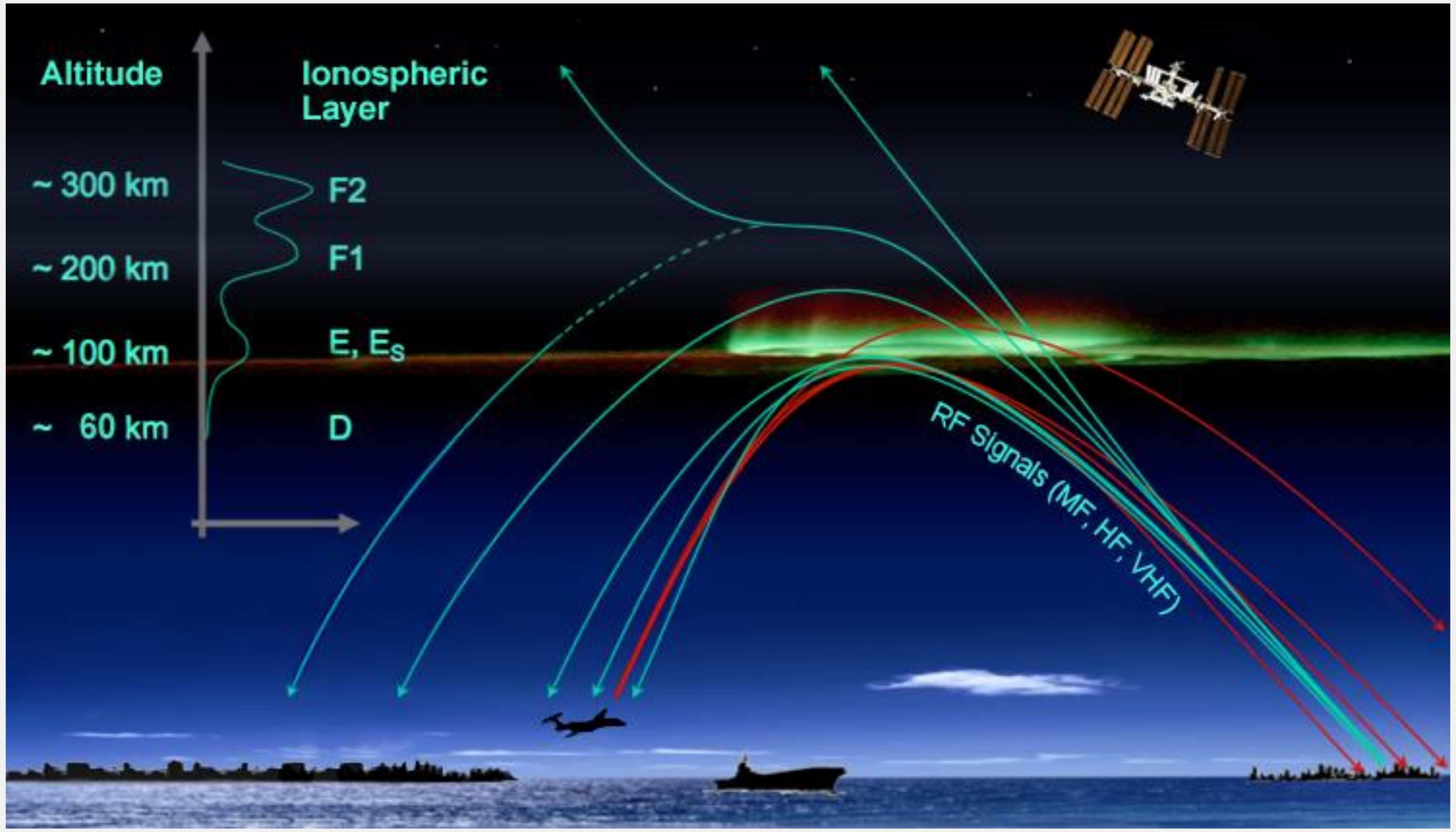
at $\omega = \omega_p$, $n = 0$

$V_p \to \infty$

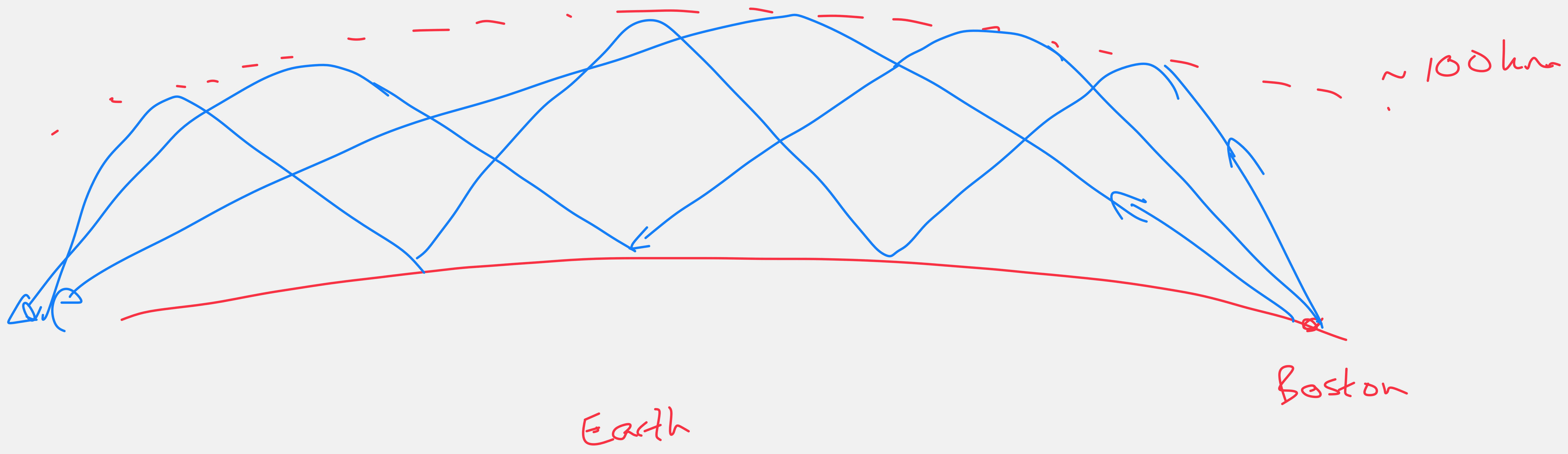
Reflection of EM Waves

- 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

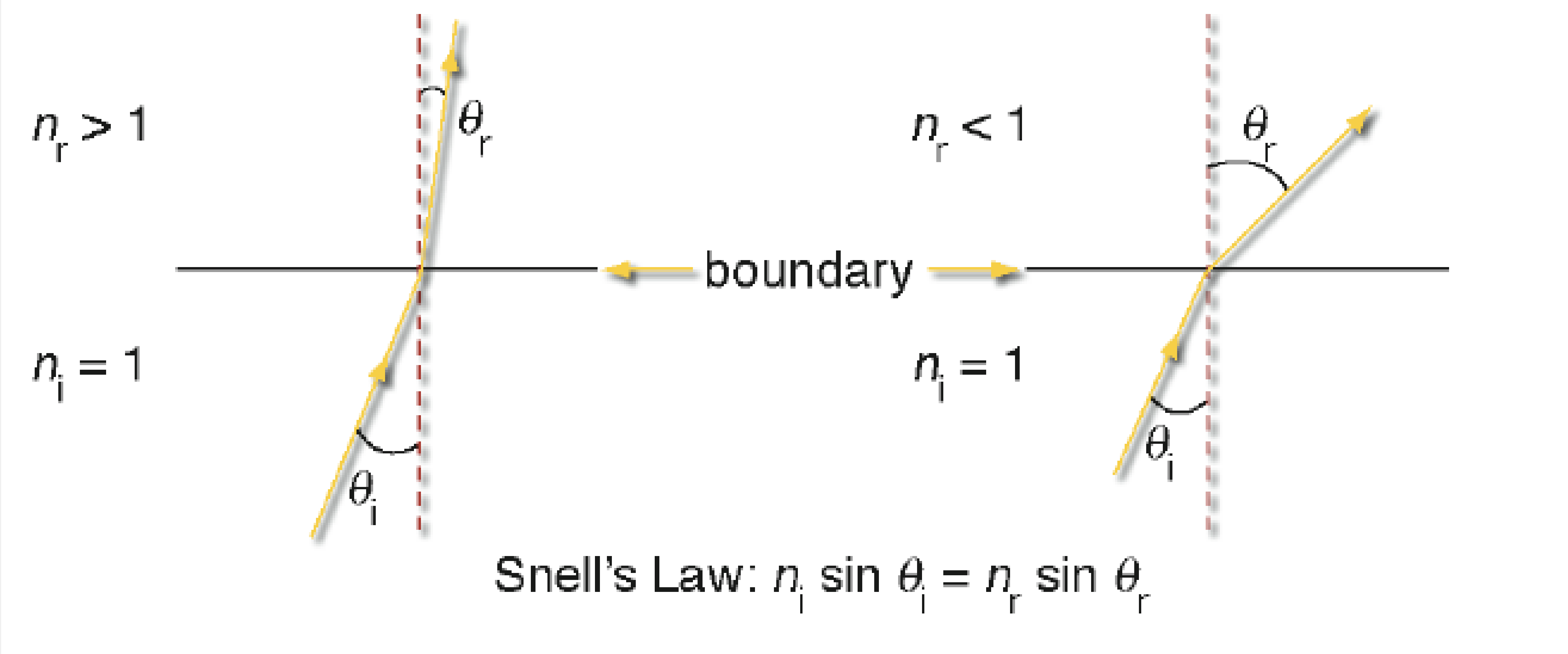


Over-the-horizon radar or communication



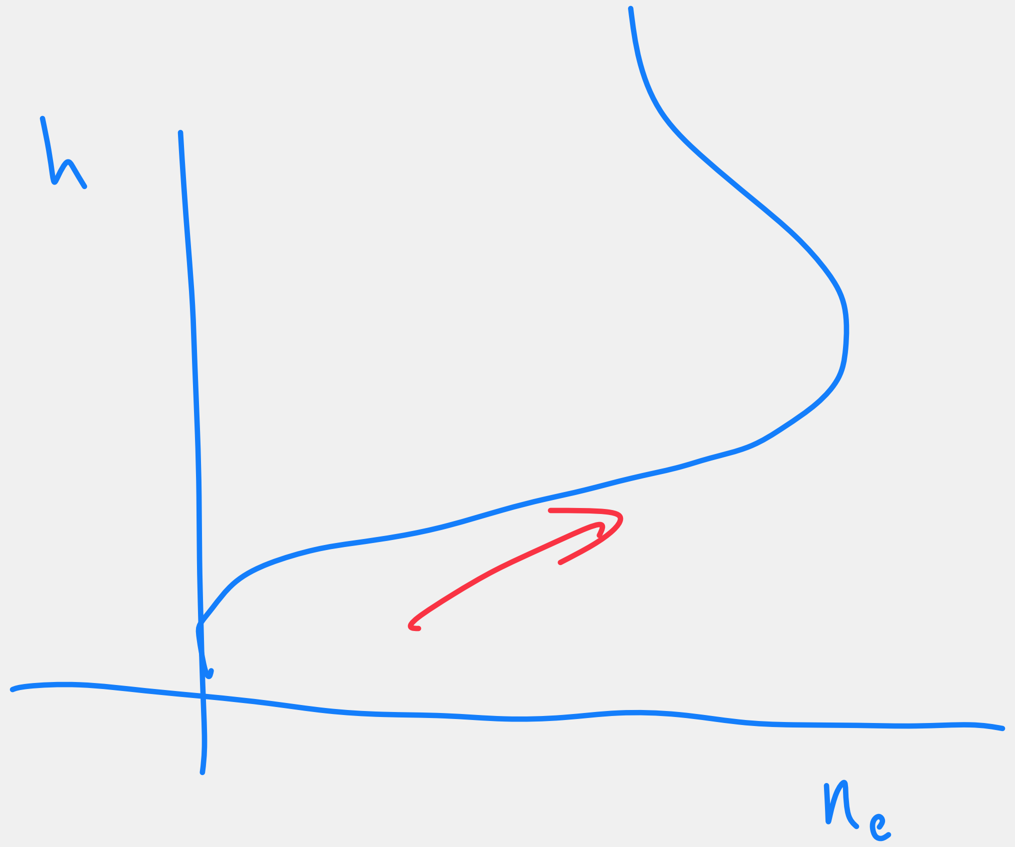
Index of Refraction

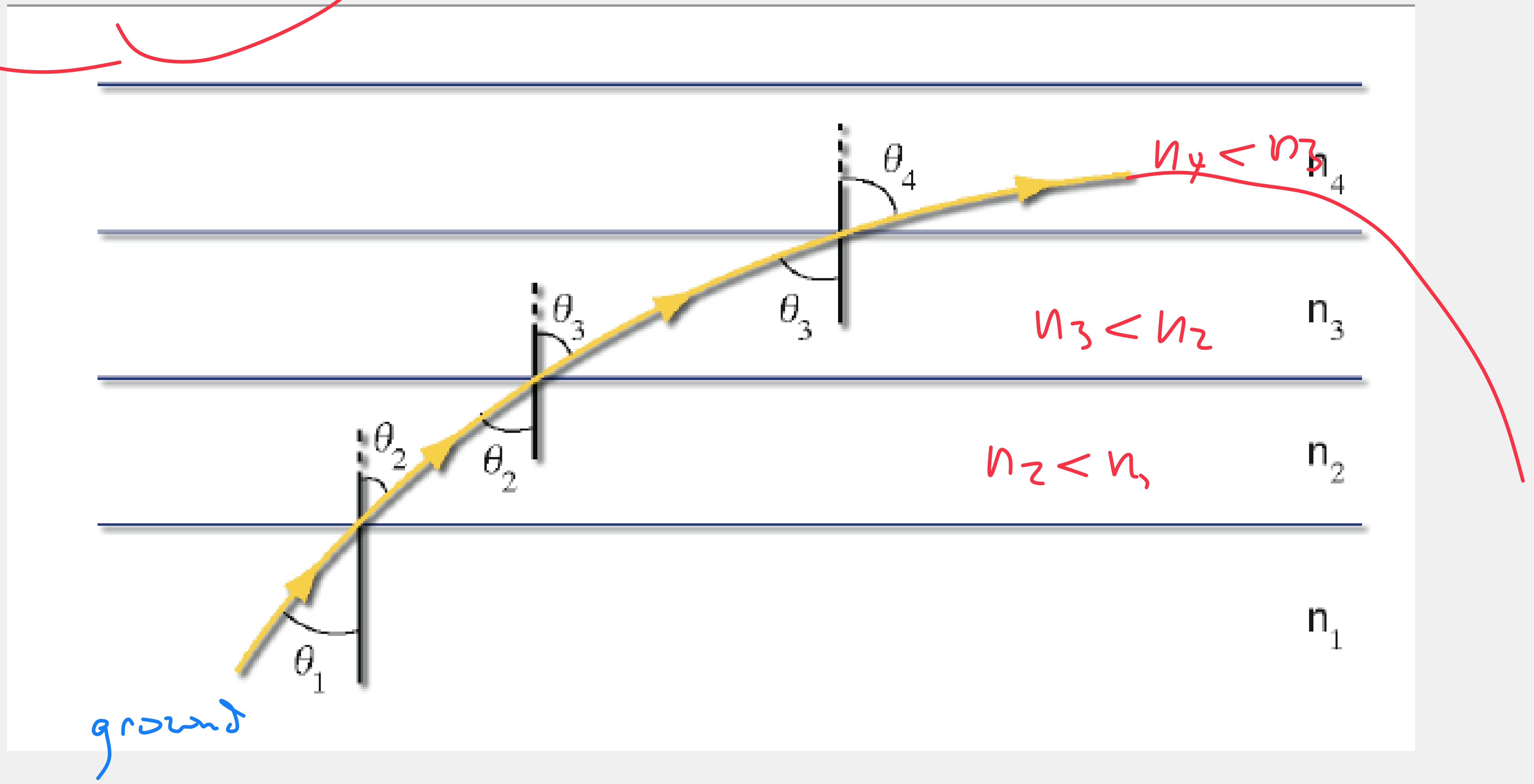
- As a radio wave propagates from one medium to another, it's propagation direction is ***refracted***, based on the **indices of refraction**, n_1 and n_2.



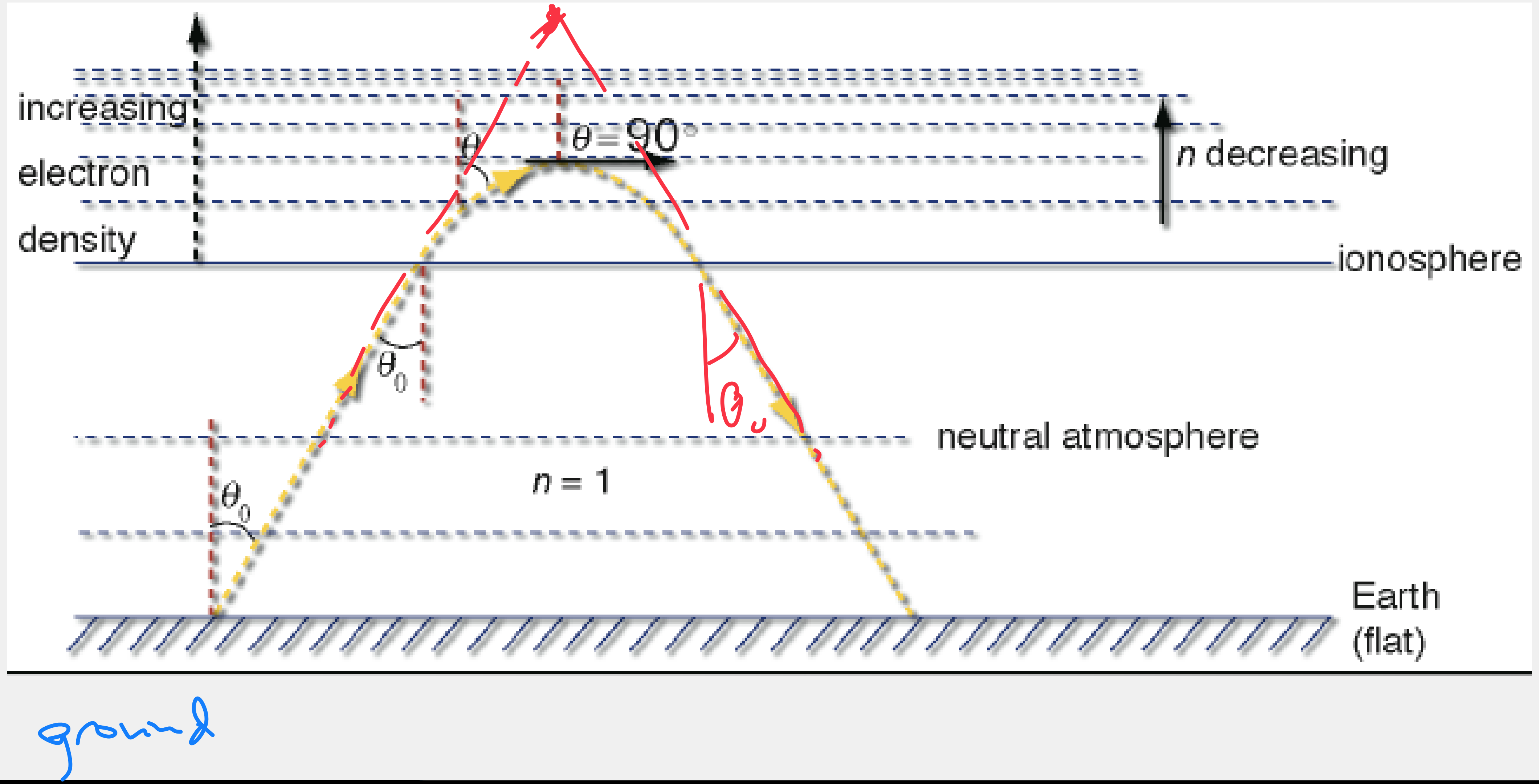
Ionospheric Refraction

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





- We can treat the ionosphere as successive layers, and look at refraction from one layer to the next
  - Continuous refraction
- End result: ray "bends" and turns back to the ground. Not a hard reflection!



