University of Colorado **Boulder**

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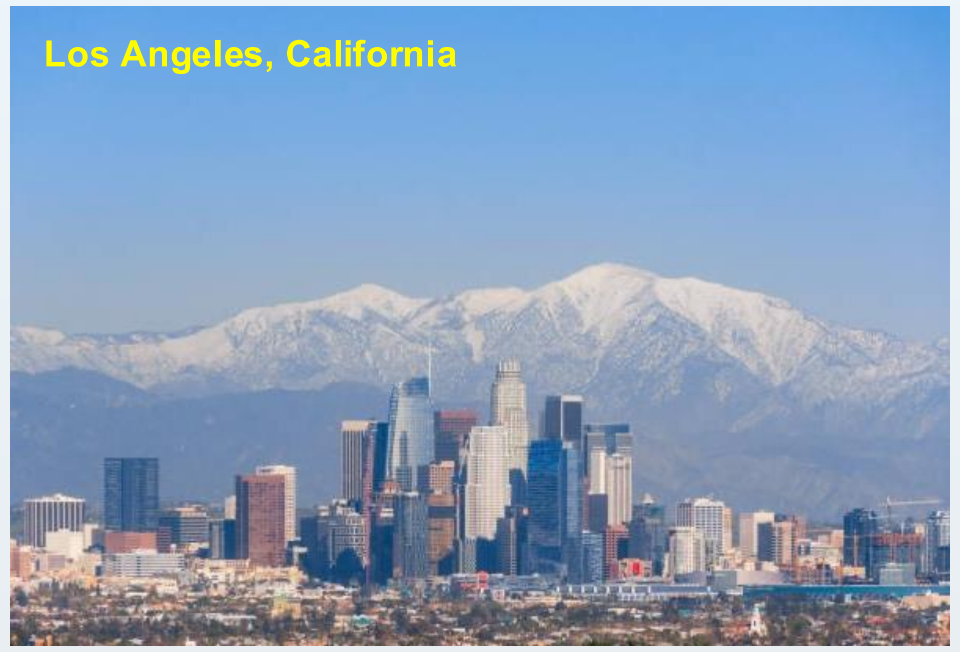
The Ionosphere and Thermosphere

Origins, Structure, and Variability

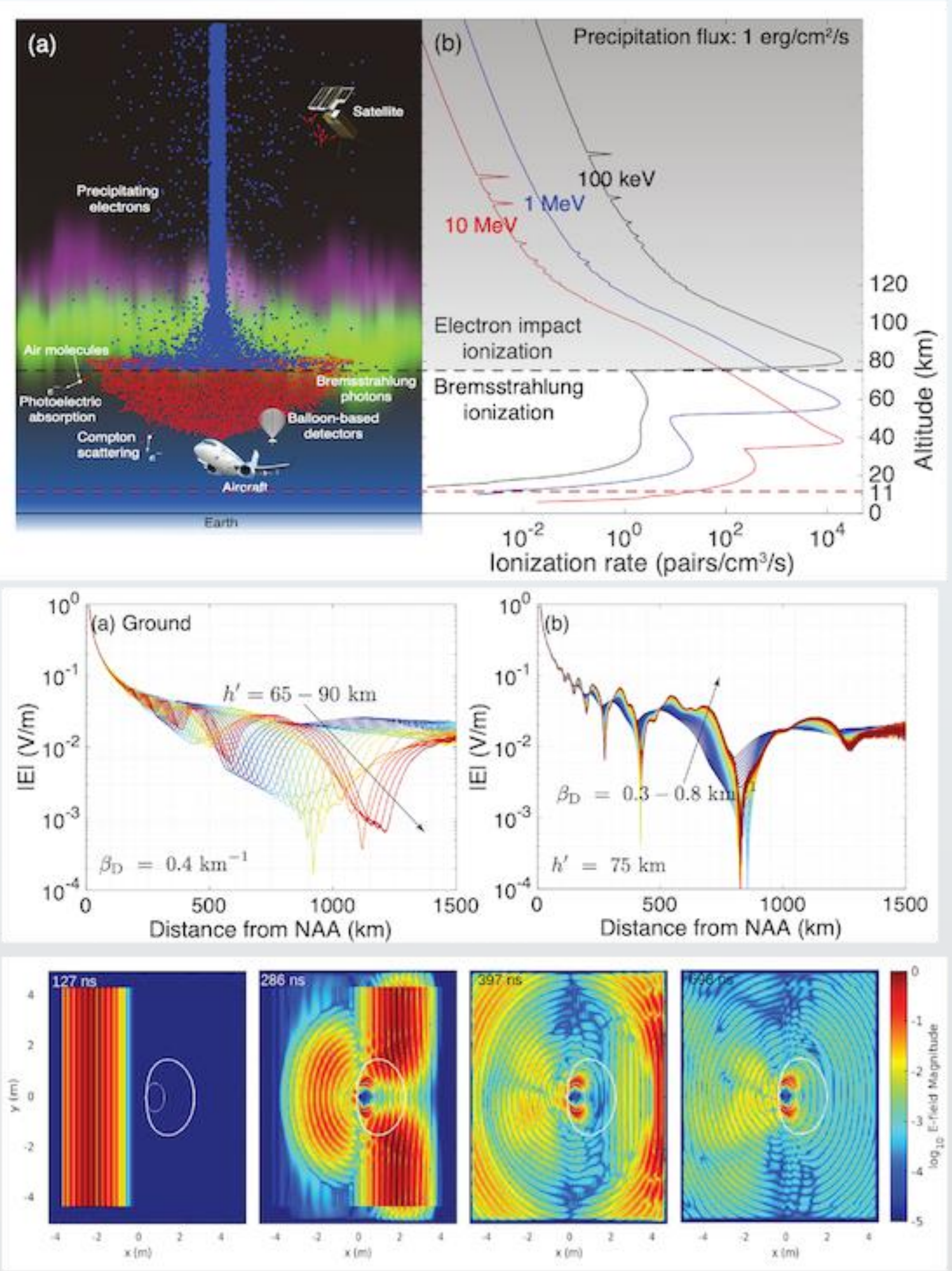
Robert A. Marshall

A bit about me

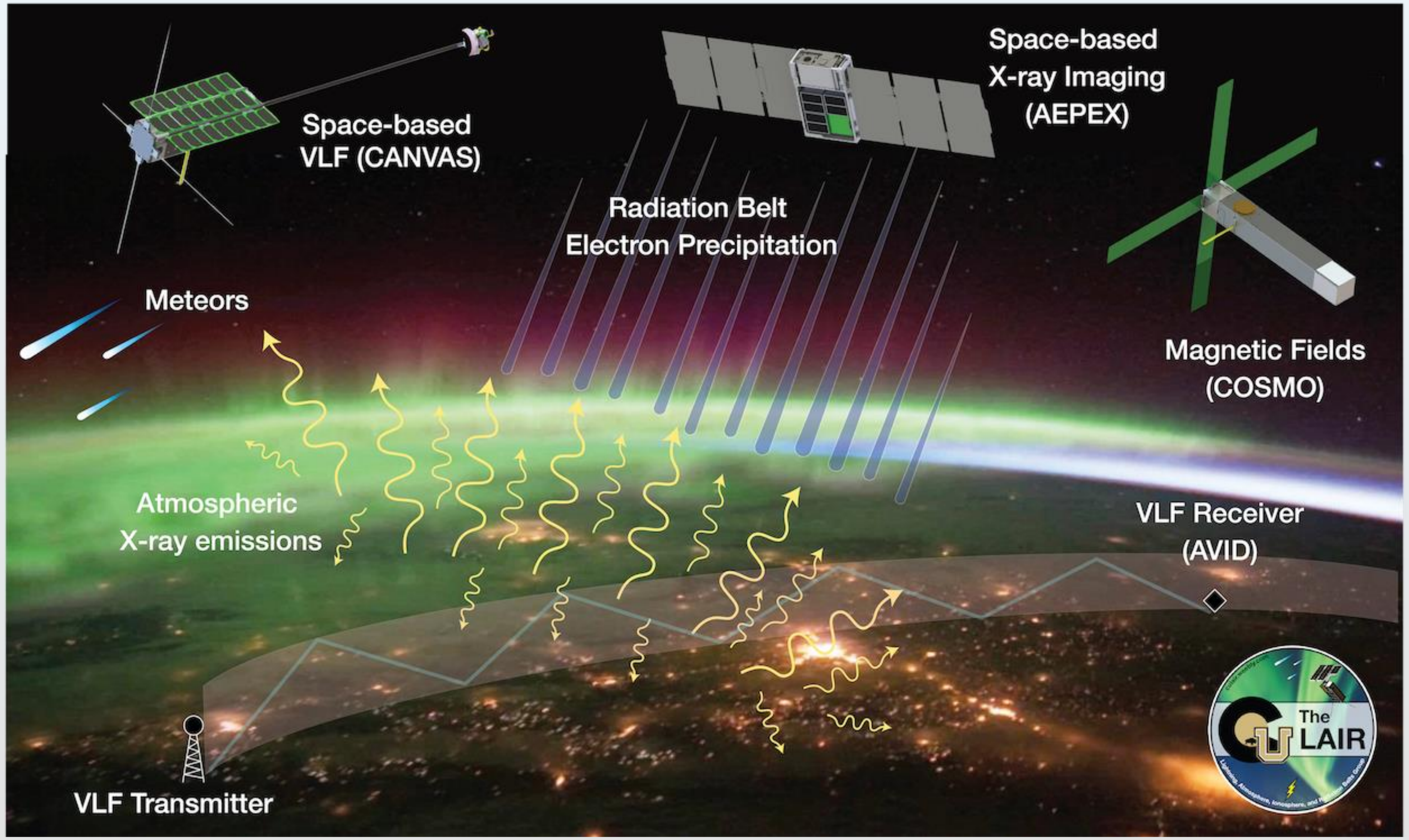
- **Grew up in Vancouver, BC, Canada**
- BS: Electrical Engineering, University of Southern California
- MS/PhD: Electrical Engineering, Stanford University
- Postdoc (< 2 years) at Boston University
- Research Associate (4 years) back at Stanford
- **Now 11 years at University of Colorado Boulder, Aerospace Engineering Sciences**
  - Tenured in 2022
  - Sabbatical in 2023: Orléans, France
  - Associate Chair for Graduate Studies: 2023—present



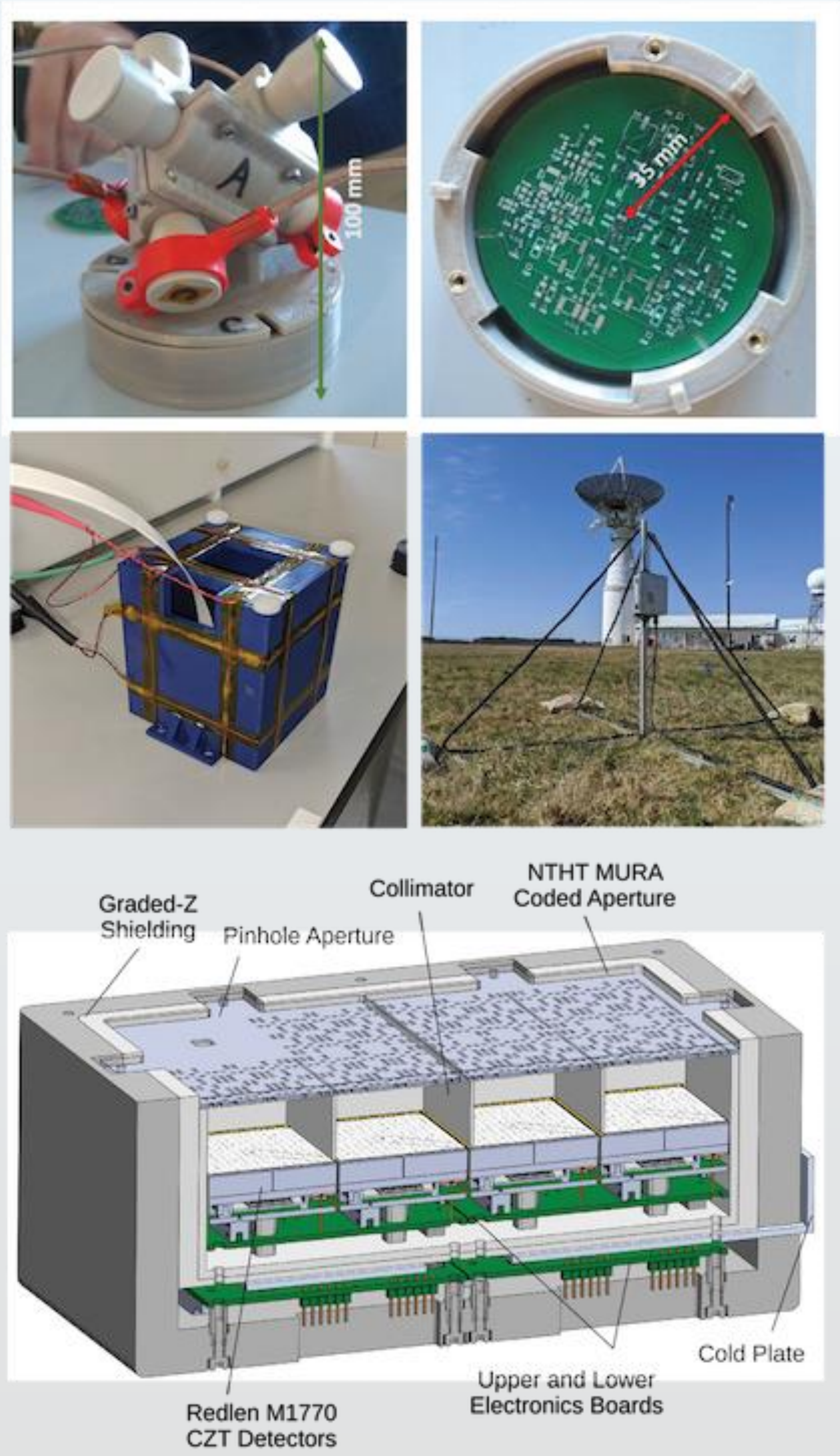
My Research Group Overview



Modeling, Simulation, and Data Analysis



CubeSats for Space Science



Instrumentation

Magnetosphere-Ionosphere-Thermosphere system

Ionosphere and Thermosphere: Goals

- **Understand basic physics of the Thermosphere**
  - Structure, temperature, variations, etc.
- **Understand basic physics of the Earth's ionosphere**
  - Origin, composition, layers
  - Variations: diurnal, seasonal, solar cycle, plus other anomalies
- **Ionosphere—Thermosphere coupling**

Hydrostatic Equilibrium (Baratropic Law)

- Consider a volume of gas with cross-section area *A* and thickness *dh*

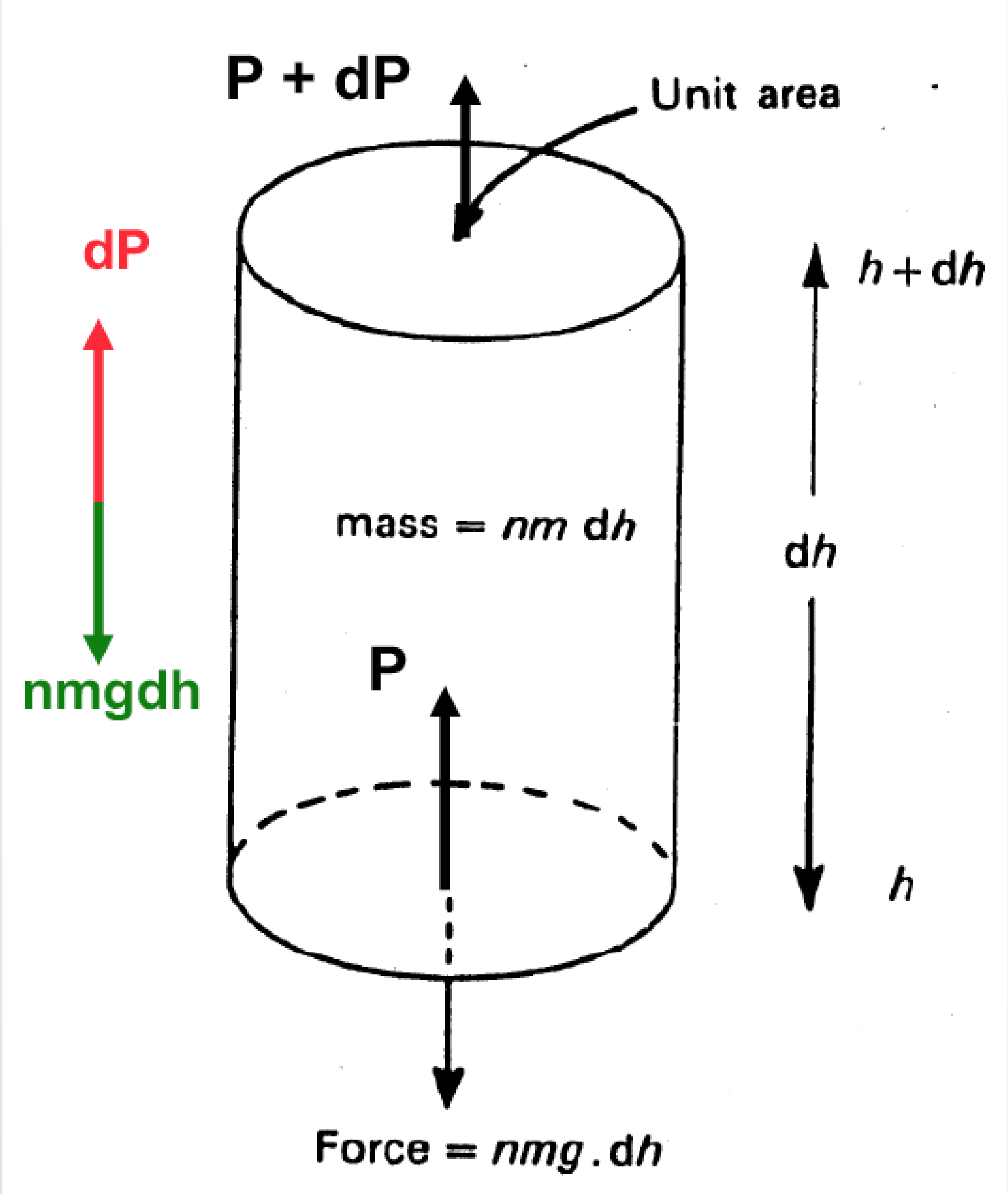
$$P = nk_BT$$

$\rho = nm =$ mass density, kg/m^3

$$P_{top} - P_{bottom} = dP = -\rho g dh$$

$$P = nk_BT = \frac{\rho}{m}k_BT \rightarrow \rho = \frac{Pm}{k_BT}$$

$$dP = -\frac{Pm}{k_BT}gdh \rightarrow \frac{1}{P}dP = -\frac{mg}{k_BT}dh$$



$$\int_{h_0}^{h}\frac{1}{P}dP = \int_{h_0}^{h} -\frac{mg}{k_BT}dh$$

$$\ln P(h) - \ln P(h_0) = -\frac{mg}{k_BT}(h - h_0)$$

$$P(h) = P_0 e^{-h/H}$$

$$P(h) = P(h_0)e^{-(h-h_0)/H}$$

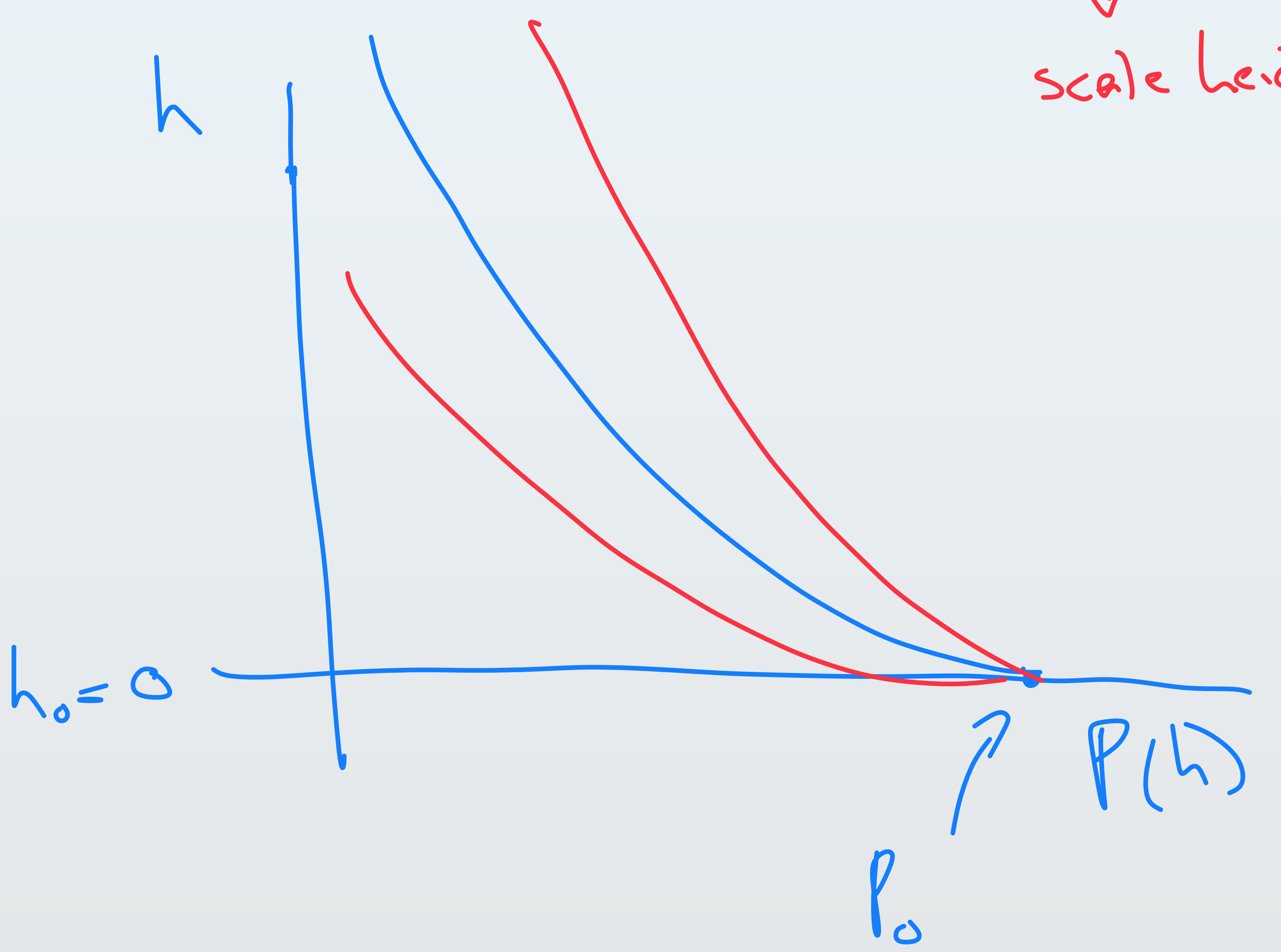
where $H = \frac{k_BT}{mg}$ = scale height