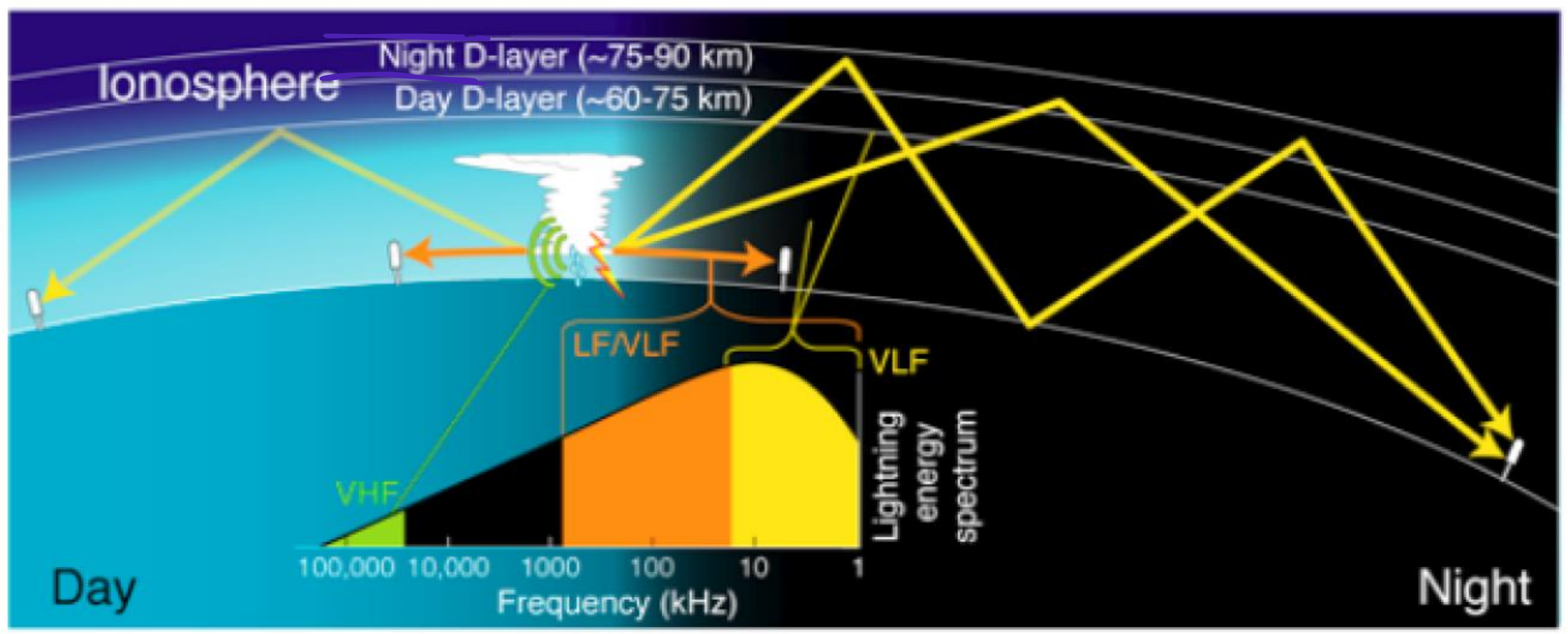
Critical Frequencies in the Ionosphere

- **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

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

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

e-n



Waves in Plasmas

- We need three equations to describe wave propagation in a cold plasma. Ampere's Law and Faraday's Law (i.e. Maxwell's equations):

$$E(t) = A e^{j(\omega t - kx)}$$

$$\boxed{\begin{aligned} \nabla \times \bar{B} &= \mu_0 \bar{J} + \mu_0 \epsilon_0 \frac{d\bar{E}}{dt} \\ \nabla \times \bar{E} &= -\frac{d\bar{B}}{dt} \end{aligned}}$$

$$\rightarrow \quad d/dt \Rightarrow j\omega = i\omega$$

$$\rightarrow \quad \bar{\nabla} \times \Rightarrow j\bar{k} \times \qquad k = \frac{2\pi}{\lambda}$$

- And the Langevin equation (simply F = ma):

"nu"

$$m_e \frac{dv_e}{dt} = \sum F = q_e \bar{E} + q_e(\bar{v}_e \times \bar{B}) - \nu m_e \bar{v}_e + \ldots$$

$$\bar{J}_e = q_e n_e \bar{v}_e \qquad n = \frac{kc}{\omega}$$

$$\boxed{\frac{d\bar{J}_e}{dt} = \frac{q_e^2 n_e}{m_e}\left(\bar{E} + \bar{v} \times \bar{B}_0\right) - q n_e \nu \bar{J}}$$

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 $\bar{B}_0$ and $\bar{k}$

$X = \frac{\omega_p^2}{\omega^2} = \frac{q_e^2 n_e}{m_e \epsilon_0 \omega^2}$

$Y = \frac{\omega_c}{\omega} = \frac{q_e B_0}{m_e \omega}$ → gyrofrequency

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

$n = \alpha + j\beta$

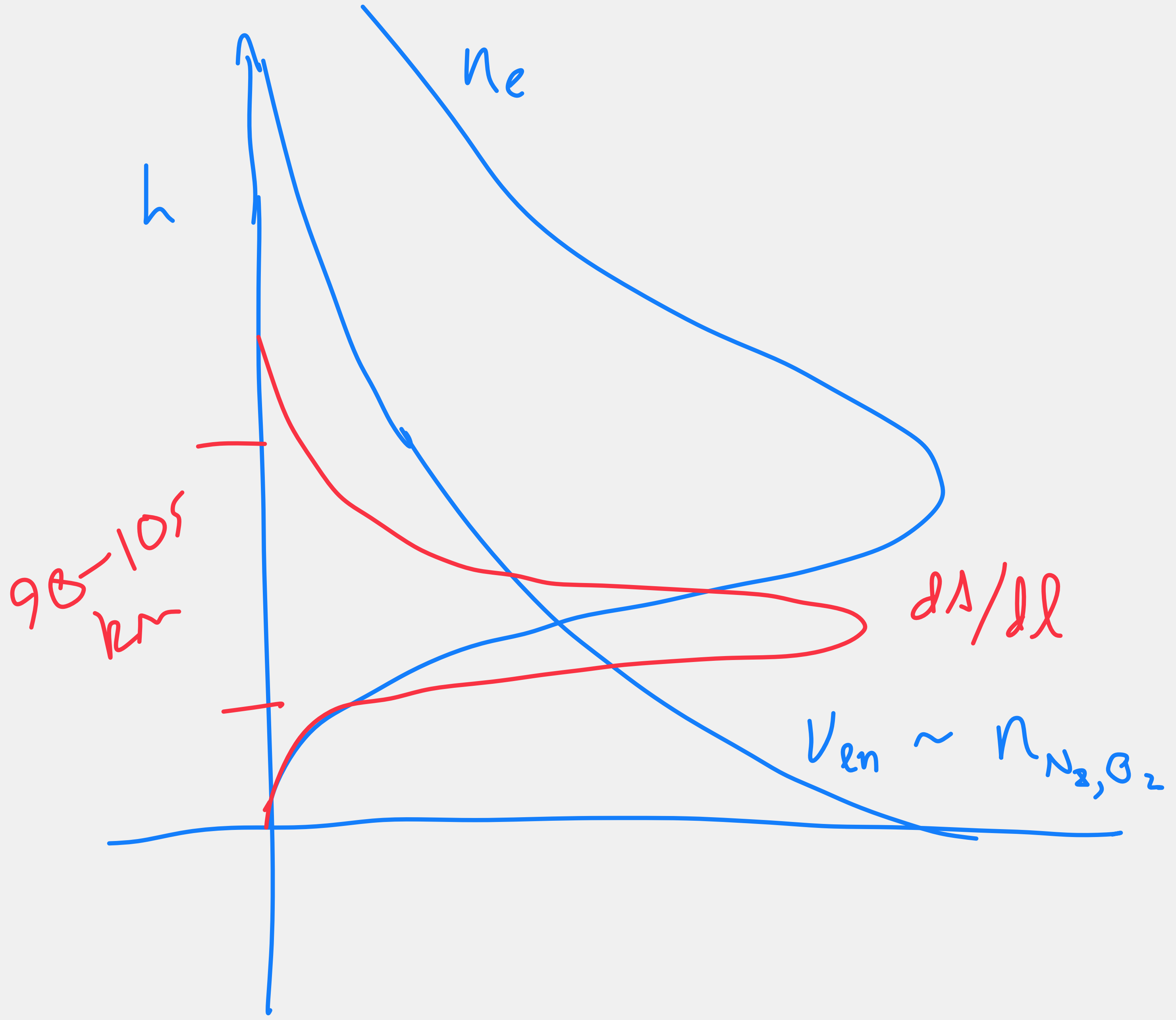
D-region absorption

- 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?

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

$\omega_c = \frac{qB_0}{m_e}$

$f_c \sim 1\text{–}2$ 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**?

~Te

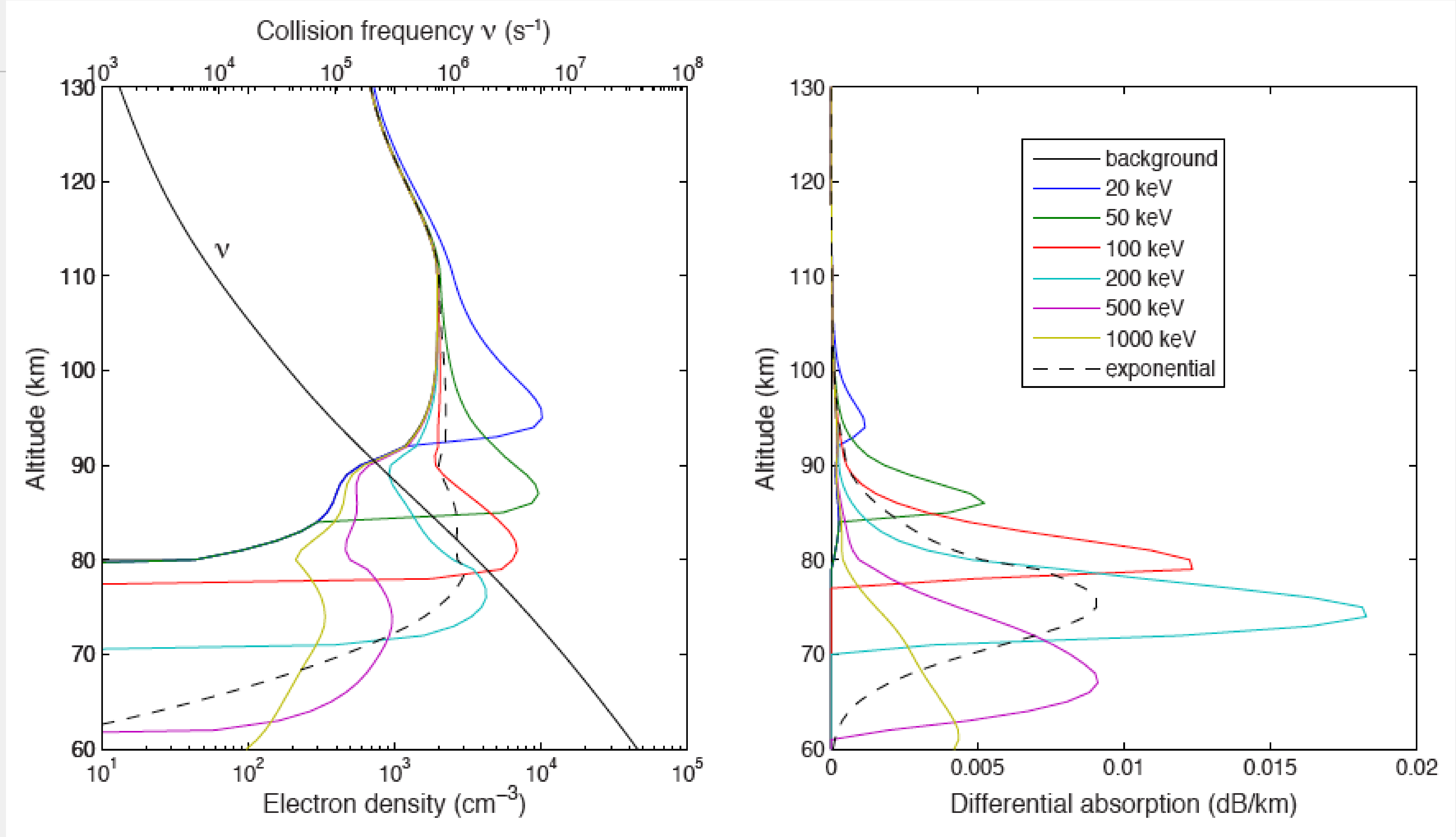
$$\nu_{av}(e, \mathrm{N_2}) = 2.33 \times 10^{-17} \underline{N_{\mathrm{N_2}}} (1 - \overbrace{1.21 \times 10^{-4}\, T_e}^{\text{small}})\, T_e$$

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

$$\underbrace{\nu_{en} = \nu_{av}(e, \mathrm{N_2}) + \nu_{av}(e, \mathrm{O_2})}_{\text{per electron}} \qquad 1/\mathrm{sec}$$