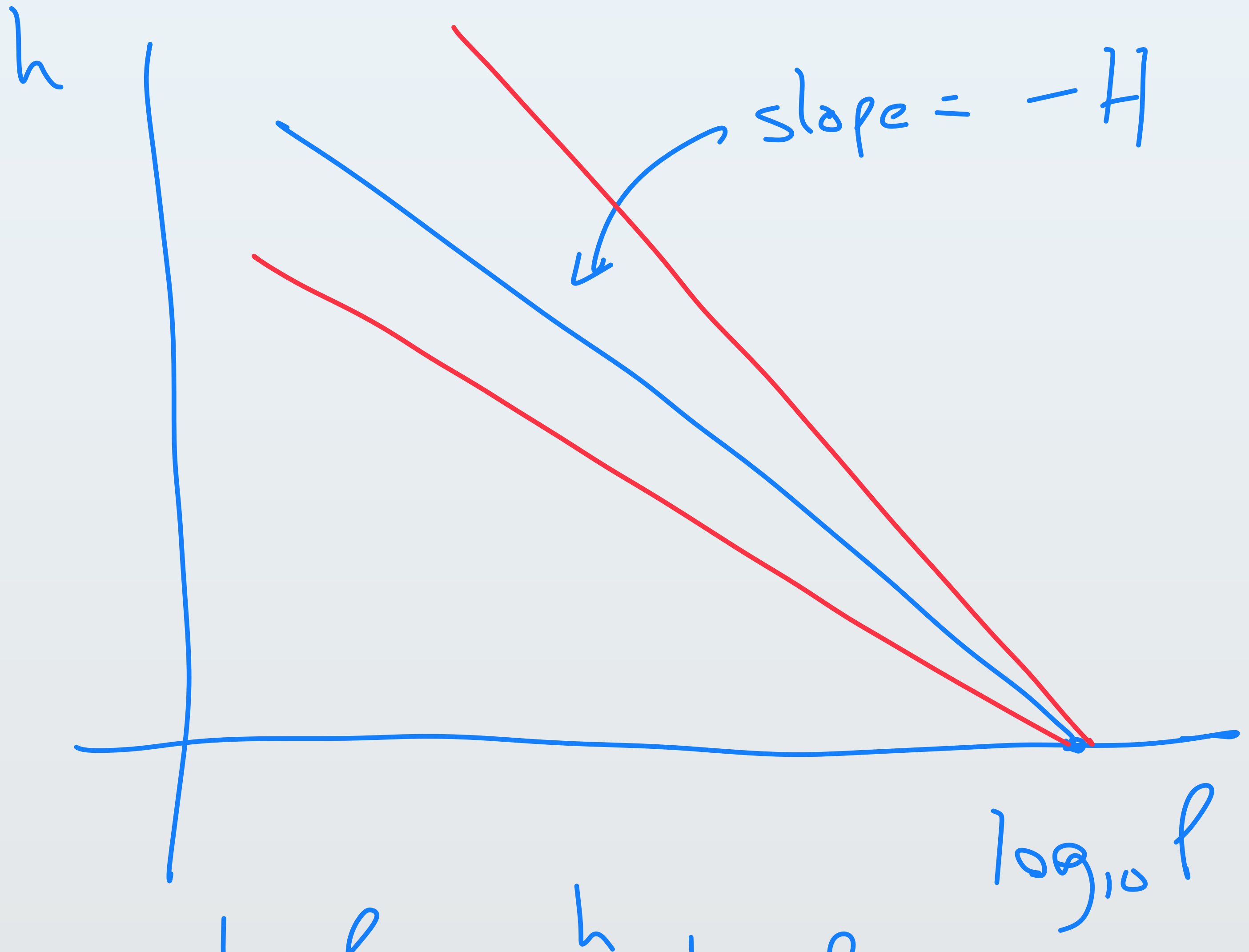
Hydrostatic Eq. cont.

$$H = \frac{k_B T}{mg}$$

$$P(h) = P(h_0)\, e^{-(h-h_0)/H}$$

H → scale height





$$\log P = -\frac{h}{H} \log P_0$$

$g_0 = 9.8\ m/s^2$ at surface, R_E = Earth radius ~ 6370 km

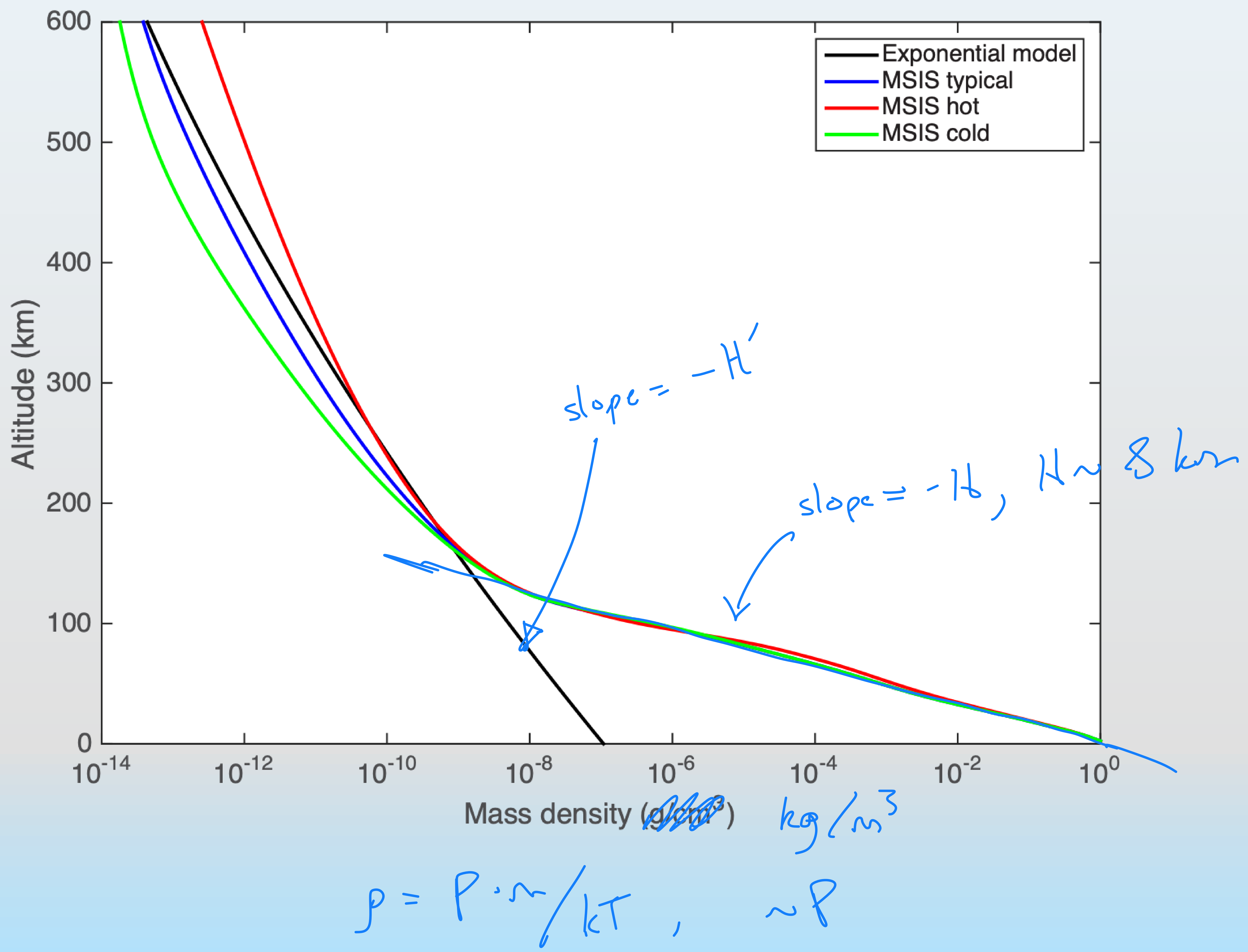
$$g(h) = g_0 \frac{R_E^2}{(R_E + h)^2}$$

at 100 km: $g \sim 9.5\ m/s^2$

at 500 km: $g \sim 8.4\ m/s^2$

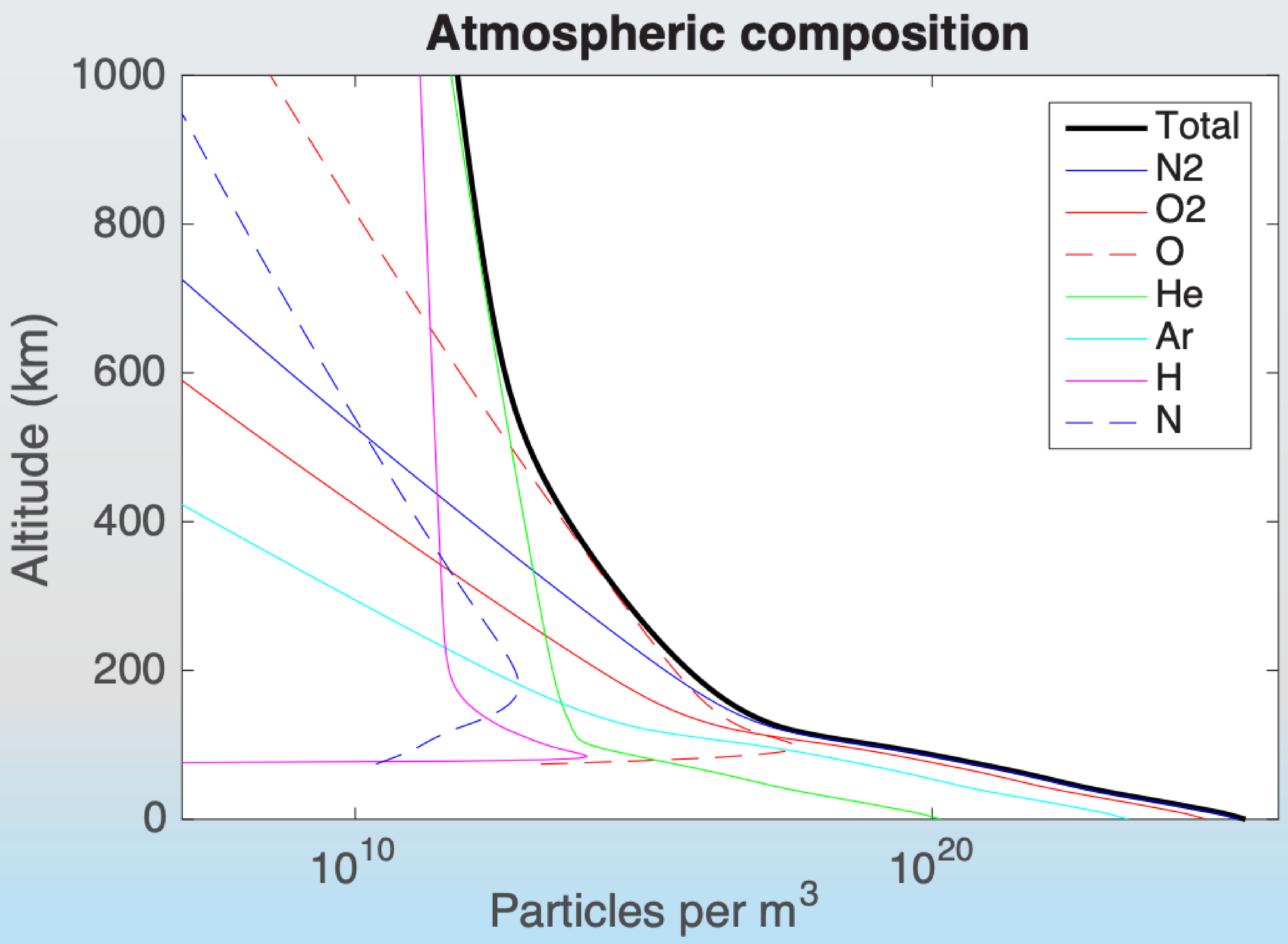
Actual Atmosphere Profile

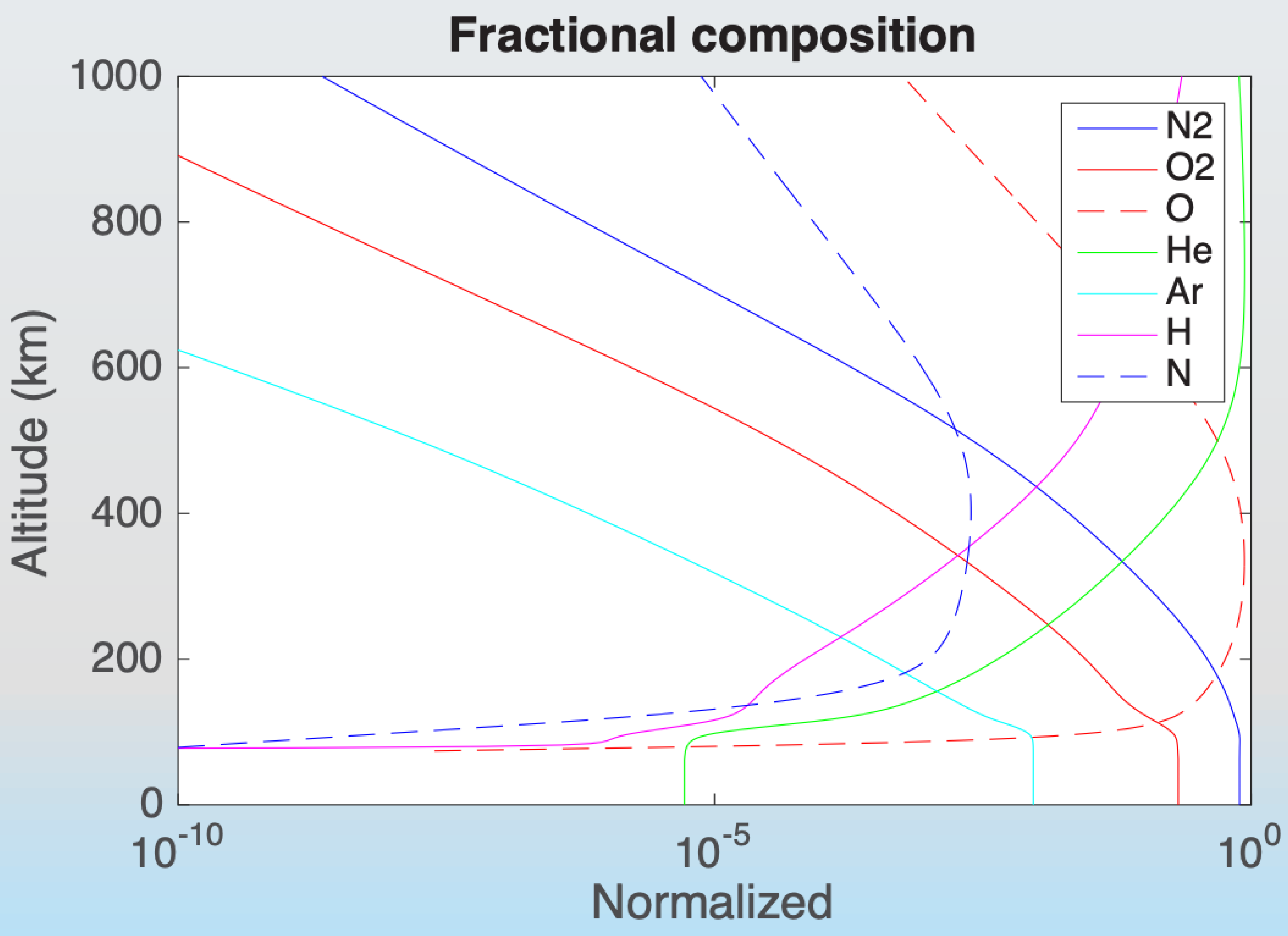
- In reality, T is not constant, nor is m, nor is the atmosphere truly in hydrostatic equilibrium