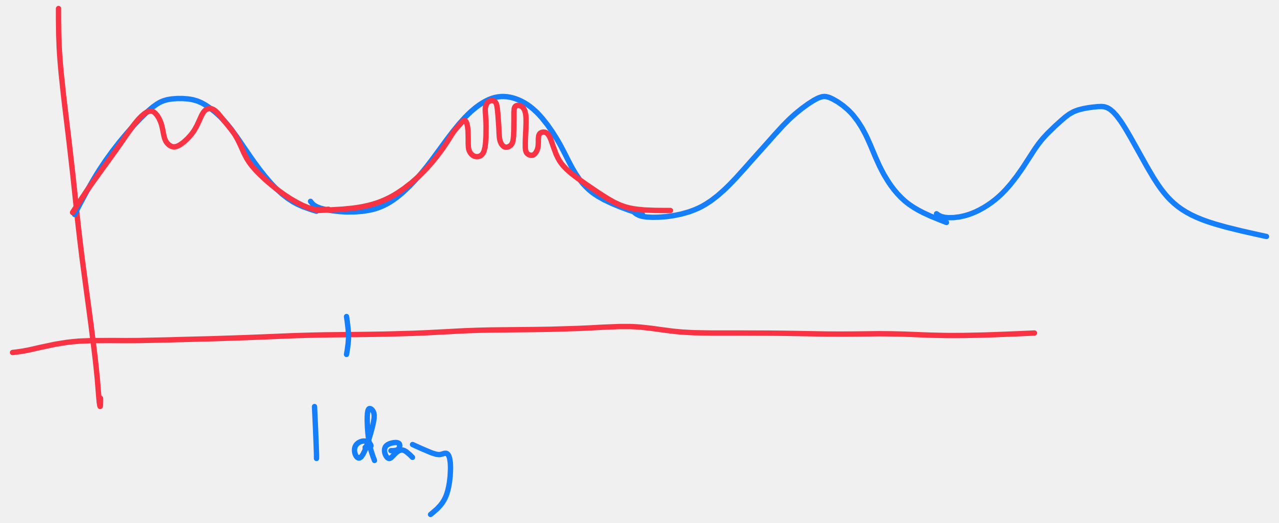
D-region absorption

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



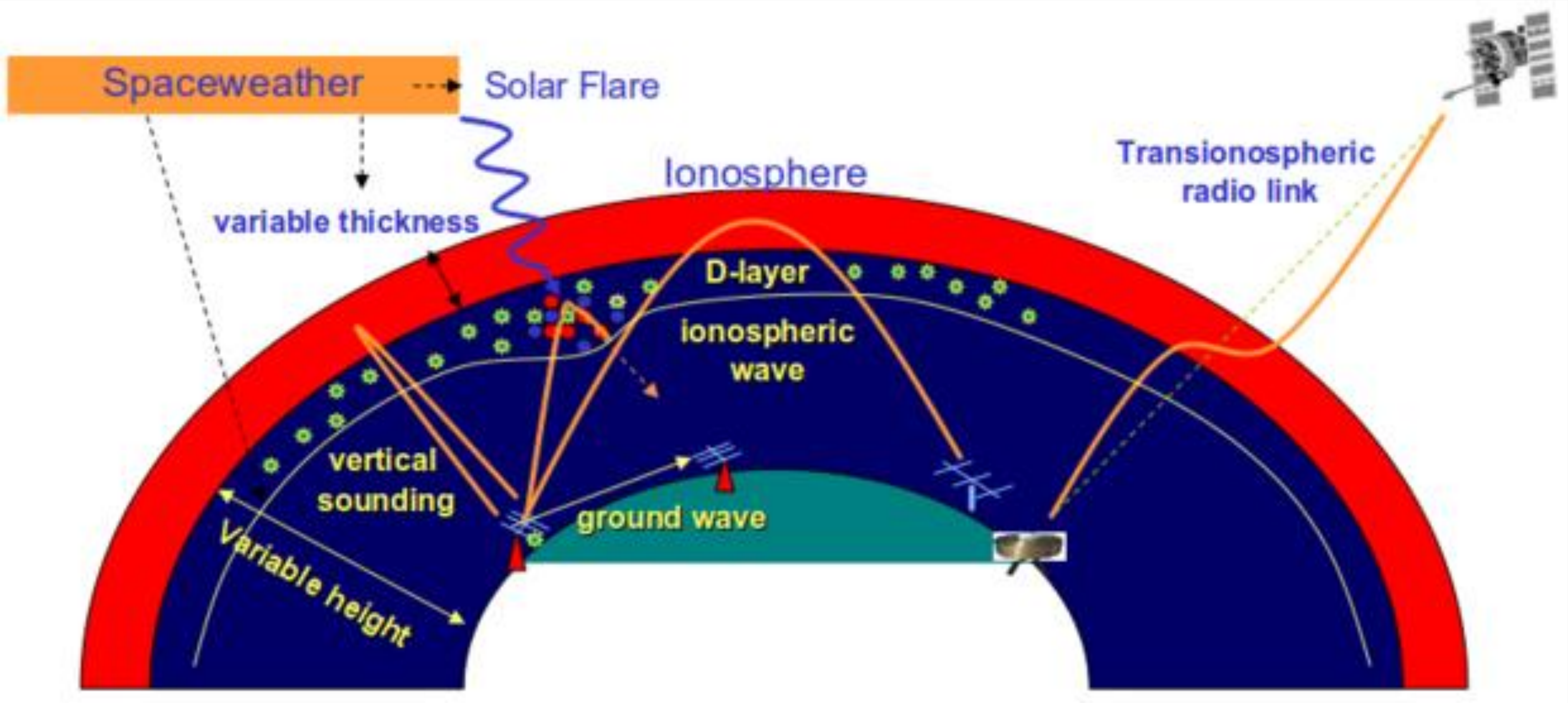
Alaska

- **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

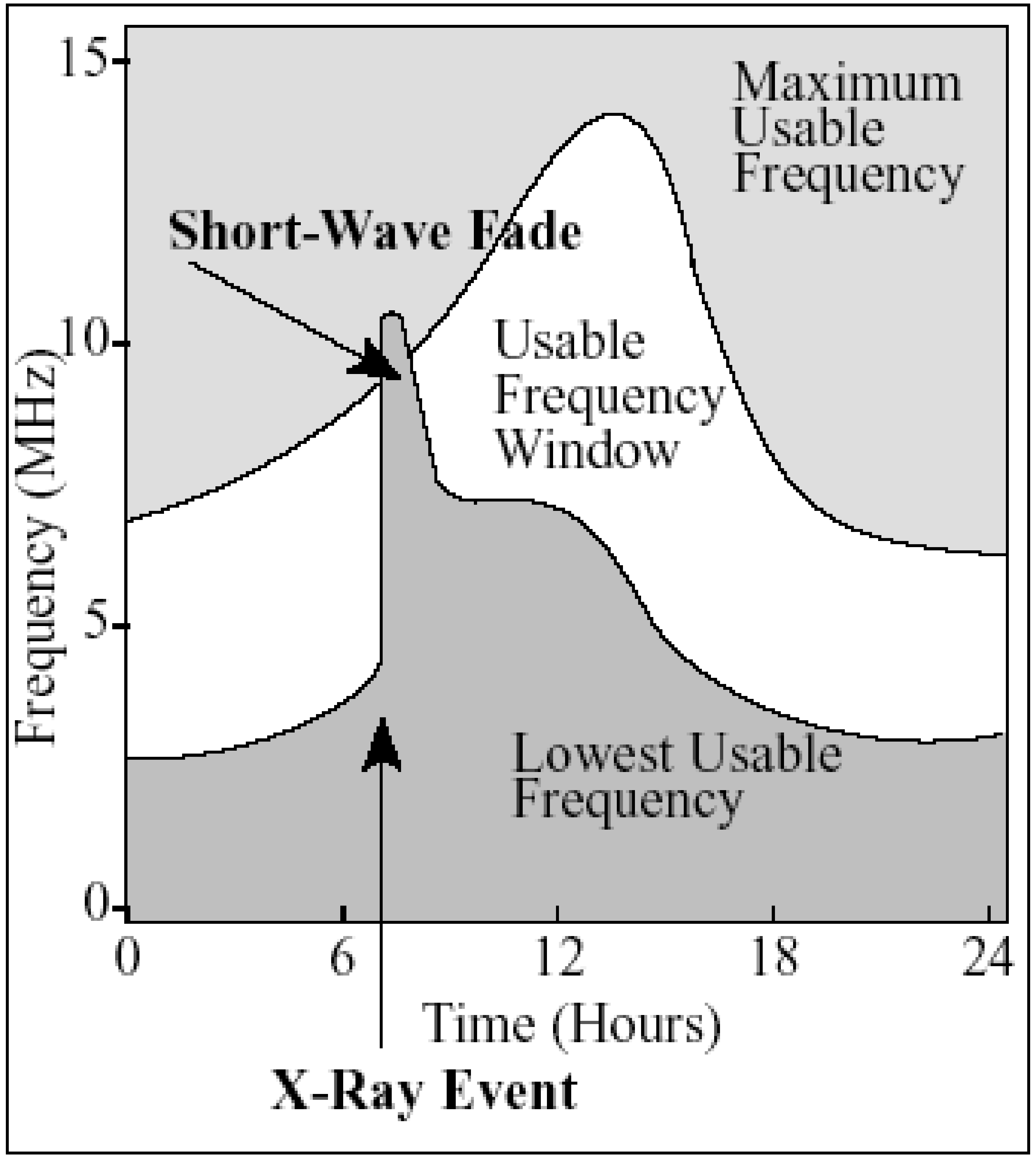


Short-Wave Fade

- **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



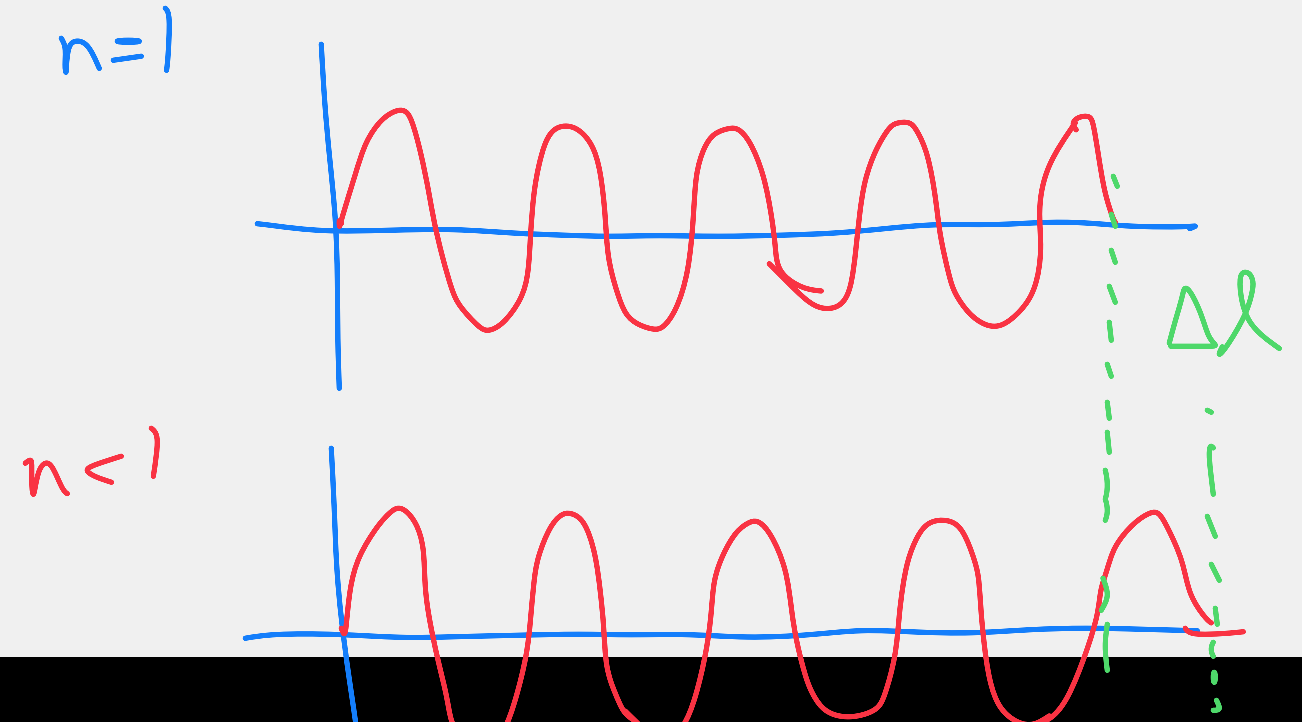
GPS and TEC

$f \sim 1\text{–}1.5\ \text{GHz}, \quad f \gg f_p, f_c$

- Even for frequencies above f_c, the ionosphere introduces some interesting effects
  - Small change in index of refraction from
    $$\boxed{n^2 = 1 - \frac{\omega_p^2}{\omega^2}}$$
  - 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:
    $$\boxed{n = 1 + \frac{c_2}{f^2}}$$
  - Change in path length:
    $$\boxed{\Delta l_{\text{iono}} = -\frac{40.3}{f^2} TEC}$$
  - Where TEC is total electron content, integrated along signal path

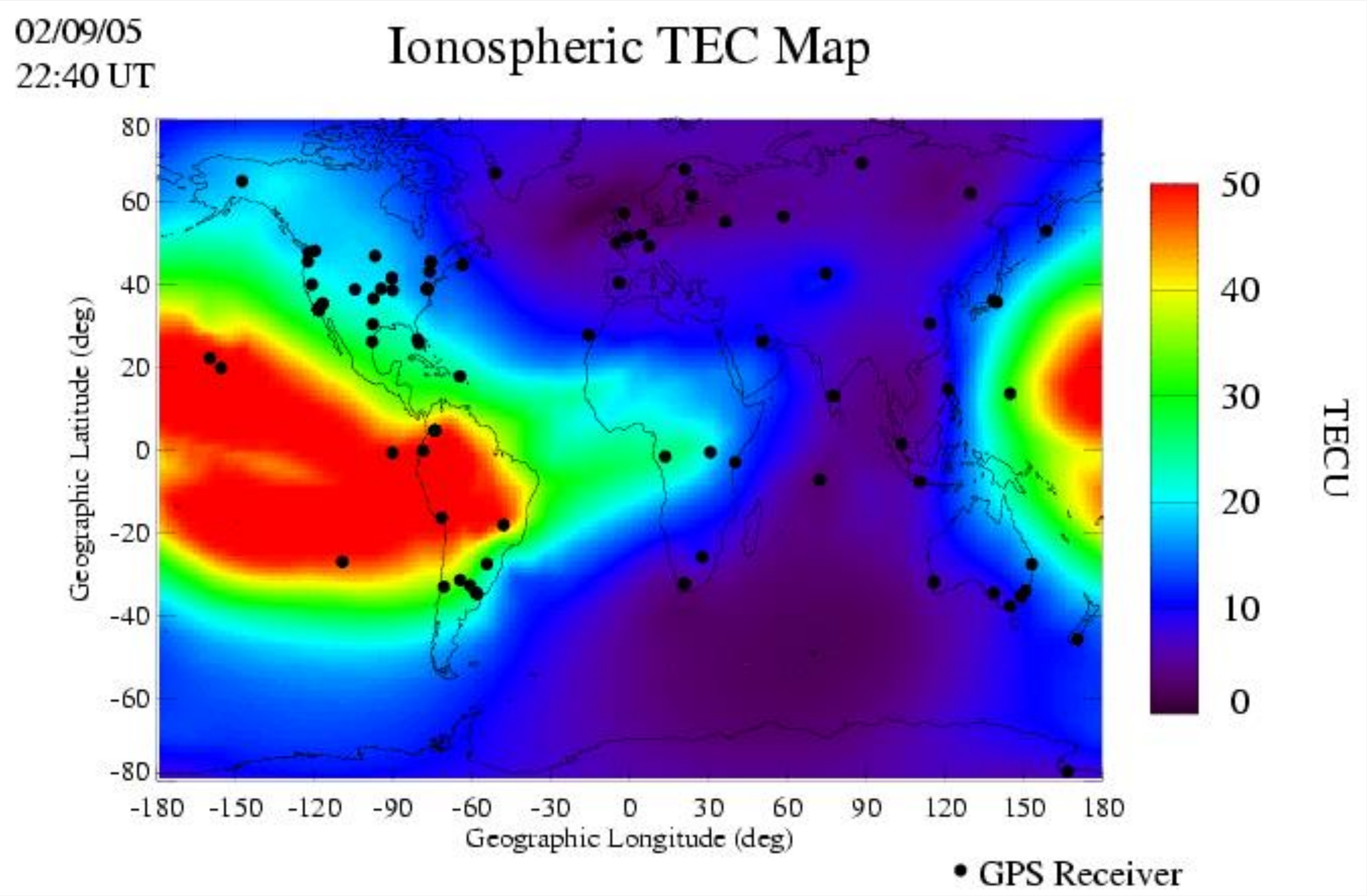
$$TEC = \int_{\infty}^{0} n_e(l)\, dl$$

(m^{-2})



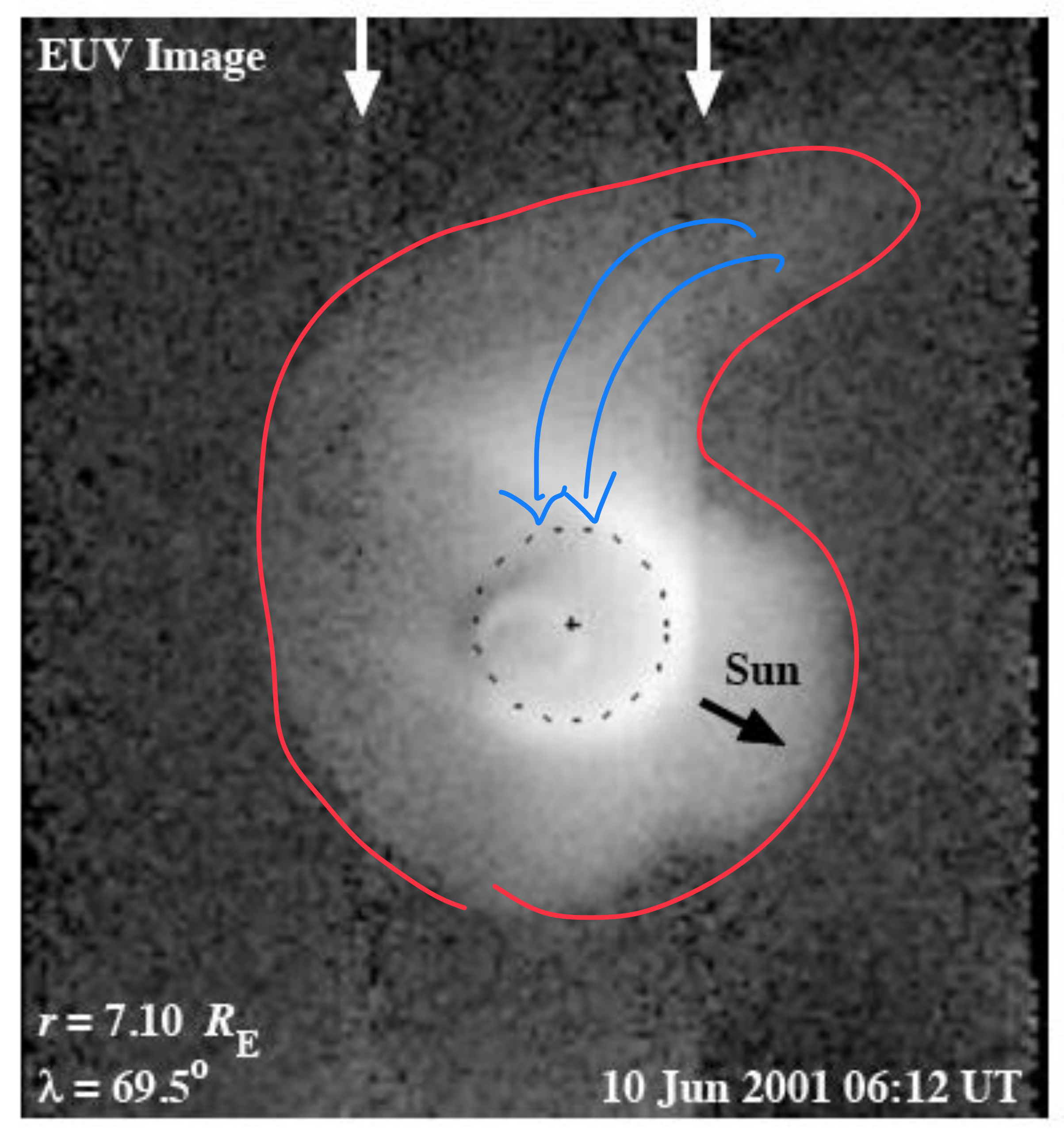
TEC maps

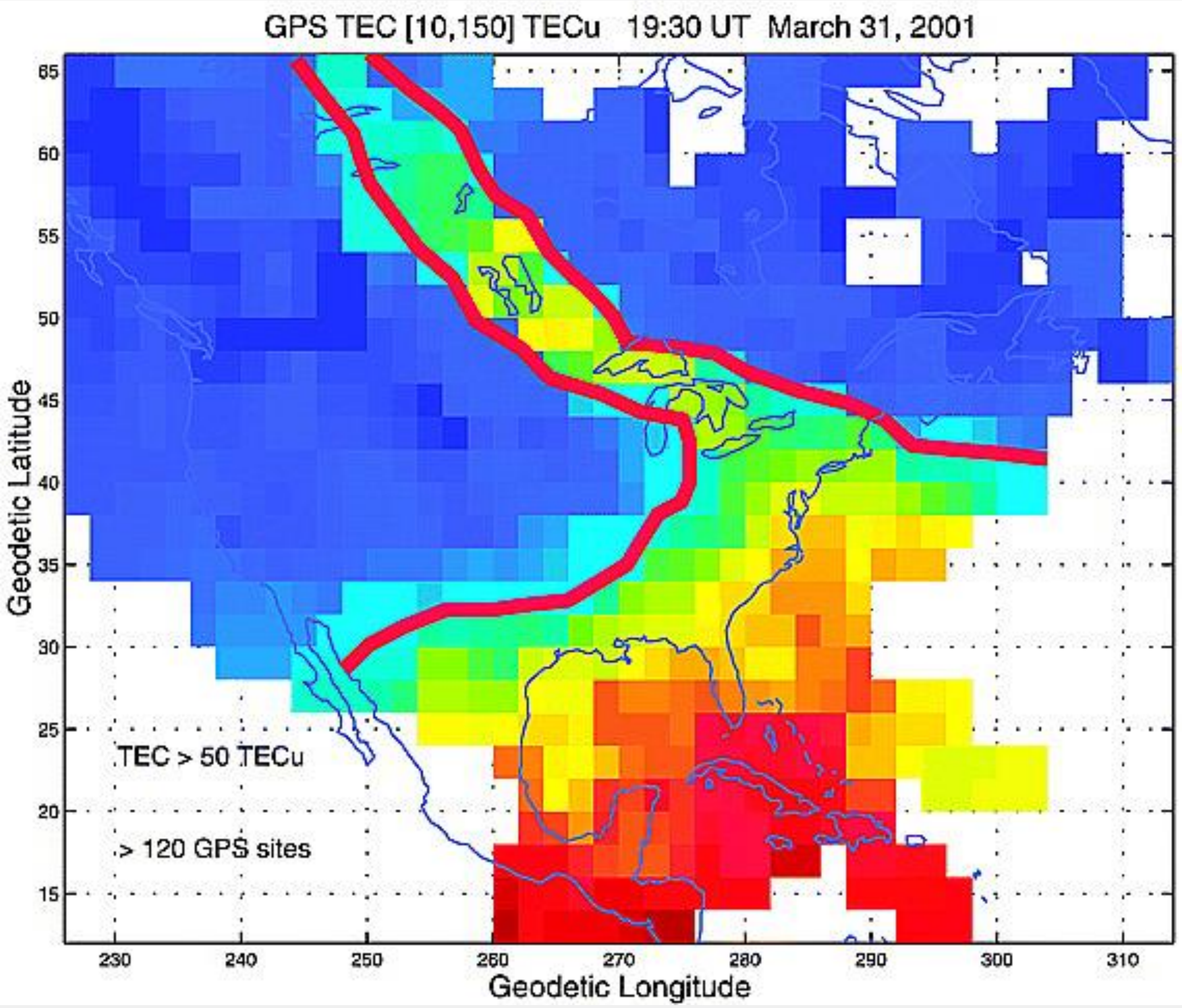
- 1 TECU = 10^{16} el/m^2
- receivers all over the Earth's surface; 20+ satellites to provide pierce-points
- Interpolate results onto 2D (or 3D) map



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



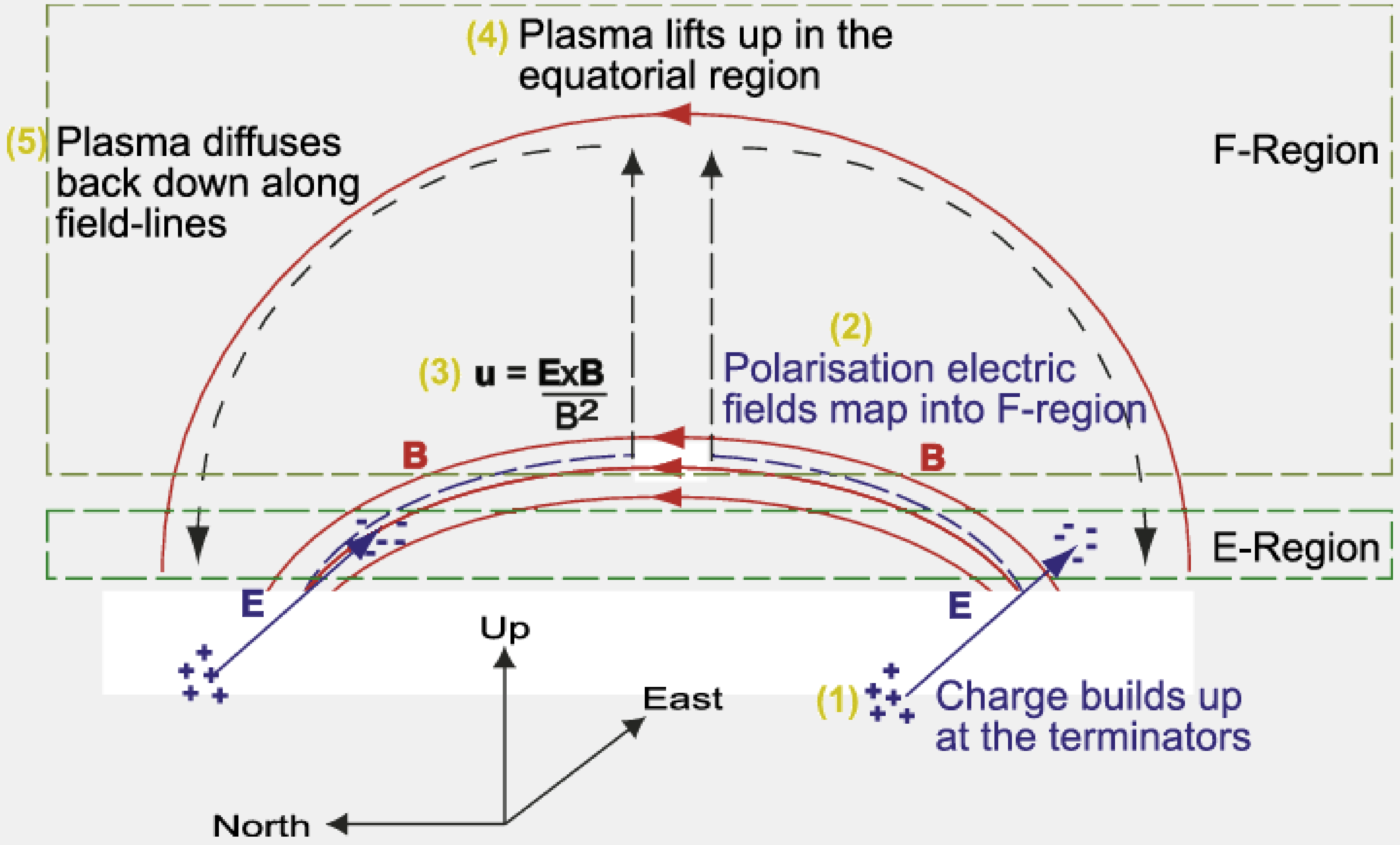


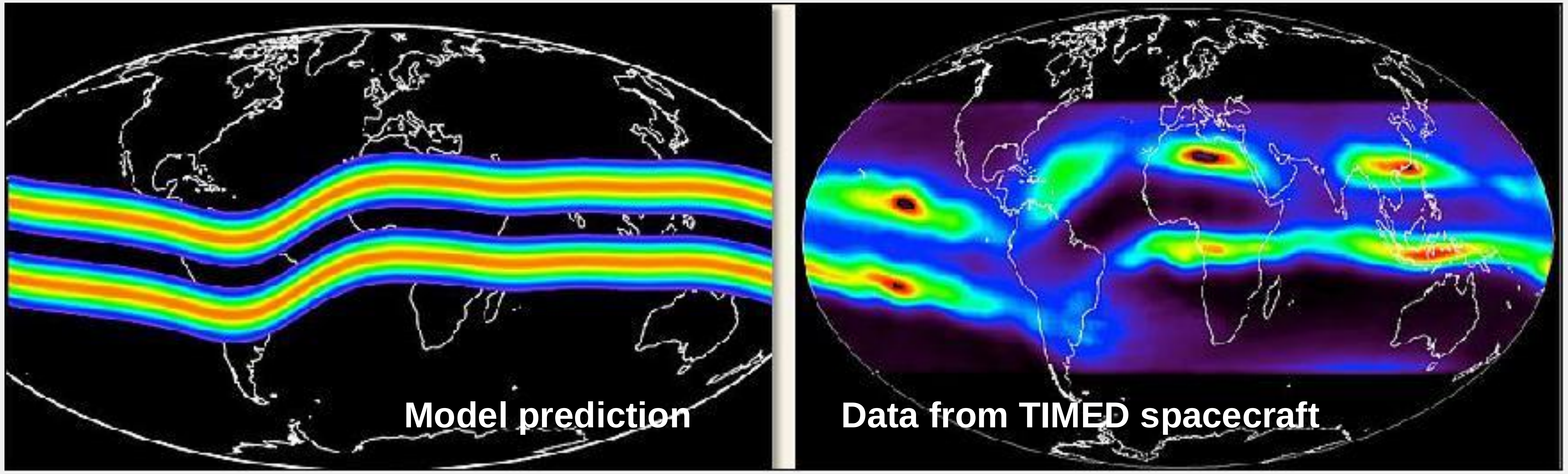
Ionosphere Missions

- **ICON**
  - Using airglow to infer ion densities and winds
- **Ampere**
  - Using magnetic fields to measure currents
- **COSMIC** and **GPS**
  - Measuring the ionosphere using radio occultation / path delay
- *Hidden Figures* and *Apollo 13*: Re-entry comm problem

The Equatorial Ionosphere

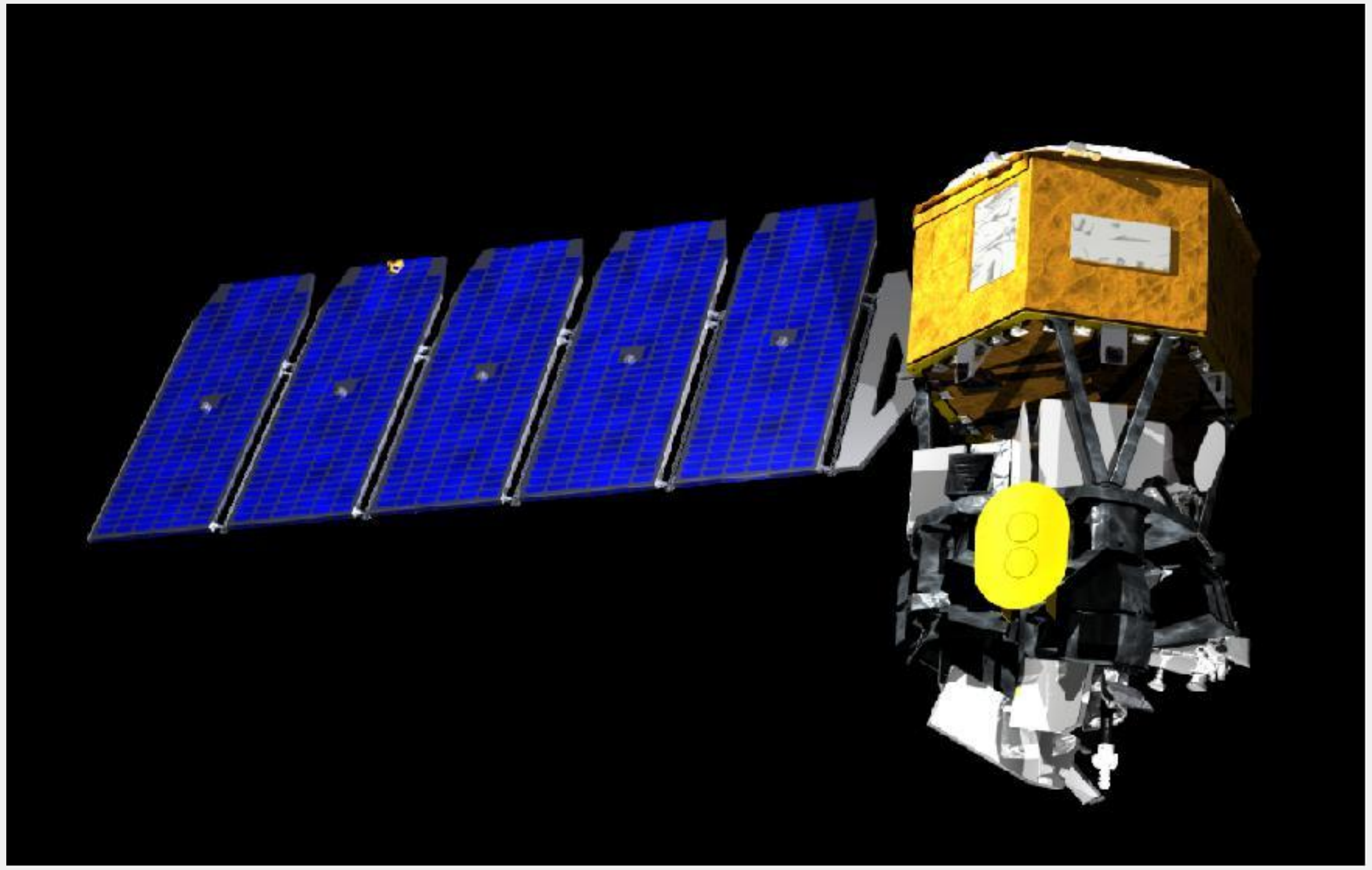
- The Fountain effect predicts two bands of enhanced electron density above and below the magnetic equator
- The truth? A bit more complicated….





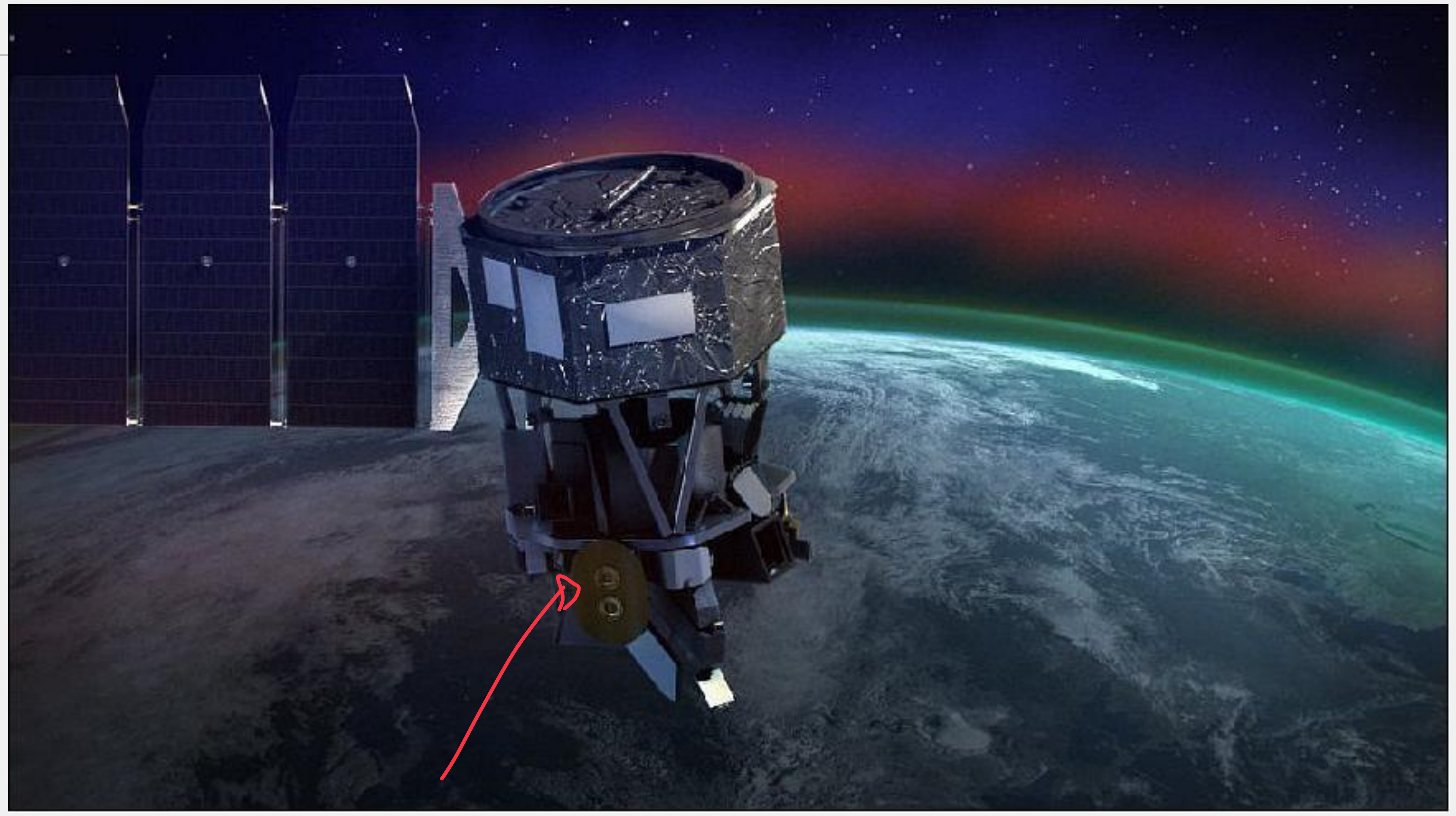
ICON Science and Spacecraft

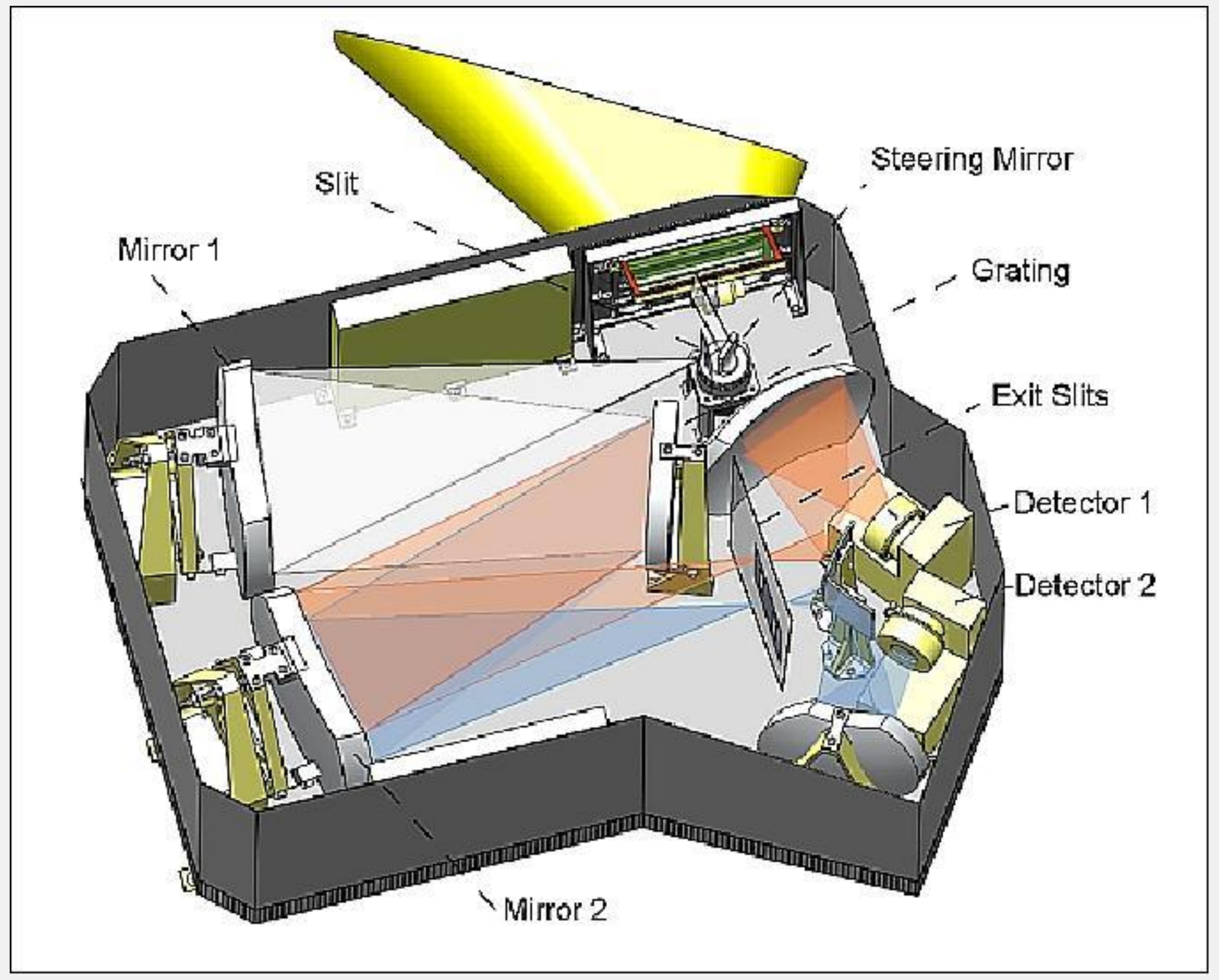
- Understand drivers of ionospheric variability
- Explain how energy / momentum from lower atmosphere reach the space environment (e.g. gravity waves!)
- Explain how drivers create extreme conditions observed during solar-driven geomagnetic storms