Atmospheric Composition (with altitude)

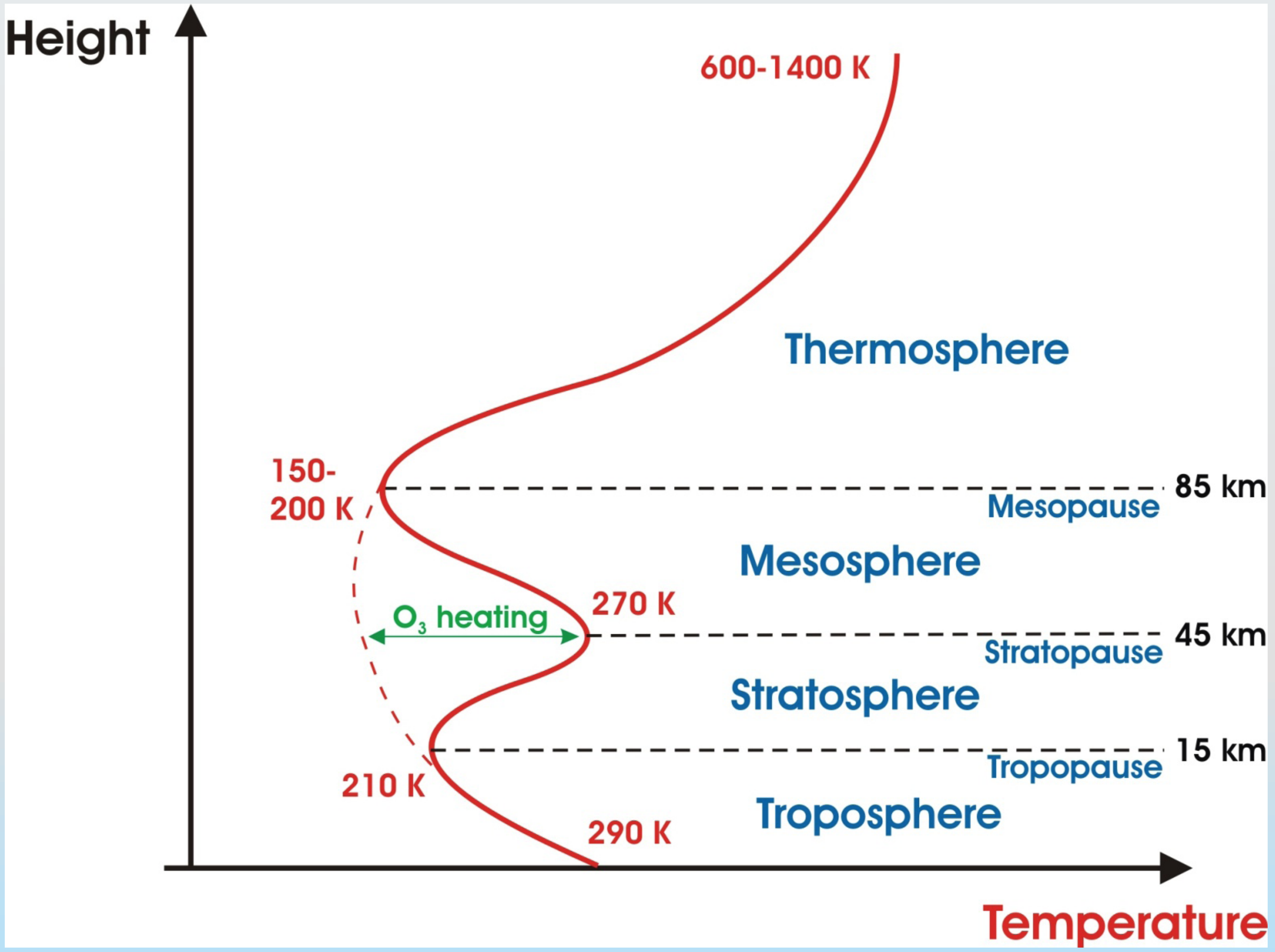
- **Homosphere**: region below 100 km where composition is constant (N2, O2, Ar)
  - H = 8 km
  - Temperature drops exponentially with pressure
- **Heterosphere**: region above 100 km where composition changes with altitude (O, then He, then H)
  - Different scale heights
  - Different regions and effects

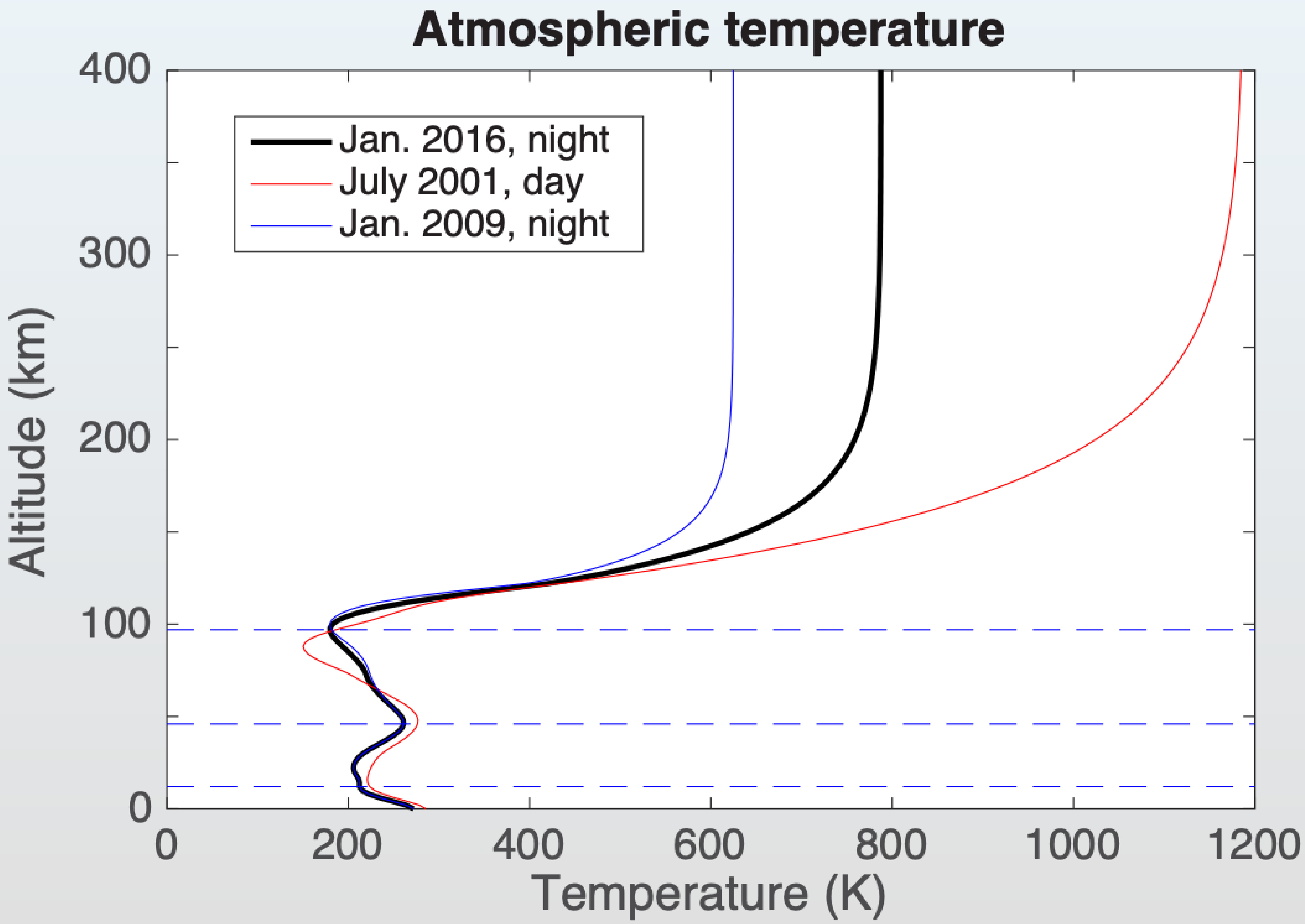




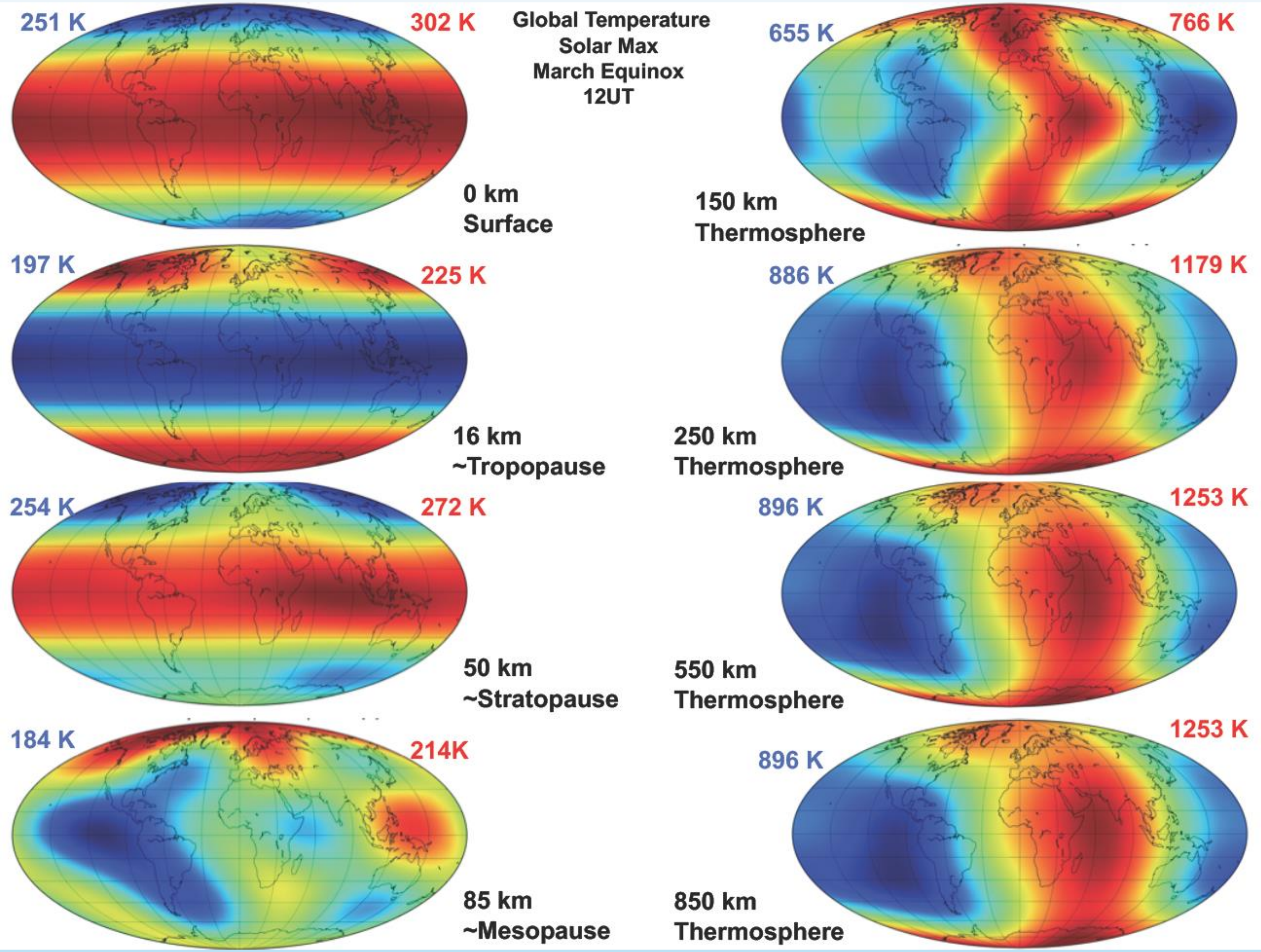
Atmosphere by Temperature

- Troposphere: weather
- Stratosphere: temperature inversion; layering
- Mesosphere: middle
- Thermosphere: hot!
- Exosphere: uppermost layer
- Pause: interruption

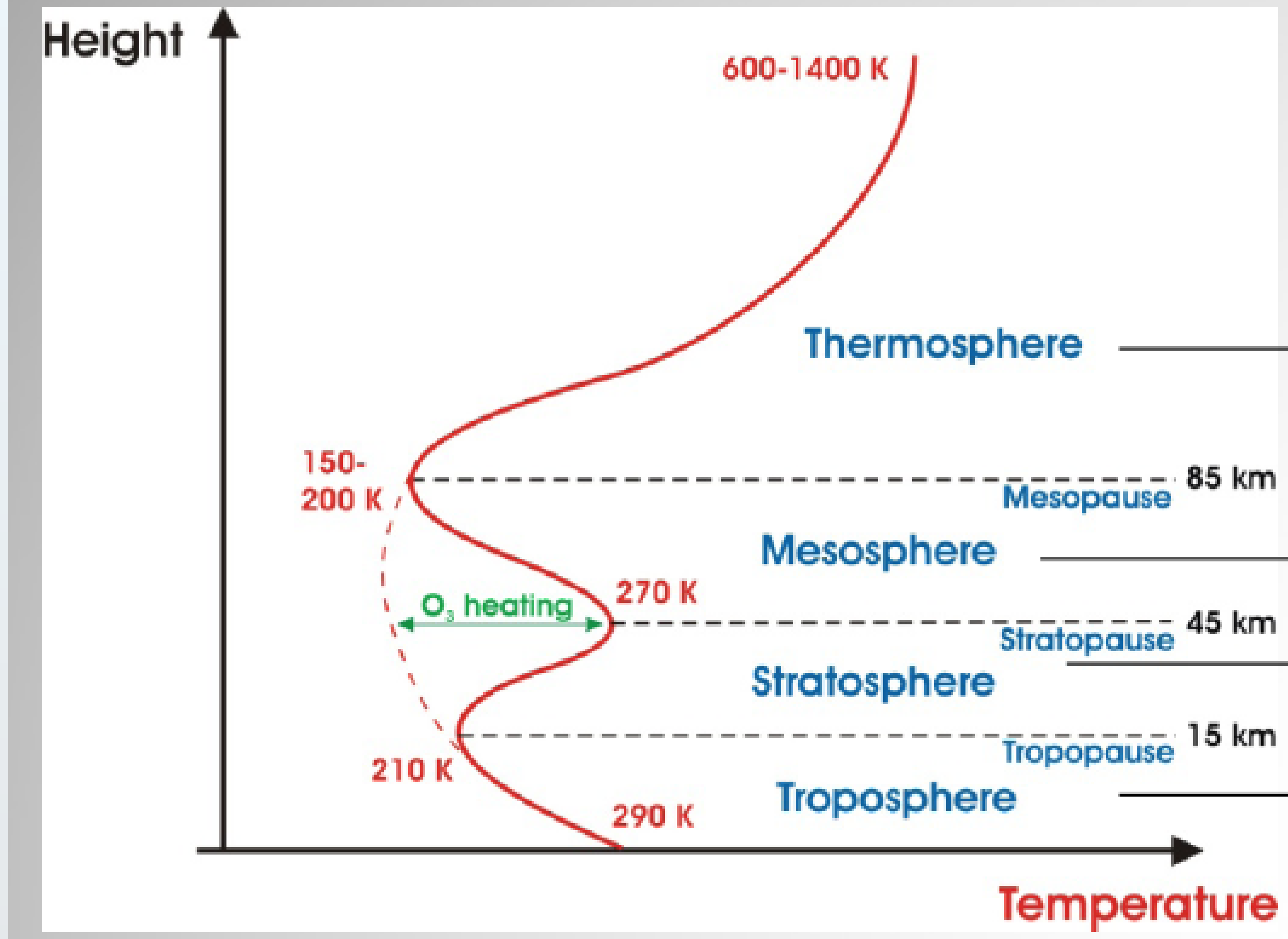




Variation with Latitude / Longitude



Sources and Sinks



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

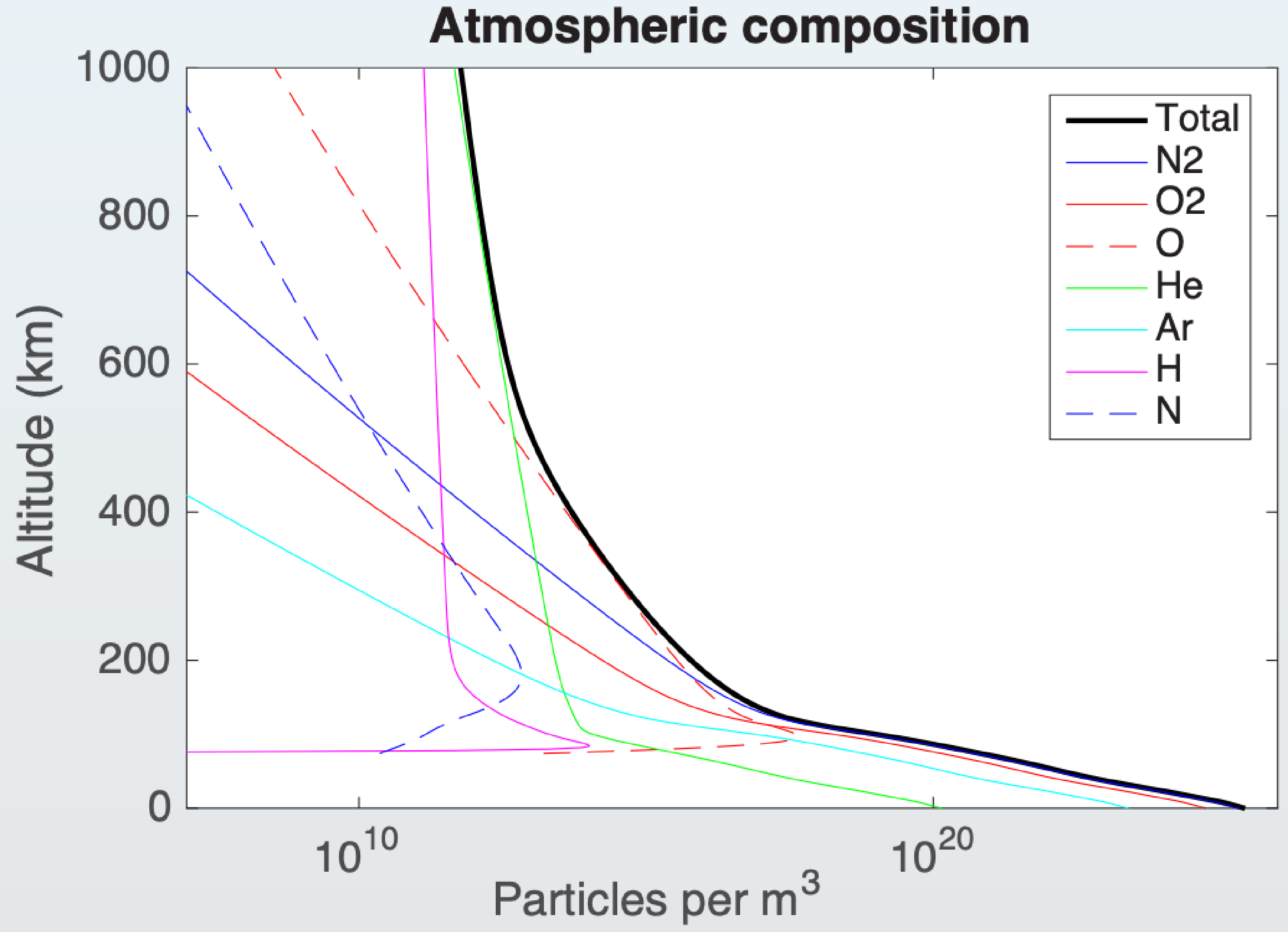
Mesosphere:
- Energy sources:
  - Some UV absorption by O_3 (lower heights)
  - Heat transport down from thermosphere (minor, upper heights only)
  - Chemical heating
- Energy sinks:
  - IR radiation by CO_2 H_2O, OH

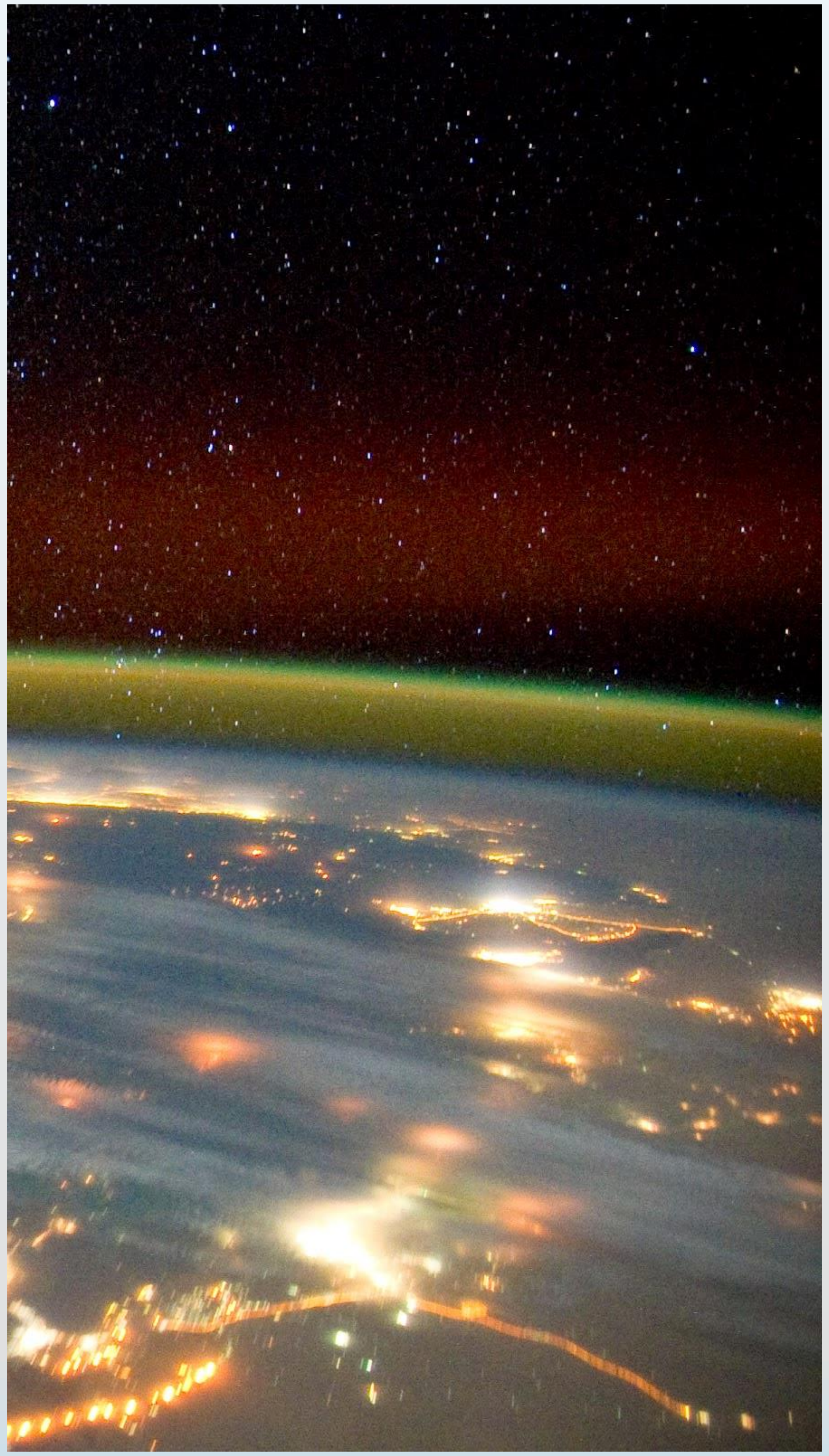
Stratosphere:
- Energy sources:
  - Strong absorption of UV by ozone (causing stratopause temperature peak)
- Energy sinks:
  - IR radiation by O_3 , CO_2 , H_2O