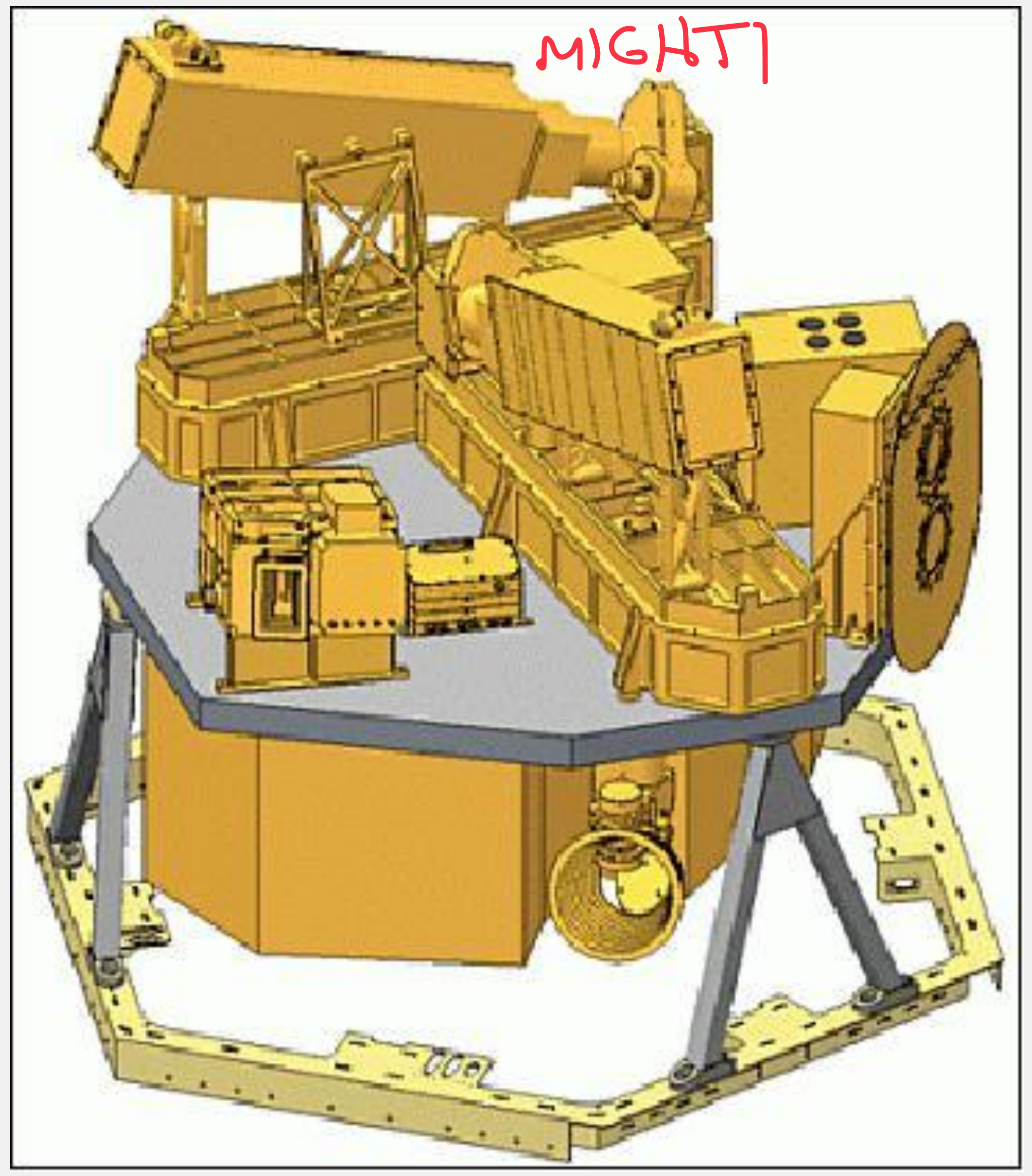
ICON instrumentation

- Four main instruments:
  - **MIGHTI** is a Michelson Interferometer to measure winds and temperatures
  - **FUV** is an FUV imager; observes UV emissions of N_2 and O to determine O/N_2 ratio
  - **EUV** images 83.4 nm emission from O; resonantly scattered by O+: gives ion density
  - **IVM** is the ion velocity meter; uses a Retarded Potential Analyzer (RPA) to measure relative velocity of ions, therefore winds, as well as temperature and density





FUV



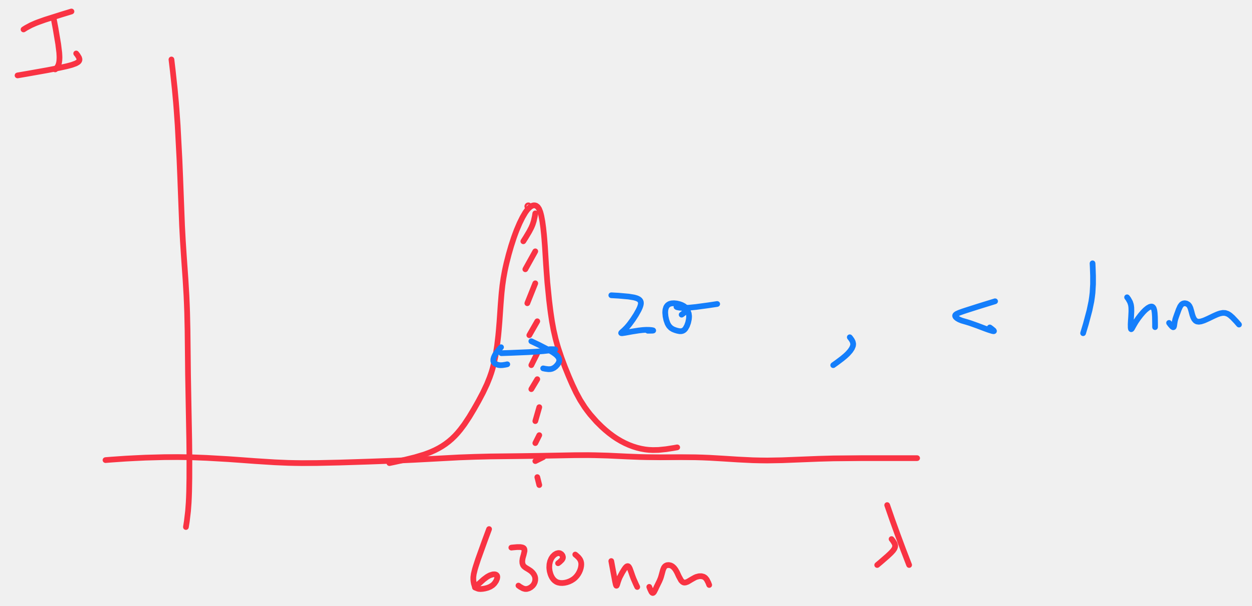
MIGHTI

How do you get wind & temperature from optical emissions?

- Line emissions: atomic oxygen has emission lines at 630.0 nm and 557.7 nm (red and green lines)
- If the O atoms were completely stationary, emissions would always be at exactly these wavelengths
- O atoms are not stationary; have some velocity in random directions due to the gas temperature
- Atom moving at v', relative to observer, will emit a photon that is Doppler shifted in wavelength by

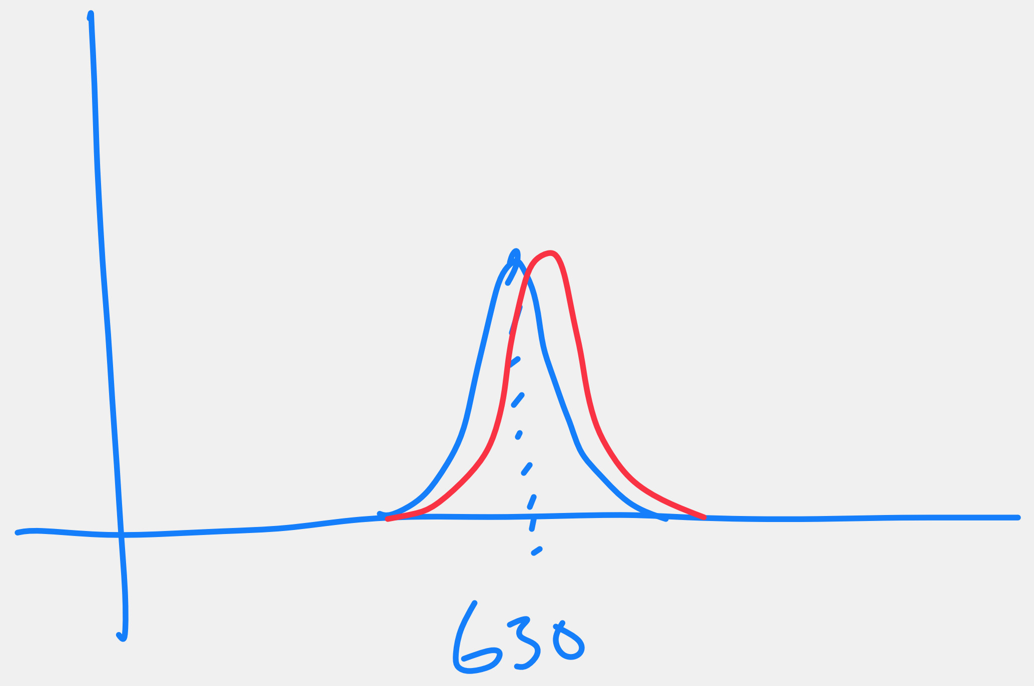
$$f' = \left(1 + \frac{v'}{c}\right) f_0$$

- Add up all the different v's in the Maxwell-Boltzmann distribution, and you get a distribution of wavelengths that is Gaussian
- Line broadening
- Line gets broader when temperature is higher
- Need a really good spectrometer to resolve this line!

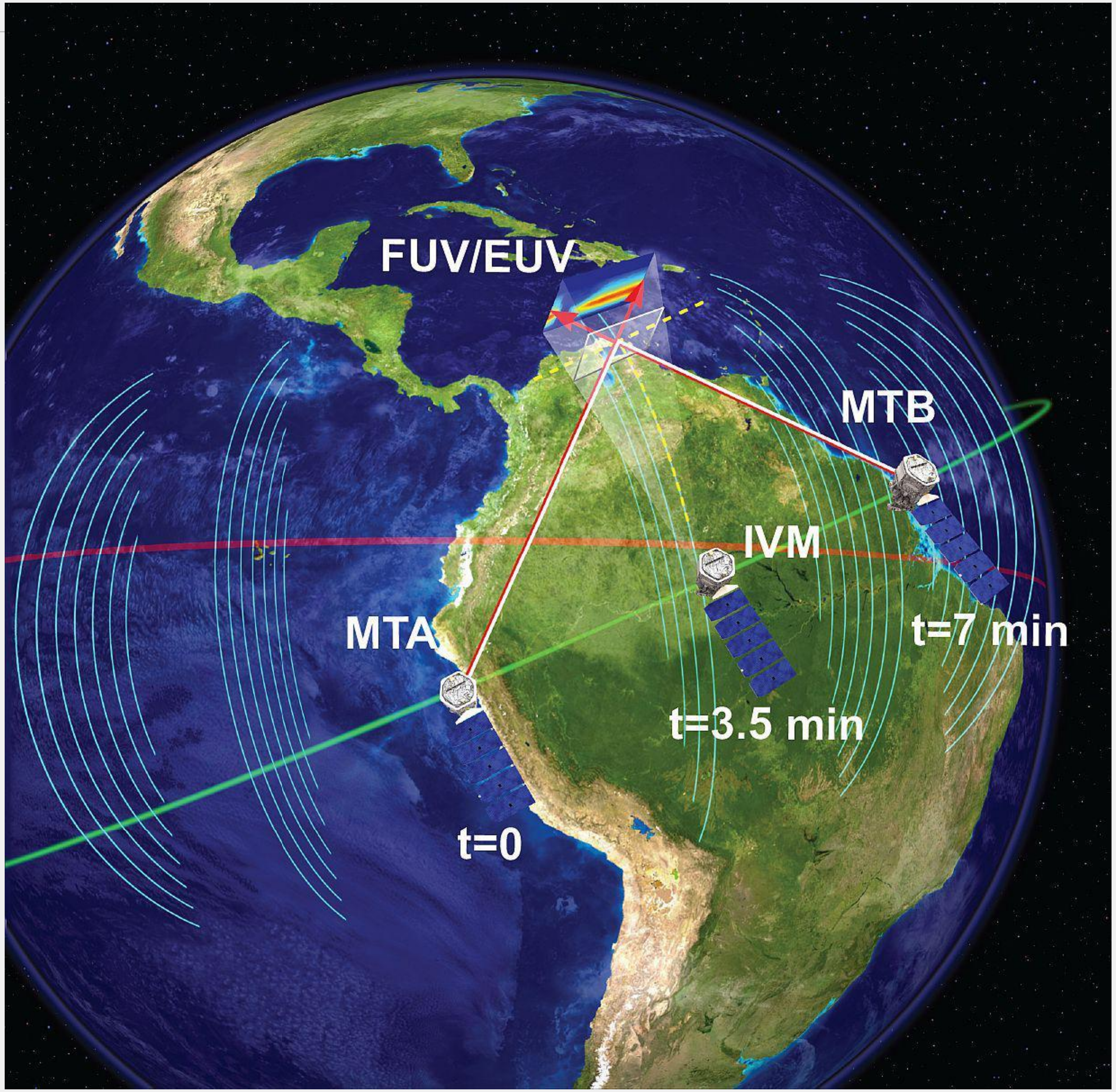


$$\sigma = \sqrt{\frac{kT}{m_e c^2}}\, f_0 ,$$

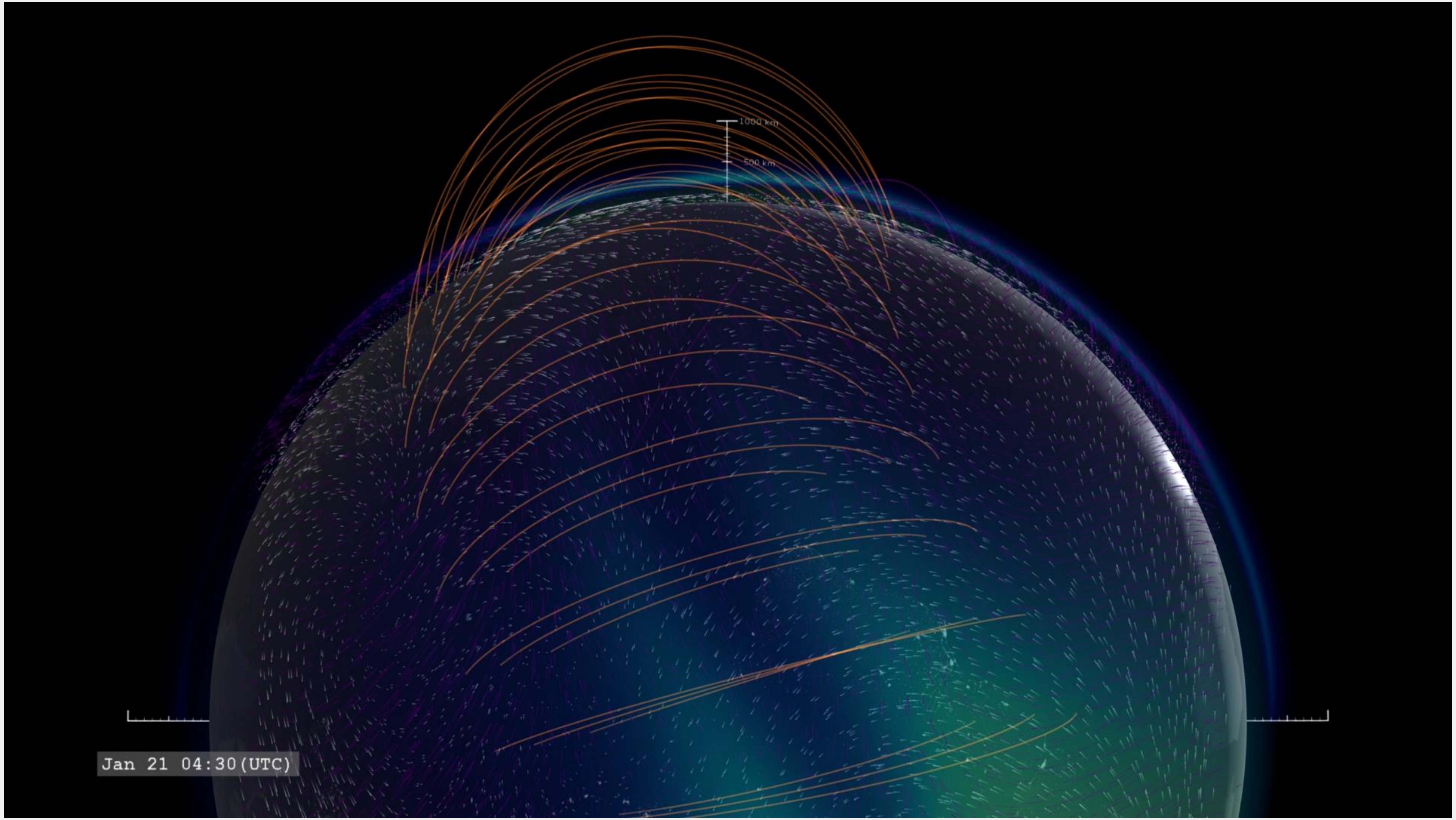
$$f_0 = c/\lambda$$



ICON CONOPS



ICON CONOPS made awesome



A word from our sponsor

Comparative Ionospheres: Jupiter and Mars

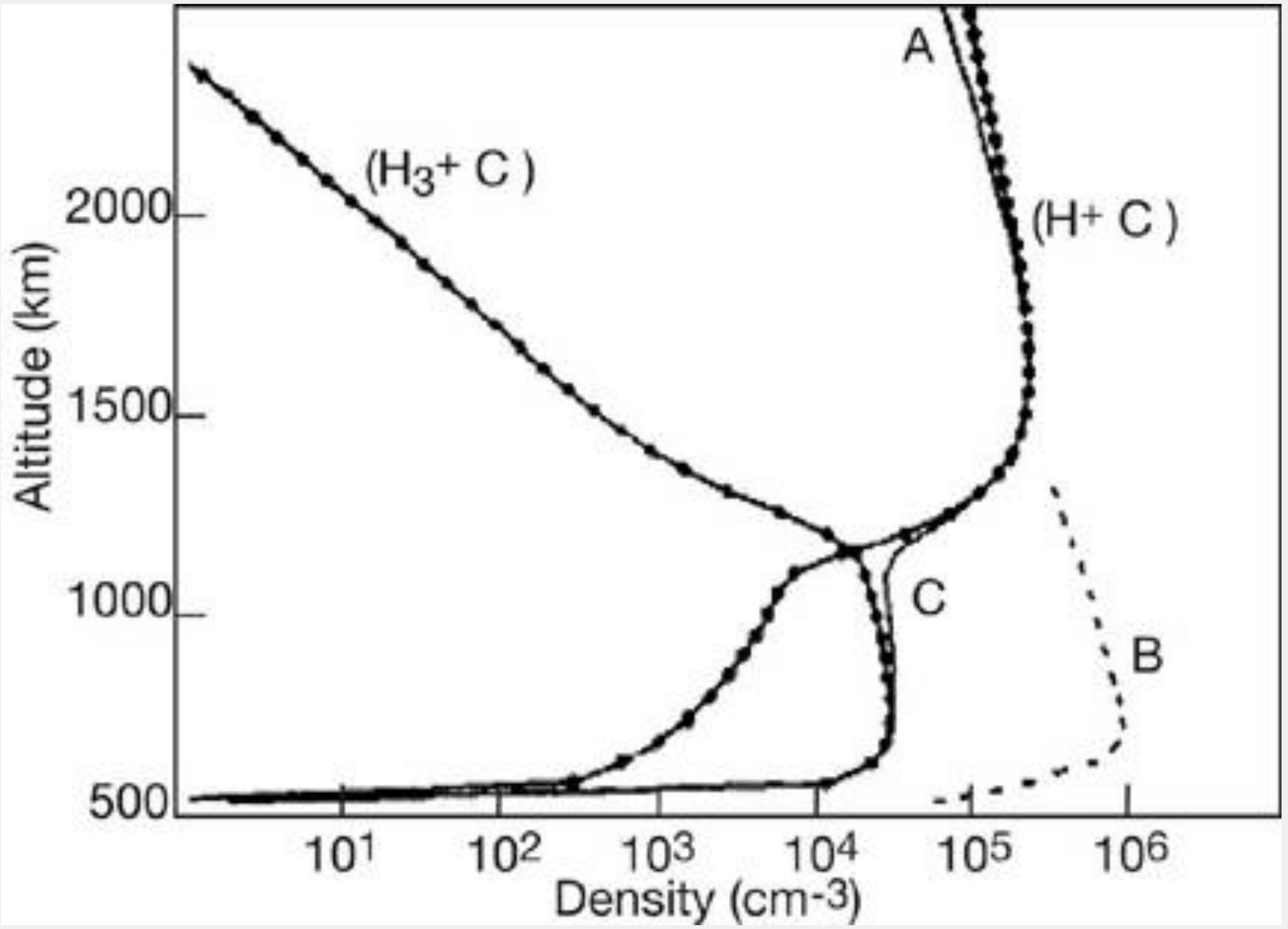
Jupiter's Ionosphere

- Atmosphere is mostly H_2, so we would expect H_2^+ (maybe H^+), right?