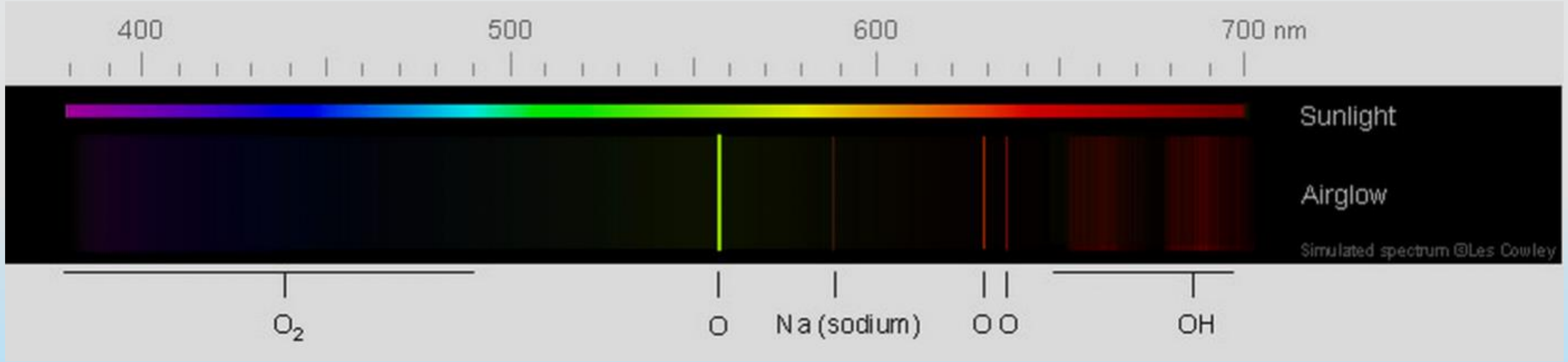
Troposphere:
- Energy sources:
  - Planetary surface absorption (IR, visible), convection & conduction to atmosphere
  - Atmospheric absorption of terrestrial and solar IR
  - Latent heat release by H_2O
- Energy sinks:
  - IR radiation
  - Evaporation of H_2O

Airglow

- The mesosphere and thermosphere "glow" in a number of wavelengths
- Emissions due to a variety of processes:
  - *recombination* of atoms which were photoionized by the sun during the day
  - *luminescence* caused by cosmic rays striking the upper atmosphere
  - *Chemiluminescence* caused mainly by oxygen and nitrogen reacting with hydroxyl (OH) ions
- Green layer at 90 km altitude; Red at 200-400 km



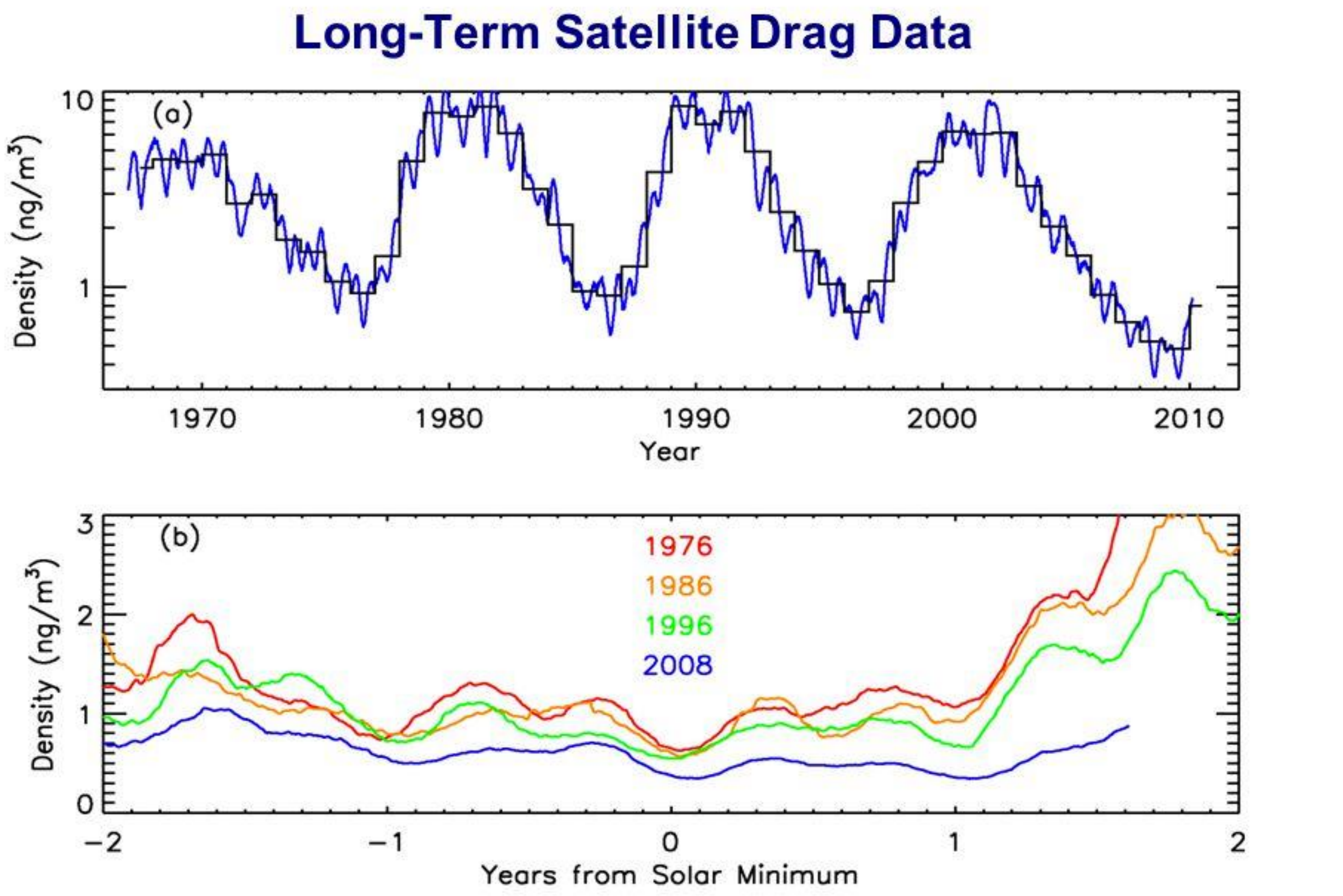




Airglow - visible with the naked eye

Solar-Cycle Variation

- Increase in solar EUV increases heating in the atmosphere, especially thermosphere;
- Increased heat => increased ionization (next module!)
- Increase in temperature => atmosphere rises, higher thermosphere density



Global average neutral density at 400 km, 81-day average and annual average (top), and superposed epoch analysis (bottom)
Emmert et al., Geophys. Res. Lett., 37, L12102, 2010
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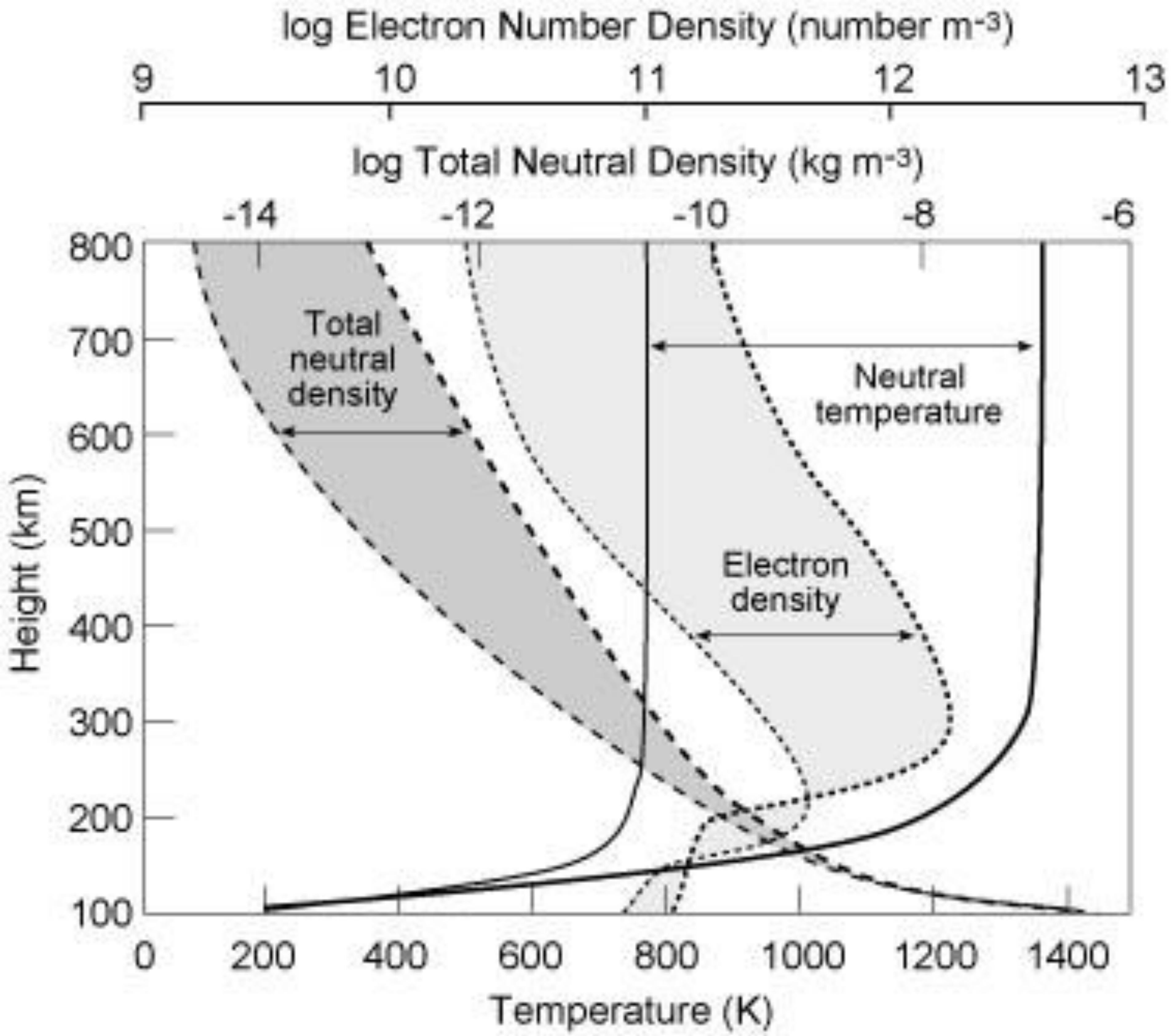
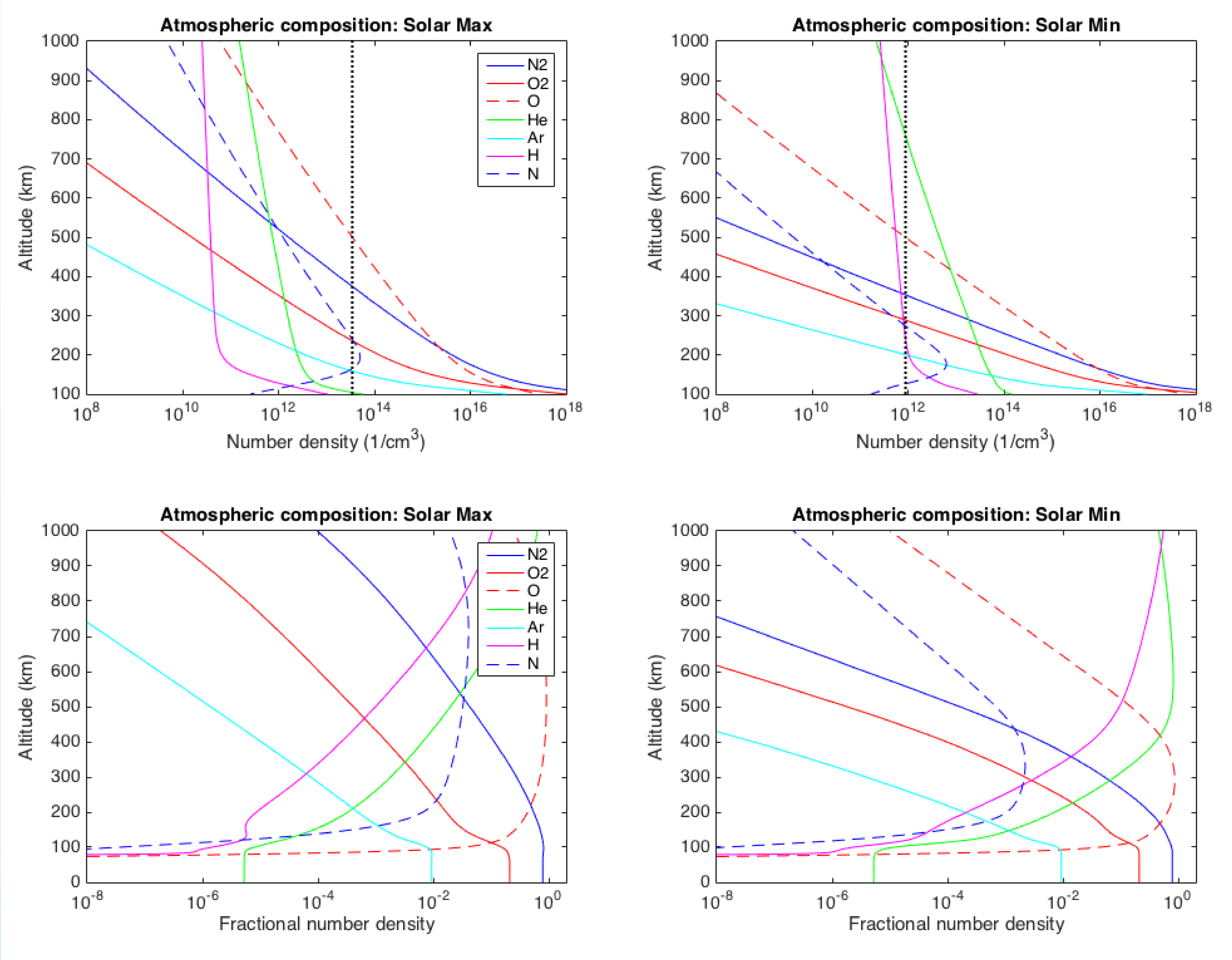