$$\underset{}{H_2} + \underset{\text{photon}}{\nu} \rightarrow \underset{\text{proton}}{\underline{\underline{H^+}}} + H + \underset{\text{electron}}{e^-}$$ dissociative ionization

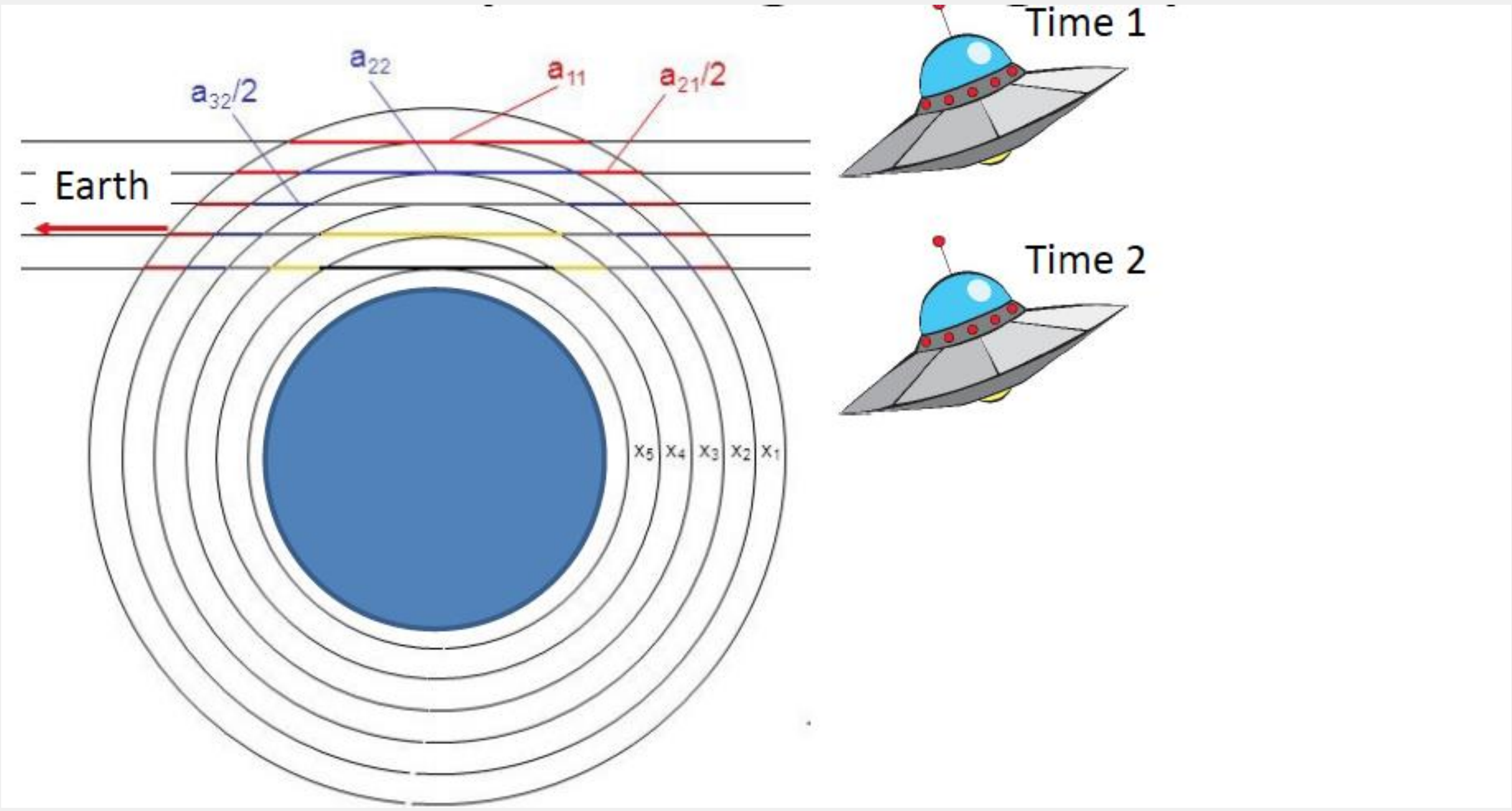
$$H_2 + H^+ \rightarrow \underline{\underline{H_2^+}} + H$$ charge exchange!

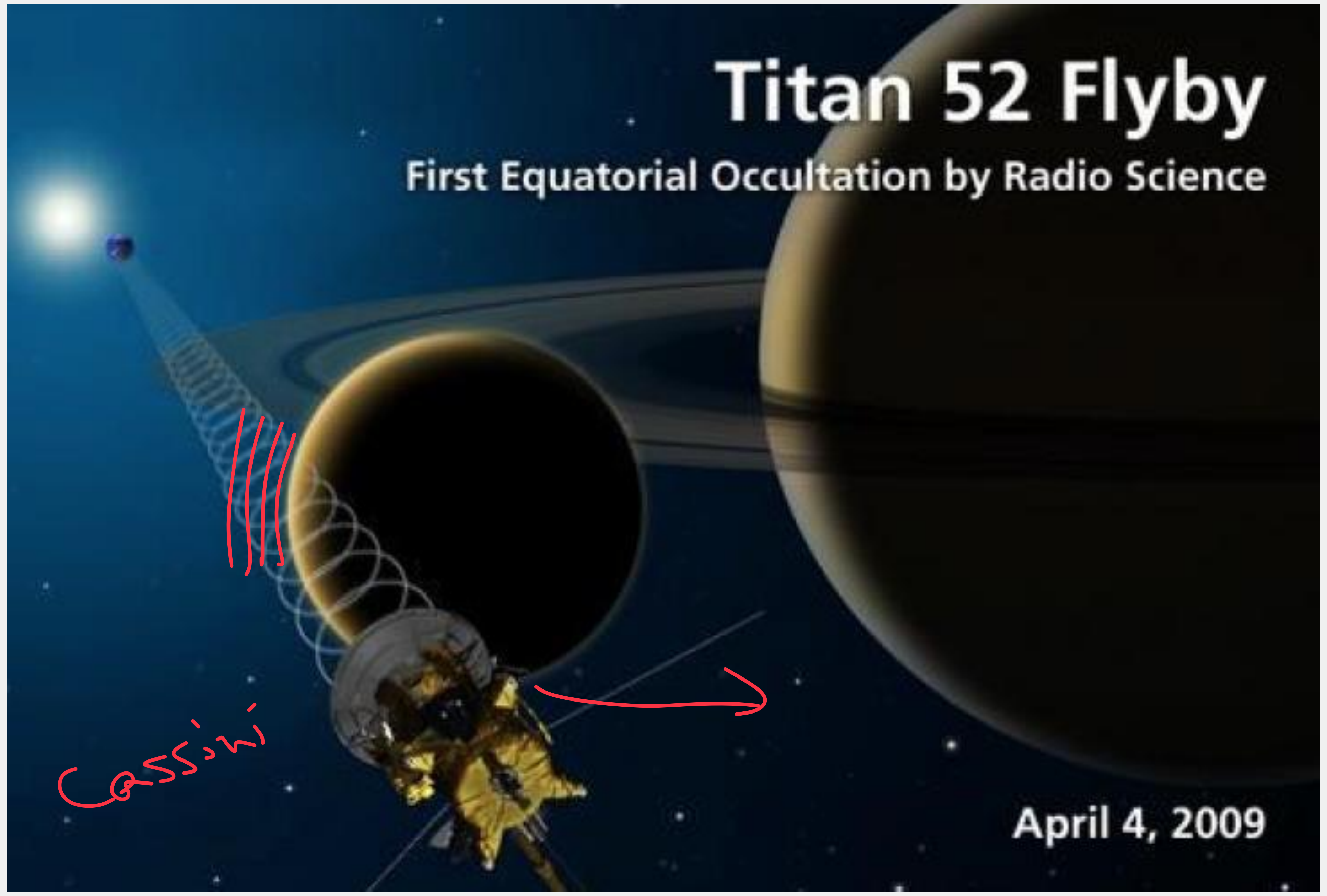
$$H_2^+ + H_2 \rightarrow \underline{\underline{H_3^+}} + H$$



How do we measure the ionosphere?

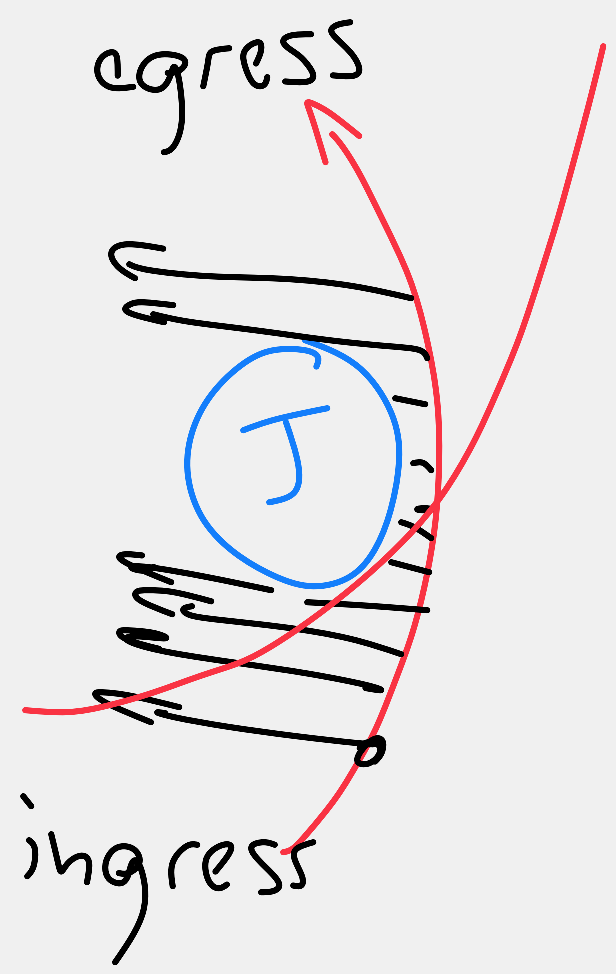
- Transmit radio waves from spacecraft to Earth
- **As we pass behind atmosphere / ionosphere, we get:**
  - Absorption at specific frequencies: atmosphere composition
  - Refraction / ray-bending: ionosphere density
  - Faraday rotation: magnetic field strength
- **Get successive slices through atmosphere as orbit progresses**
- Big matrix inversion to determine altitude profile

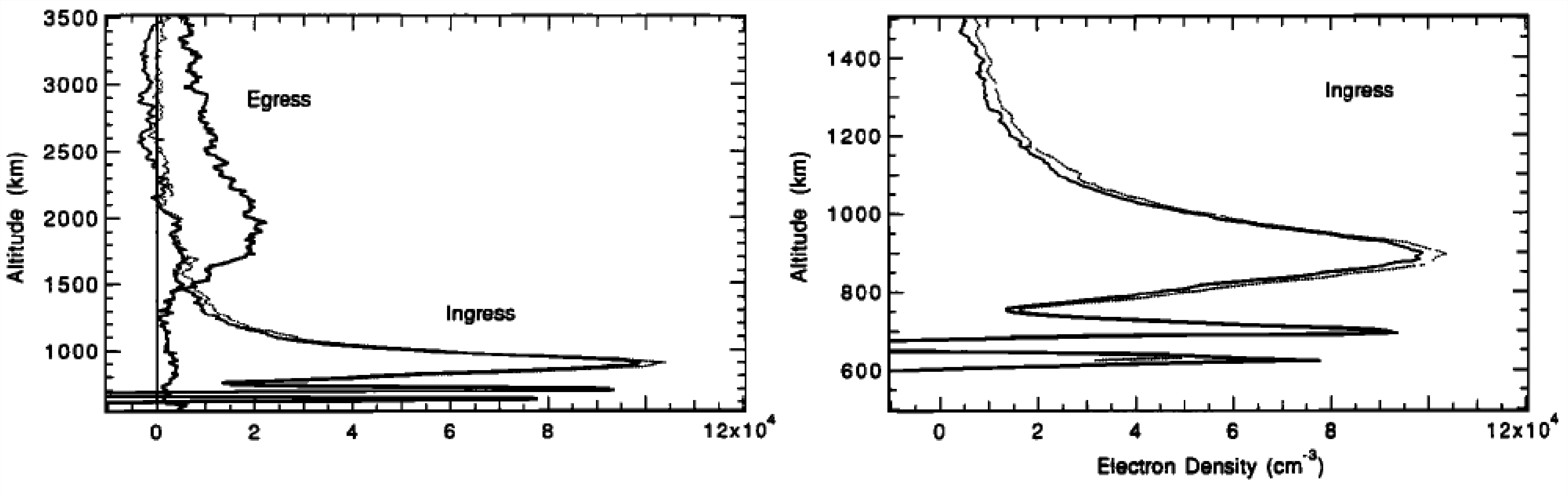




Altitude Profiles

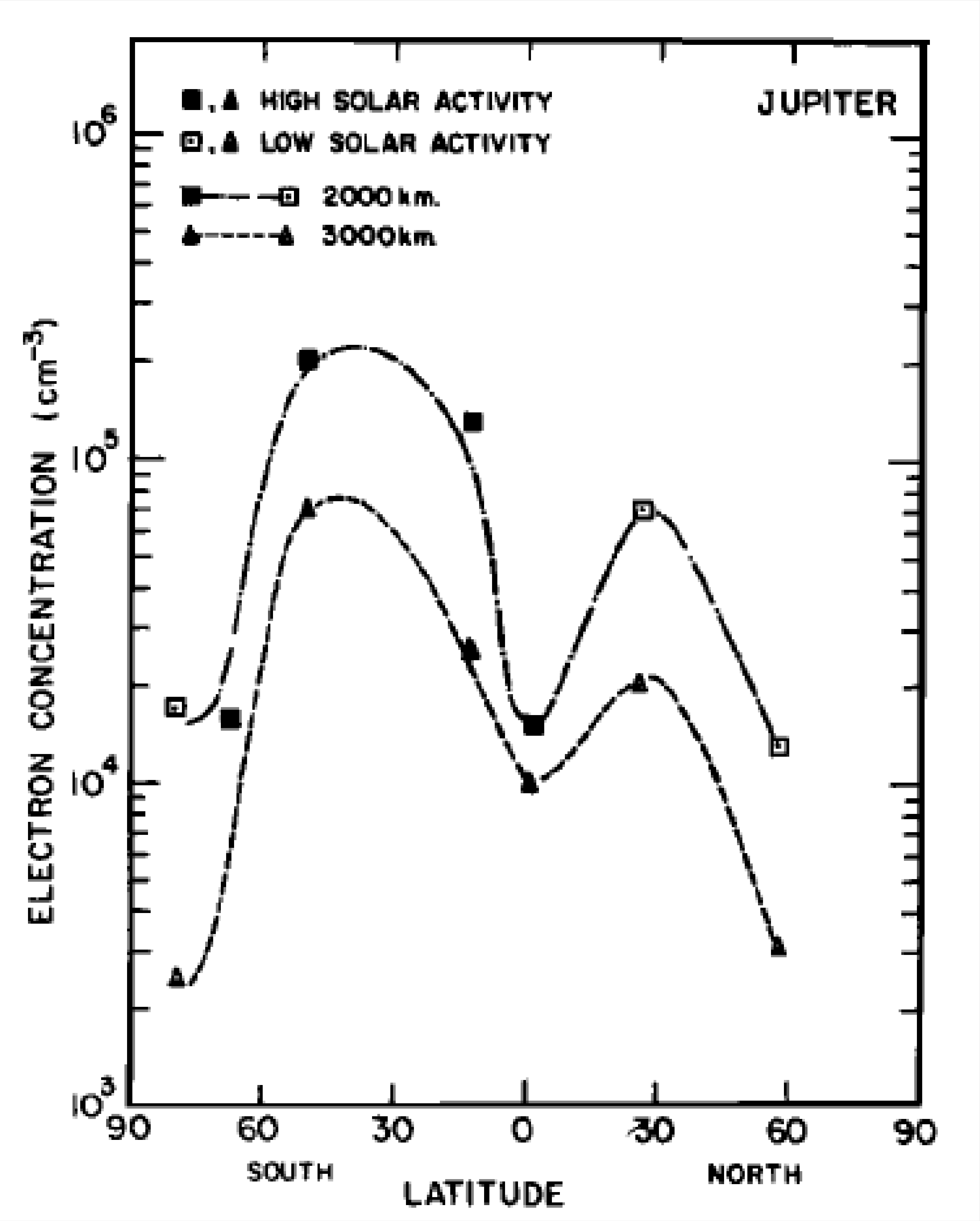
- Measured by radio occultation (Galileo spacecraft, mid-1990s)
- Ingress: passing behind planet
- Egress: emerging from behind planet
- Note very different ionospheres on the two sides of the planet!
- Lower layers potentially due to gravity waves, or other plasma processes

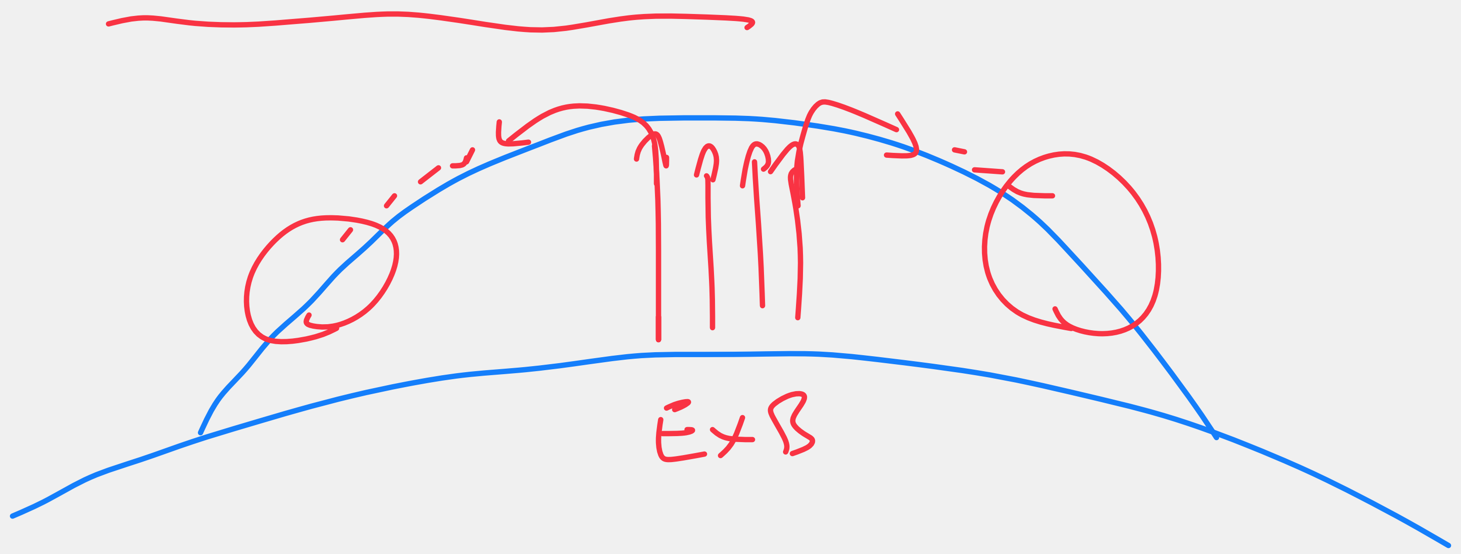




Other Features in Jupiter's Ionosphere?

- Jupiter has a nice strong magnetosphere similar in structure to Earth's
- The magnetic field is important in the ionosphere, producing interesting plasma phenomena:
  - Sporadic-E, Spread-F, the Equatorial Anomaly, Polar Cap absorption, Aurora, etc.
- We expect that many of these occur at Jupiter as well
  - Right: Equatorial Anomaly

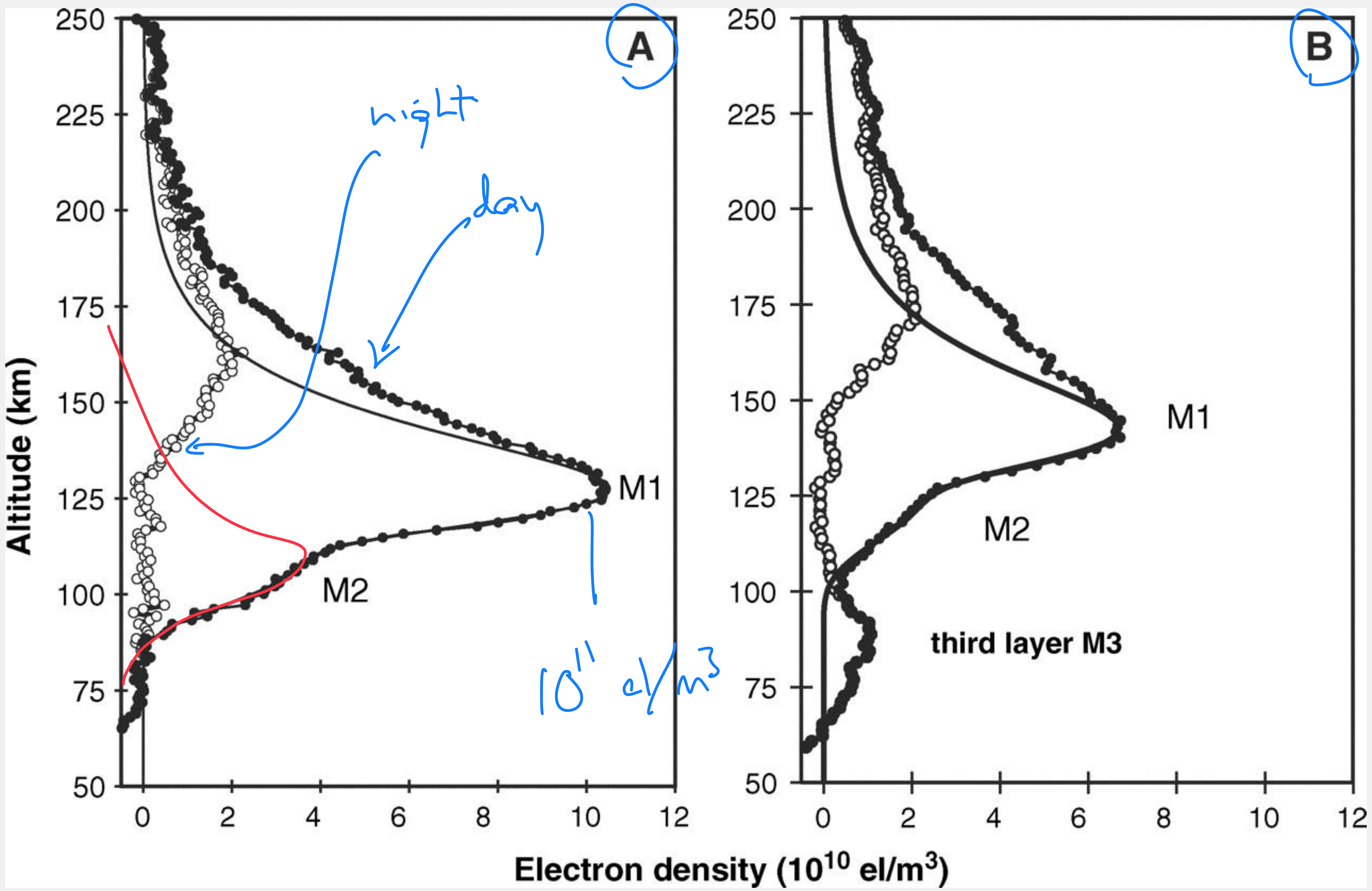




Mars' Ionosphere: Layers

- Mars' Ionosphere forms the same way as Earth's: product of solar radiation (EUV) and molecules to ionize
- Good fit to a Chapman layer

$CO_2 + \gamma \rightarrow CO_2^+ + e^-$



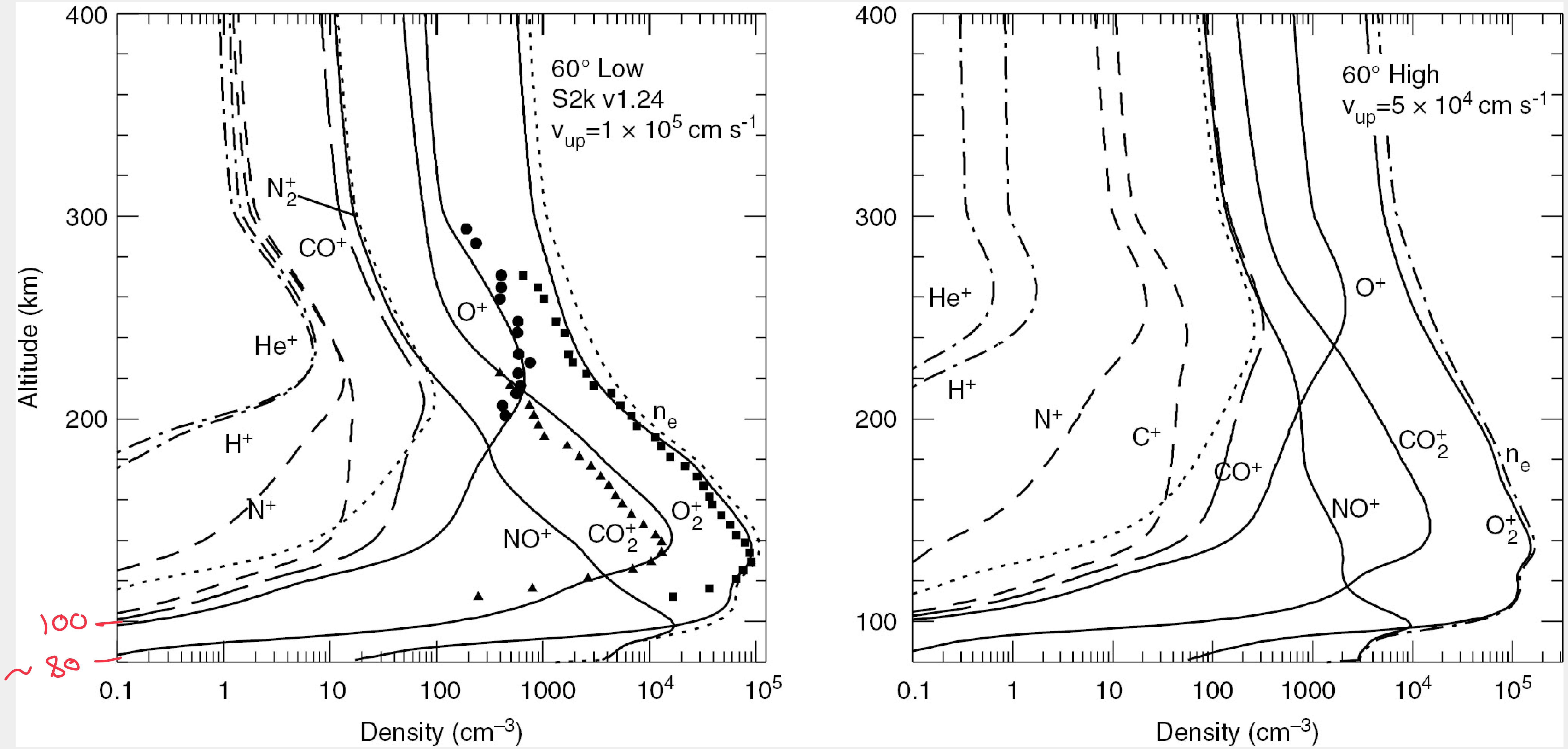
$$\frac{dn_e}{dt} = P - L$$

$$L = \alpha n_e^2$$

$$L = \alpha n_e n_i$$

Ionosphere density and composition

- Electron density peaks at about 10^{11} electrons/m^{-3}, at about 150 km altitude
- Ion composition is about 90% O_2^+ and 10% CO_2^+
- Some O^+ at higher altitudes



MIRI → n_e

Mars Ionosphere Chemistry

- How do we get O_2^+ despite not having much oxygen?

production : $CO_2 + \gamma \rightarrow CO_2^+ + e^-$ photoionization

$CO_2^+ + O \rightarrow O_2^+ + CO$ source of O_2^+ and CO

loss : $O_2^+ + e^- \rightarrow O + O^*$

excited state

$O^* \rightarrow O + \gamma$

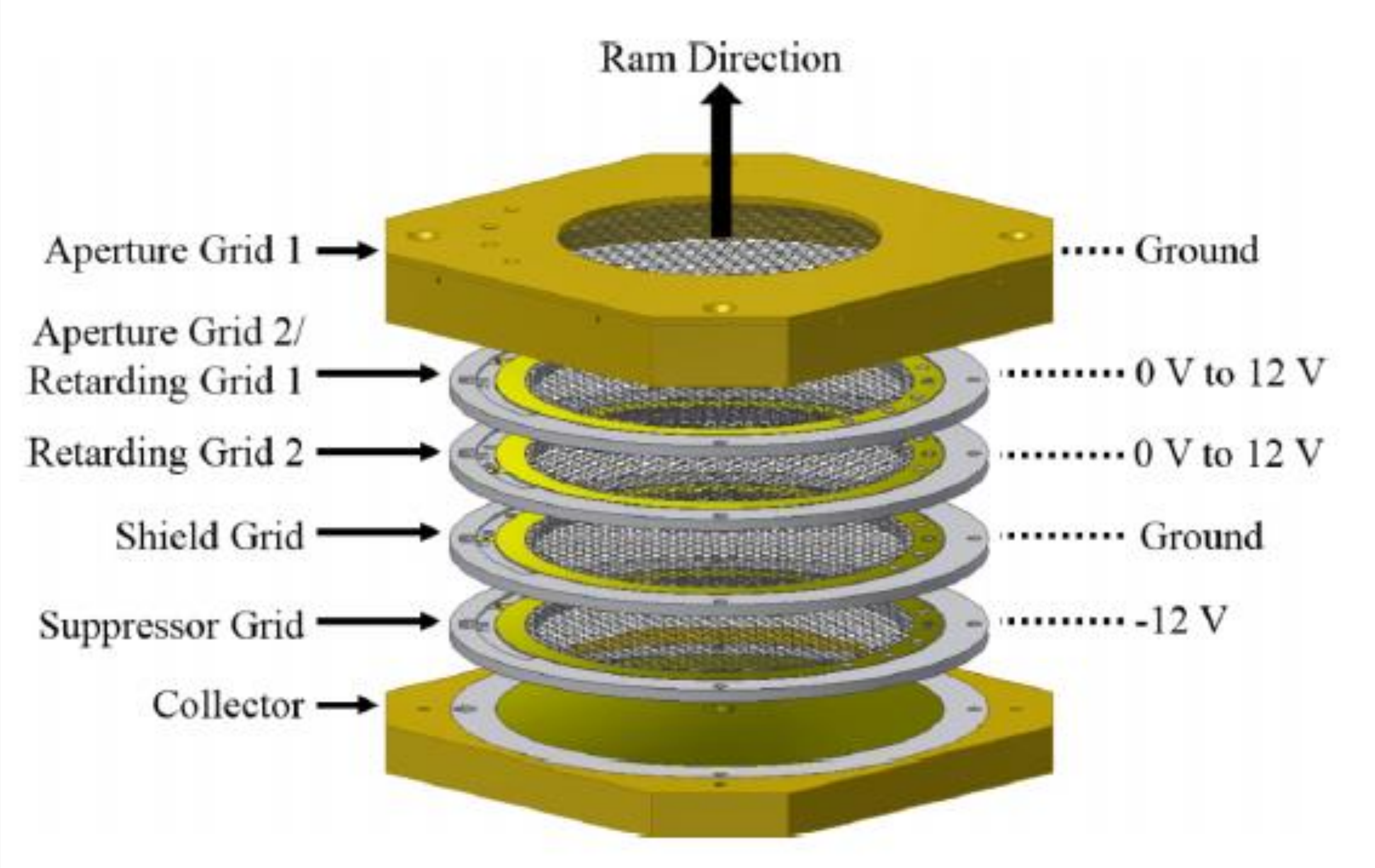
airglow, 557.7 nm

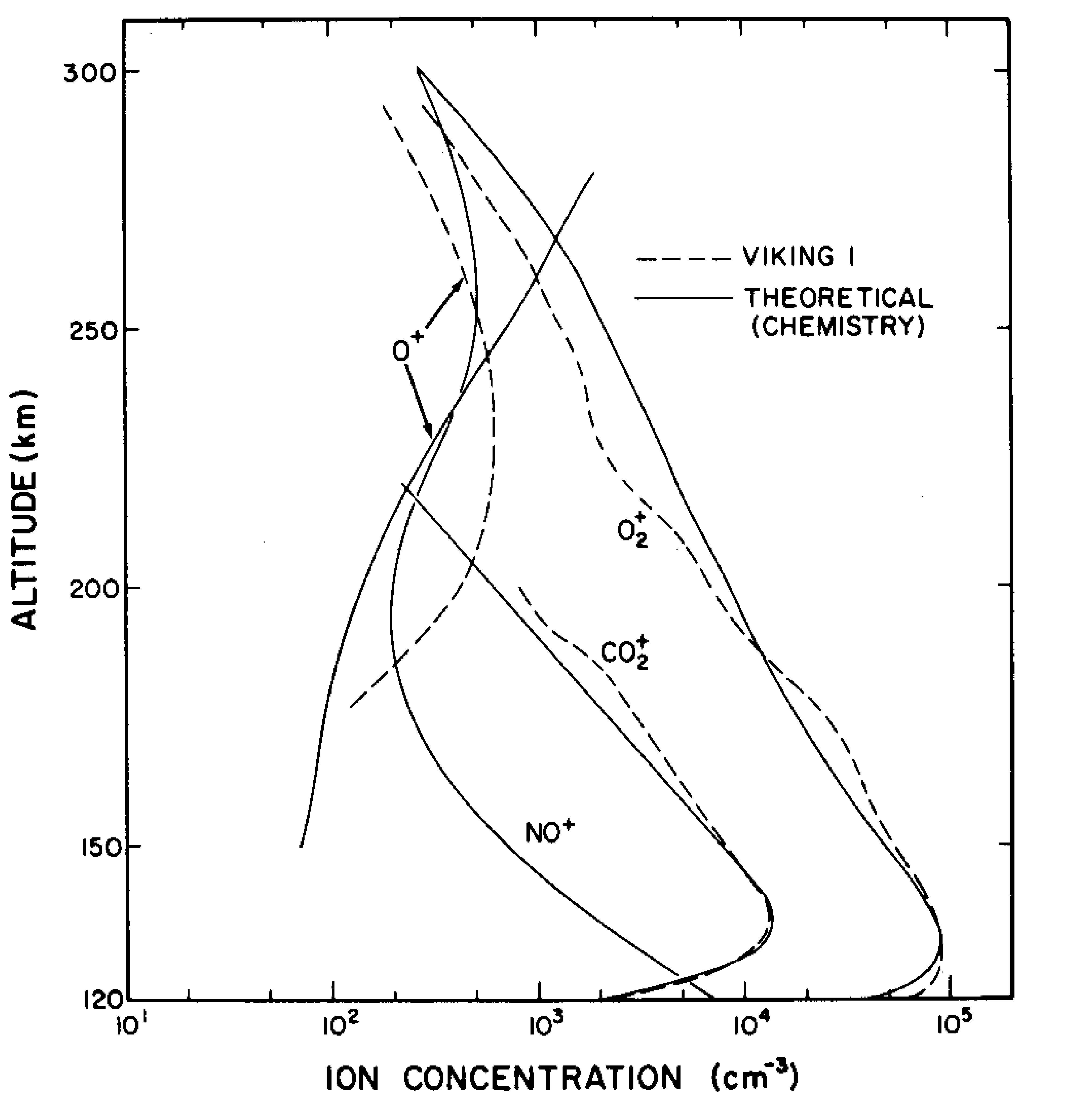
$N_2 + \gamma \rightarrow N_2^+ + e^-$

$N_2^+ + O \rightarrow NO^+ + N$ → "fast"