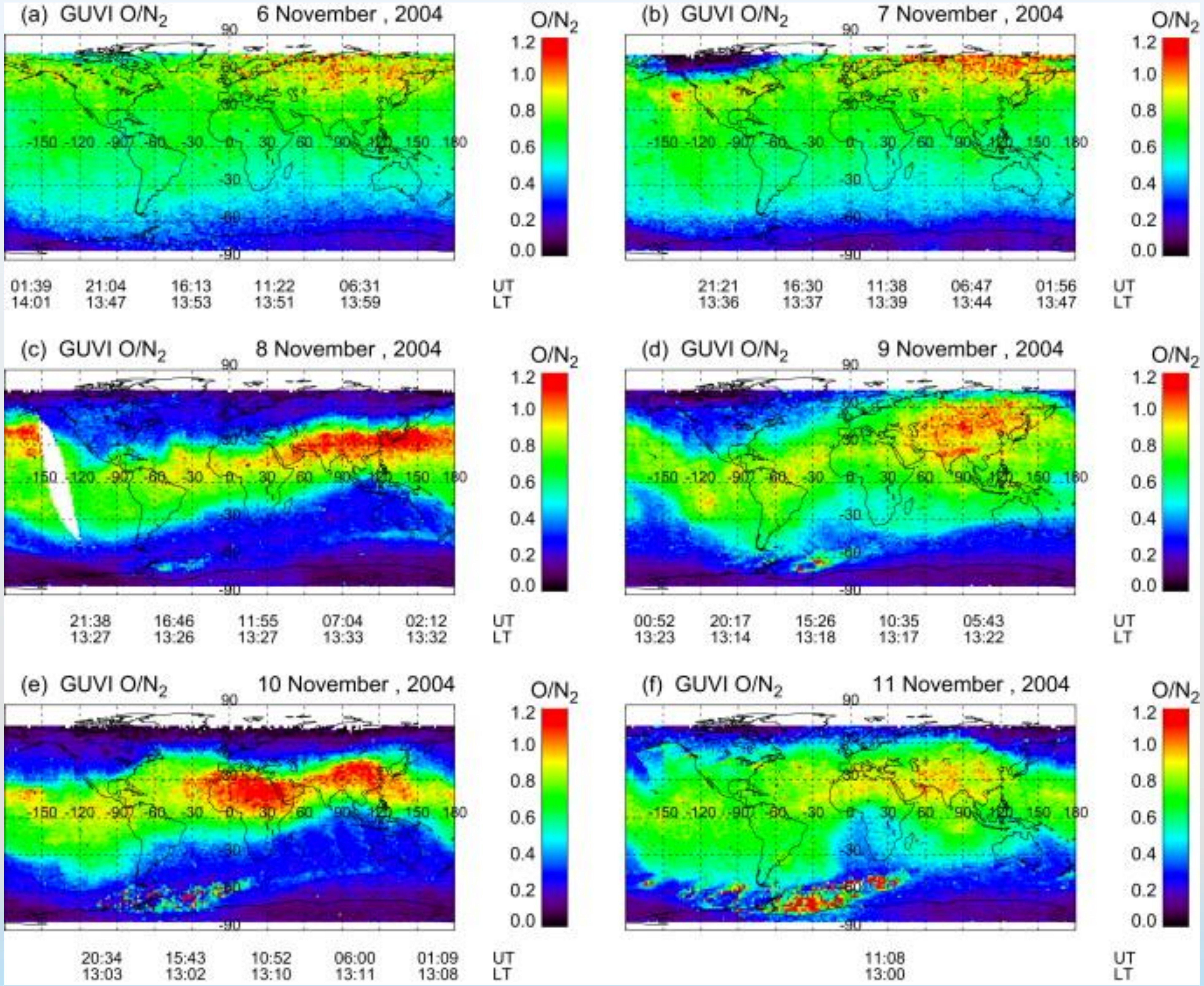
Composition Variation

- Change in temperature in the thermosphere (from 500 to 1500 K) affects diffusive equilibrium of components
- Generally, all particles get pushed to higher altitudes by higher temperatures below



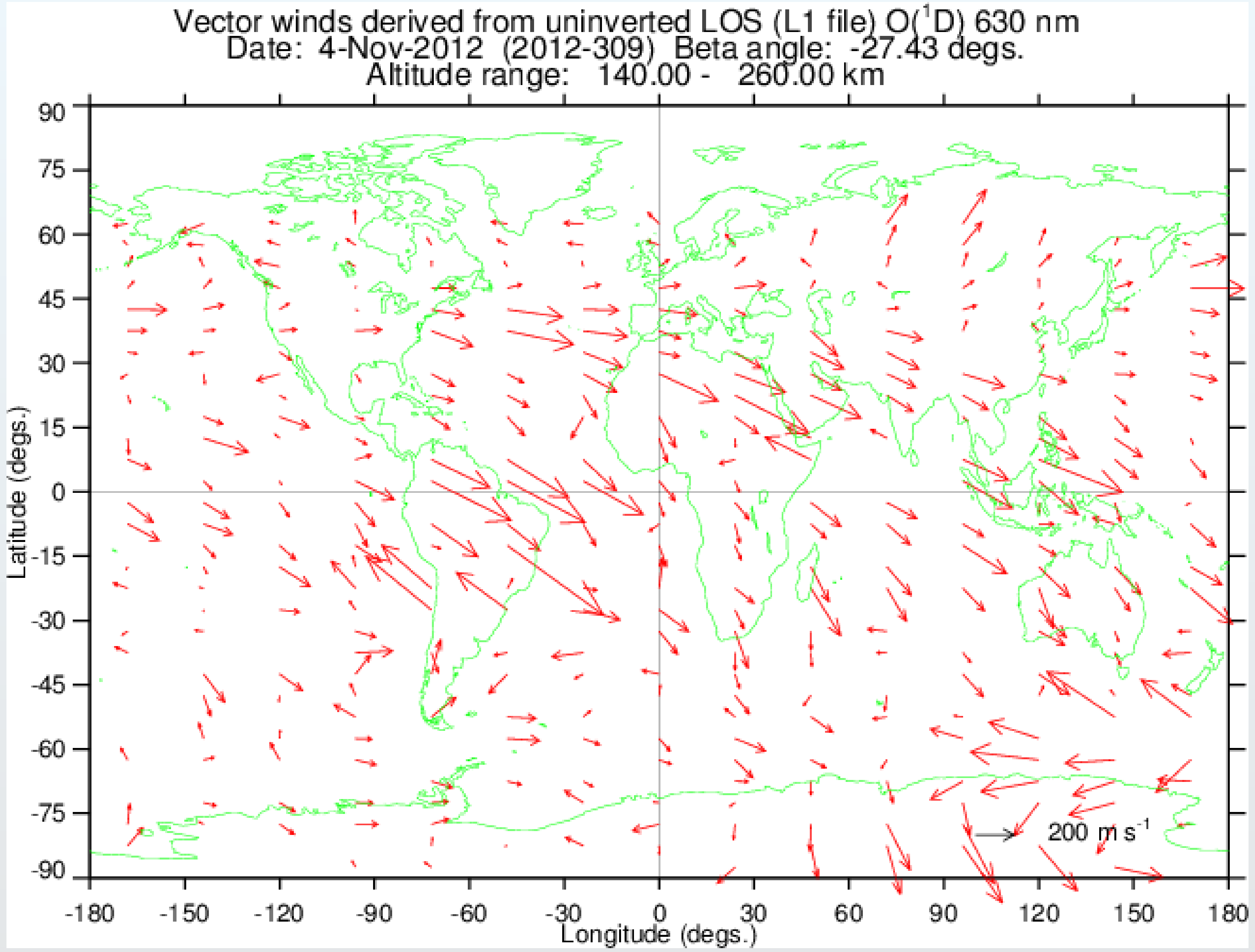
GUVI (Global UV Imager) O/N2 ratio

- GUVI (on TIMED satellite) measured the column density ratio of O to N2; used as a proxy for neutral composition / heating of the atmosphere