Viking Measurements

- Viking 1 and 2 landers took measurements of the ion densities and composition during descent to planet's surface
- Use Retarding Potential Analyzer (RPA) technique



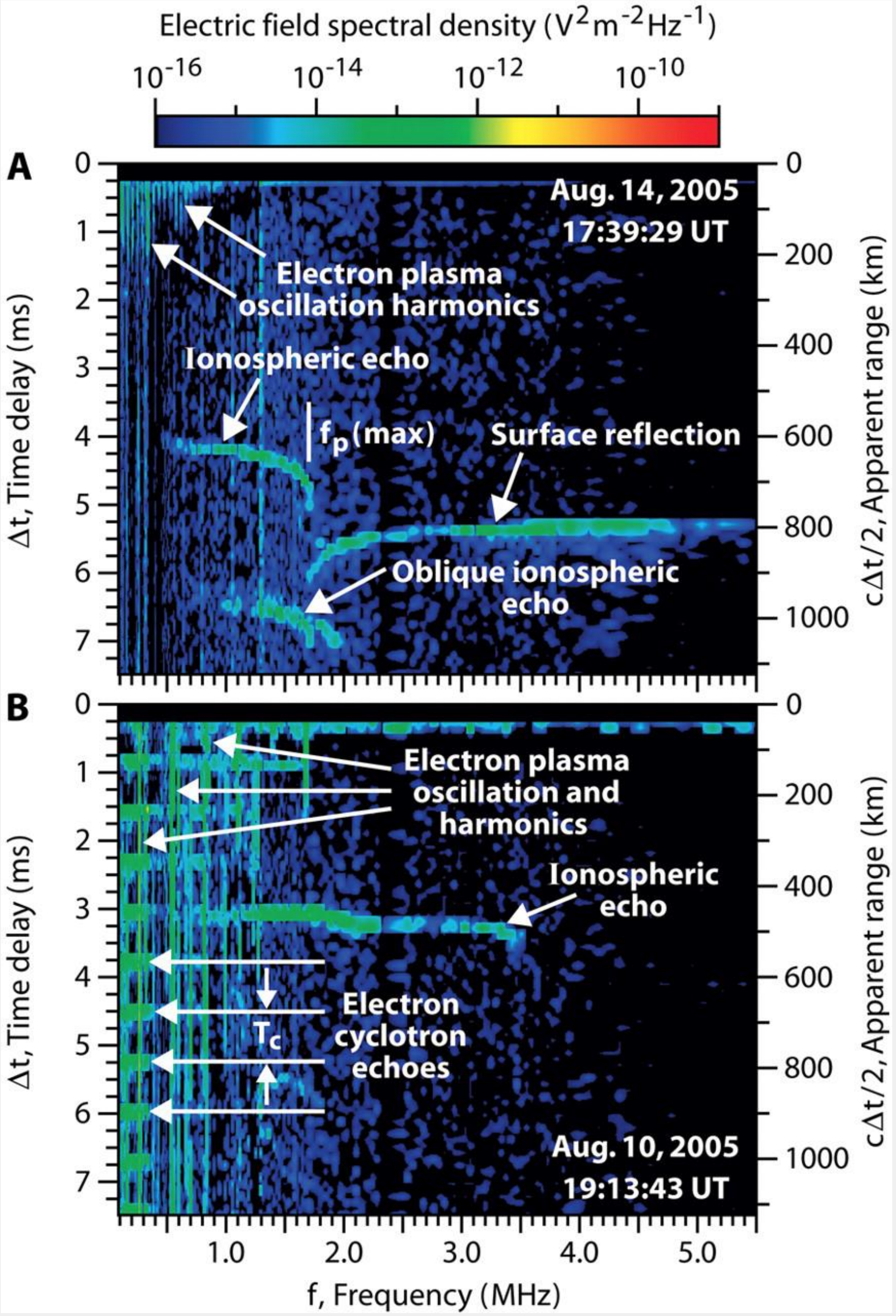


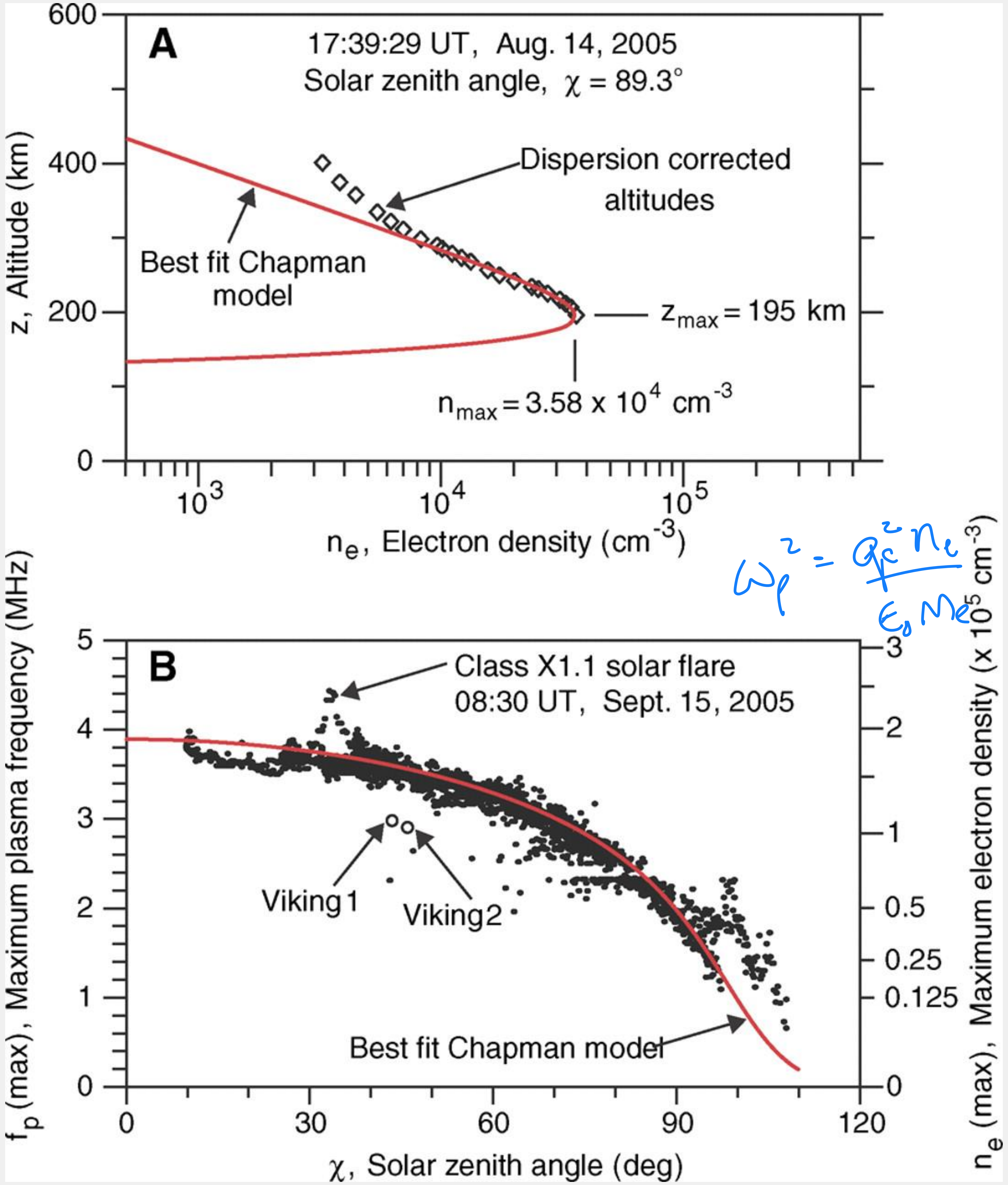
Ion densities for Mars, observed by Viking 1 (dashed lines) and calculated . [From HANSON *et al.* (1977)].

Radar Measurements

: from orbiter

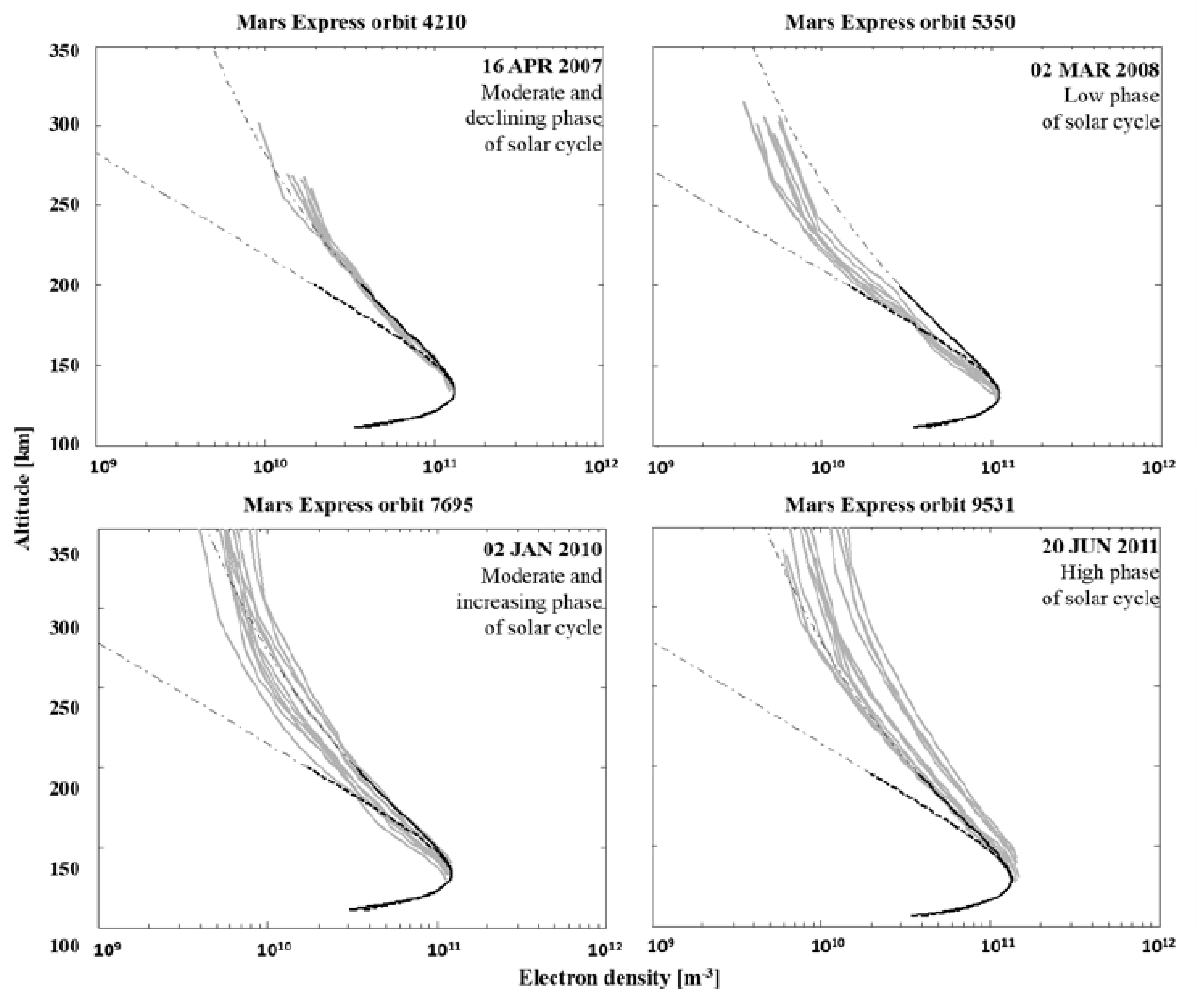
Mars Global Surveyor



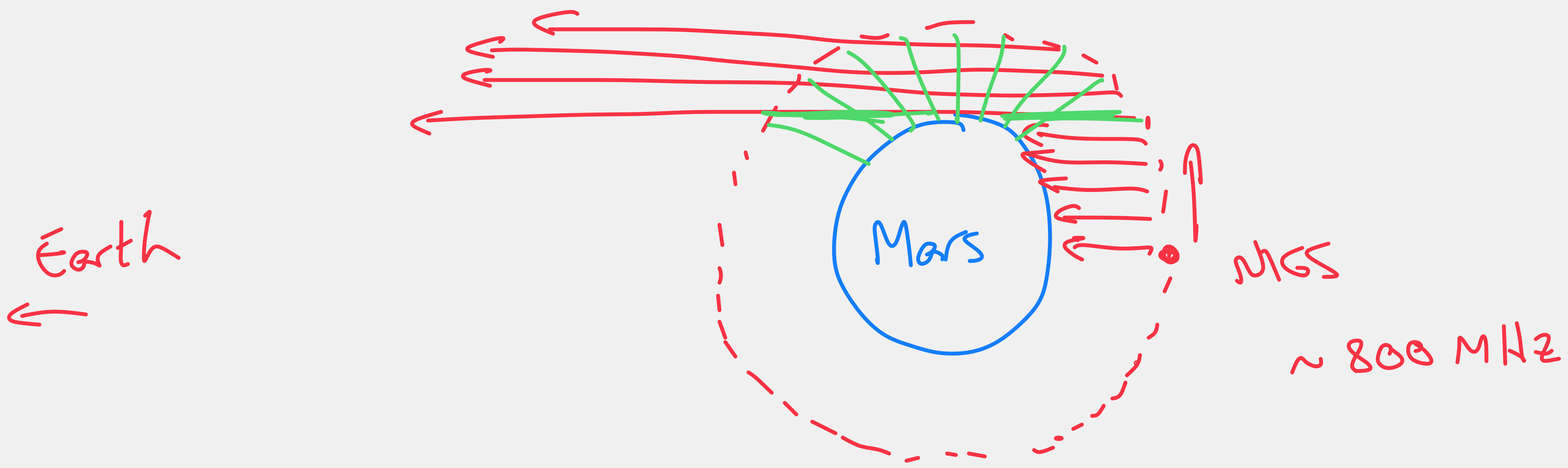


$$\omega_p^2 = \frac{q_e^2 n_e}{\epsilon_0 m_e}$$

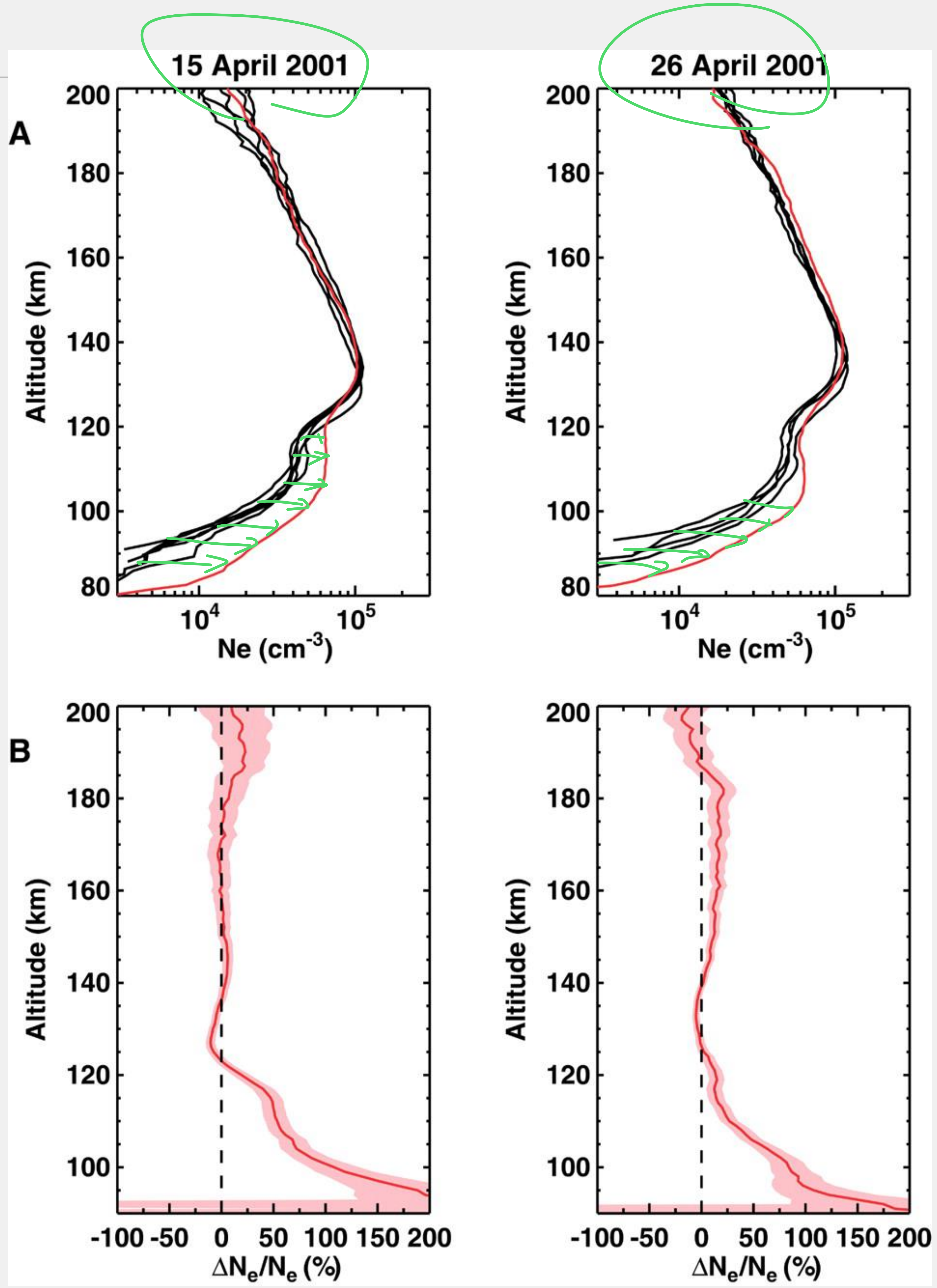
Solar cycle variation



Effect of Solar Flares



- from Mendillo et al 2006; Mars Global Surveyor radio occultation measurements
- Solar flare X-rays ionize the lowest part of the atmosphere (below 100 km or so)
- Harder x-rays reach deeper, close to Mars' surface
- This event (right) probably mostly soft x-rays (a few keV)



Summary

- **Mars has an atmosphere similar to Earth's in many ways, but also different:**
  - no stratosphere so likely no ozone layer
  - primarily CO_2 instead of N_2
  - primarily atomic oxygen (O) in thermosphere
  - Scale height of 11 km compared to Earth's 8 km
  - Homosphere and heterosphere
- **Mars has an ionosphere similar to Earth's in many ways:**
  - Peak density comparable to Earth, but at 150 km altitude
  - Mostly O_2^+ due to reaction $CO_2^+ + O \longrightarrow CO + O_2^+$
  - Variability with solar cycle and solar flares
  - Same effect on radio wave propagation