Winds

- Winds in the upper atmosphere are driven by at least four factors:
  - Pressure gradient, day-to-night
  - Coriolis force
  - Viscosity
  - Ion drag
- Different effects dominate in different regions of atmosphere (altitude, latitude)
- In Math:



from TIDI instrument on TIMED spacecraft

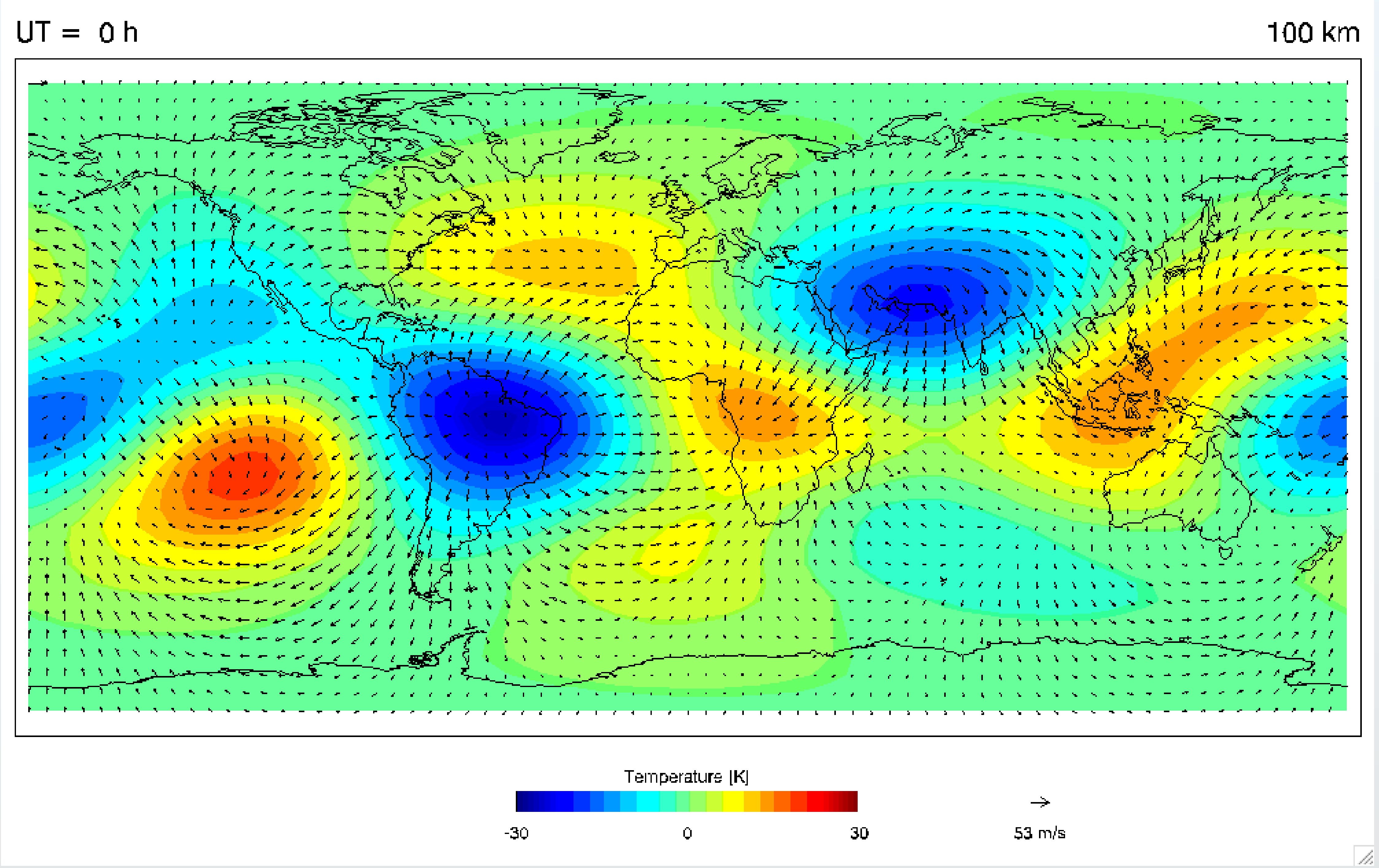
$$\frac{D\mathbf{U_h}}{Dt} = -\frac{1}{\rho}\nabla_h p - 2\Omega \times \mathbf{U_h} + \frac{\mathbf{1}}{\rho}\nabla(\mu\nabla\mathbf{U_h}) - \nu_{\mathbf{ni}}(\mathbf{U_h} - \mathbf{V_i})$$

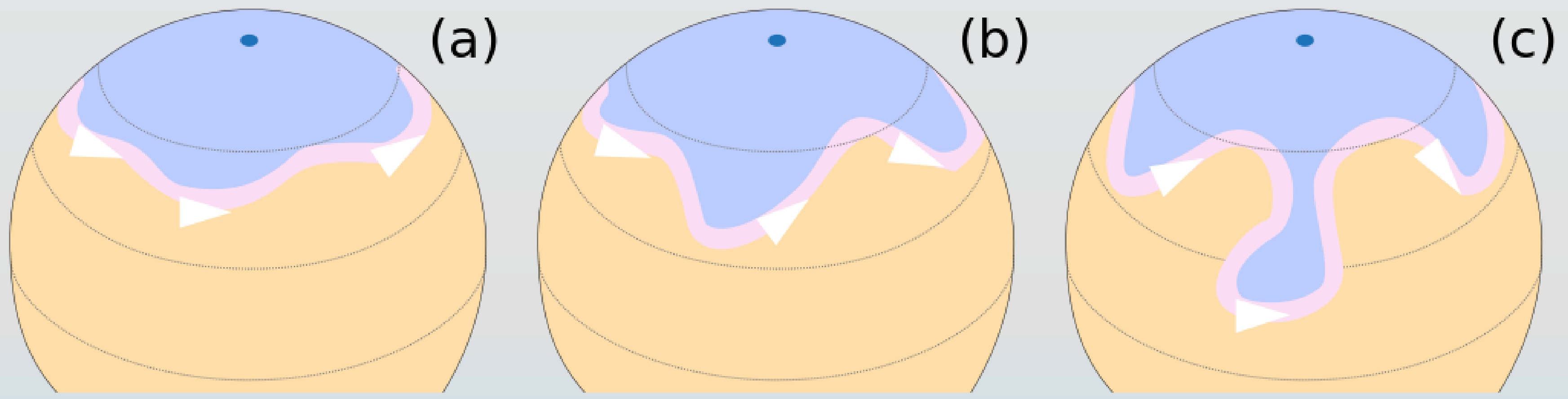
horizontal wind; vis; collision freq; ion velocity

pressure grad.; Coriolis; viscosity term; ion drag

Tides

- Periodic oscillations in the atmosphere
- **Caused by**:
  - Regular day-night cycle in the Sun's heating of the atmosphere
  - The gravitational pull of the Moon
  - Non-linear interactions between tides and *planetary waves*
  - Large-scale latent heat release due to deep convection in the tropics (thunderstorms)
- Can be migrating (sun-synchronous) or non-migrating
- Because atmosphere density falls with altitude, tide amplitude increases with altitude — exponentially!



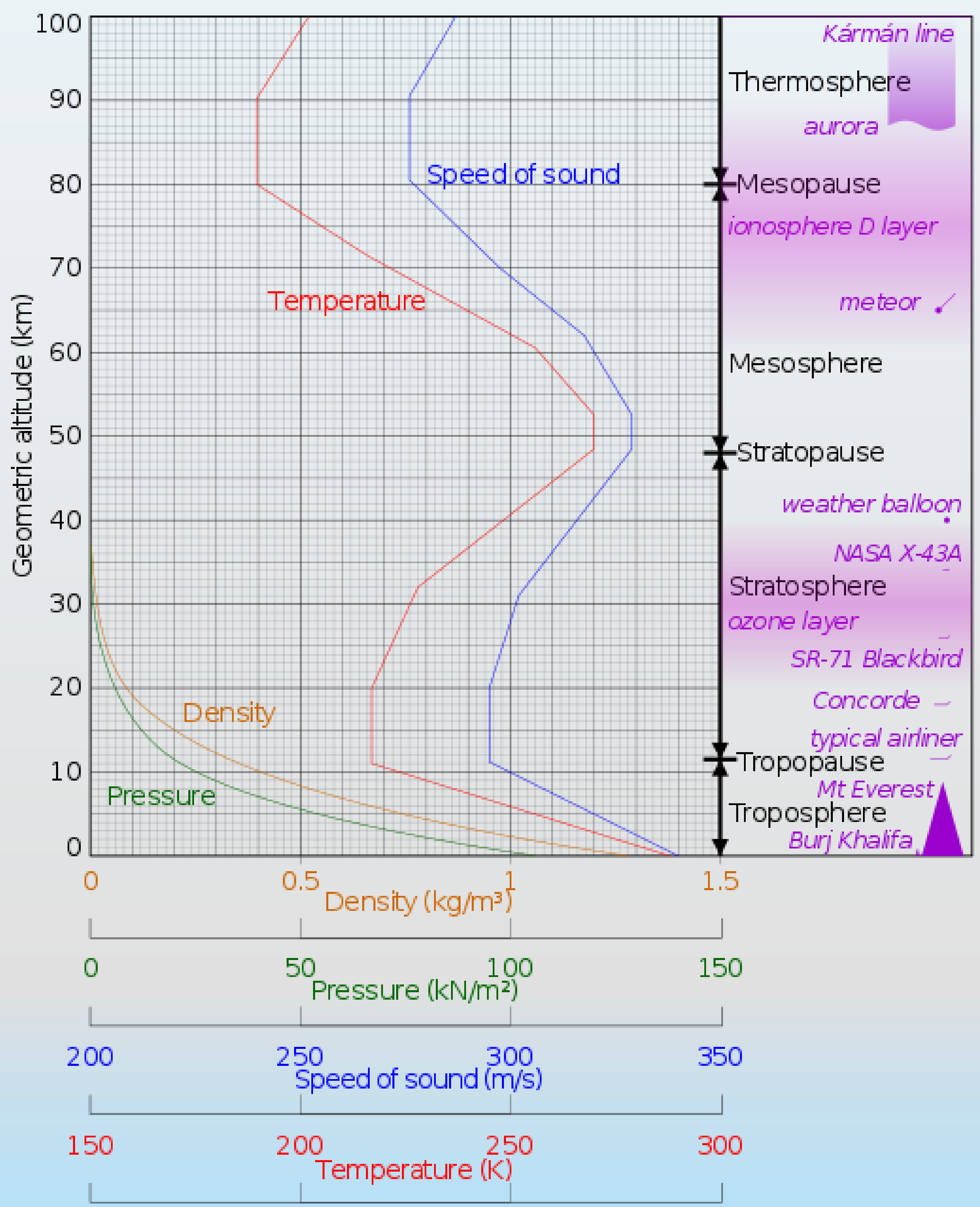


Planetary (or Rossby) waves

Atmospheric Models

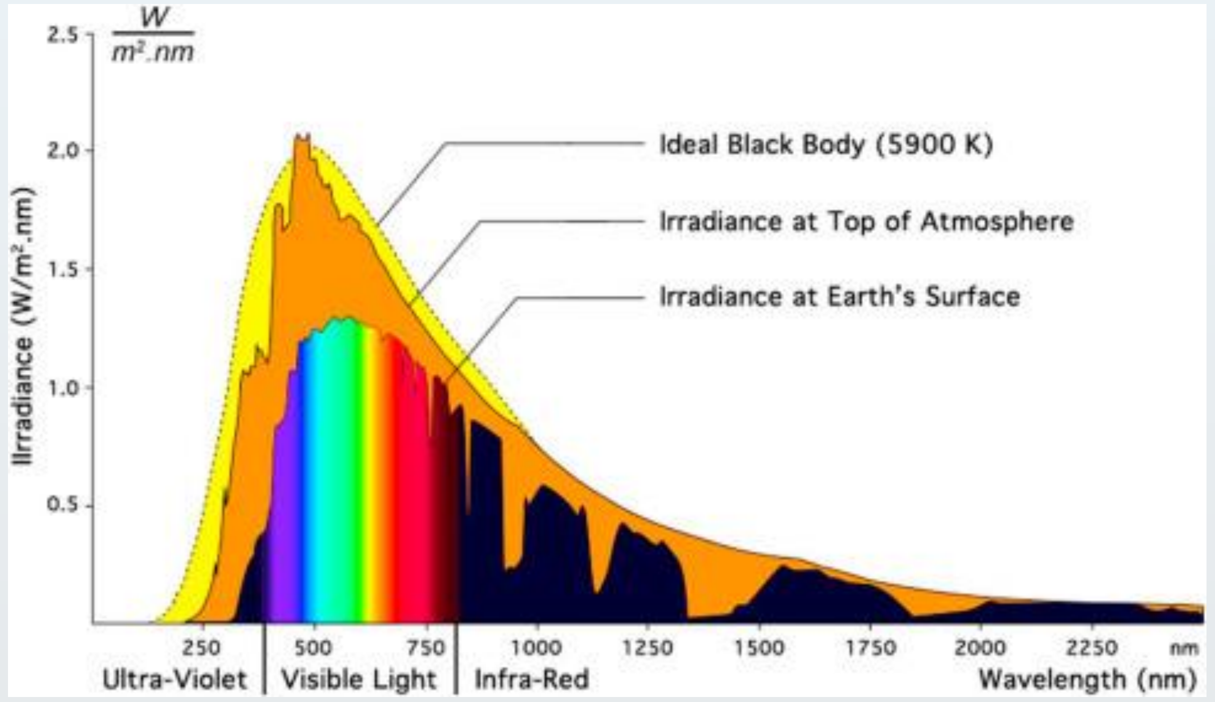
- MSIS: mass spectrometer and incoherent scatter radar (horrible name)
  - MSIS-E-90: https://ccmc.gsfc.nasa.gov/modelweb/models/msis_vitmo.php
  - NRLMSISE00: https://ccmc.gsfc.nasa.gov/modelweb/models/nrlmsise00.php
  - Global, empirical models of atmosphere density, composition, and temperature
  - Derived from data: Mass spec, radar, rocket measurements, and more
  - Include variations with solar activity, location, and more
- Other models: US Standard Atmosphere, International Standard Atmosphere, Jacchia, others

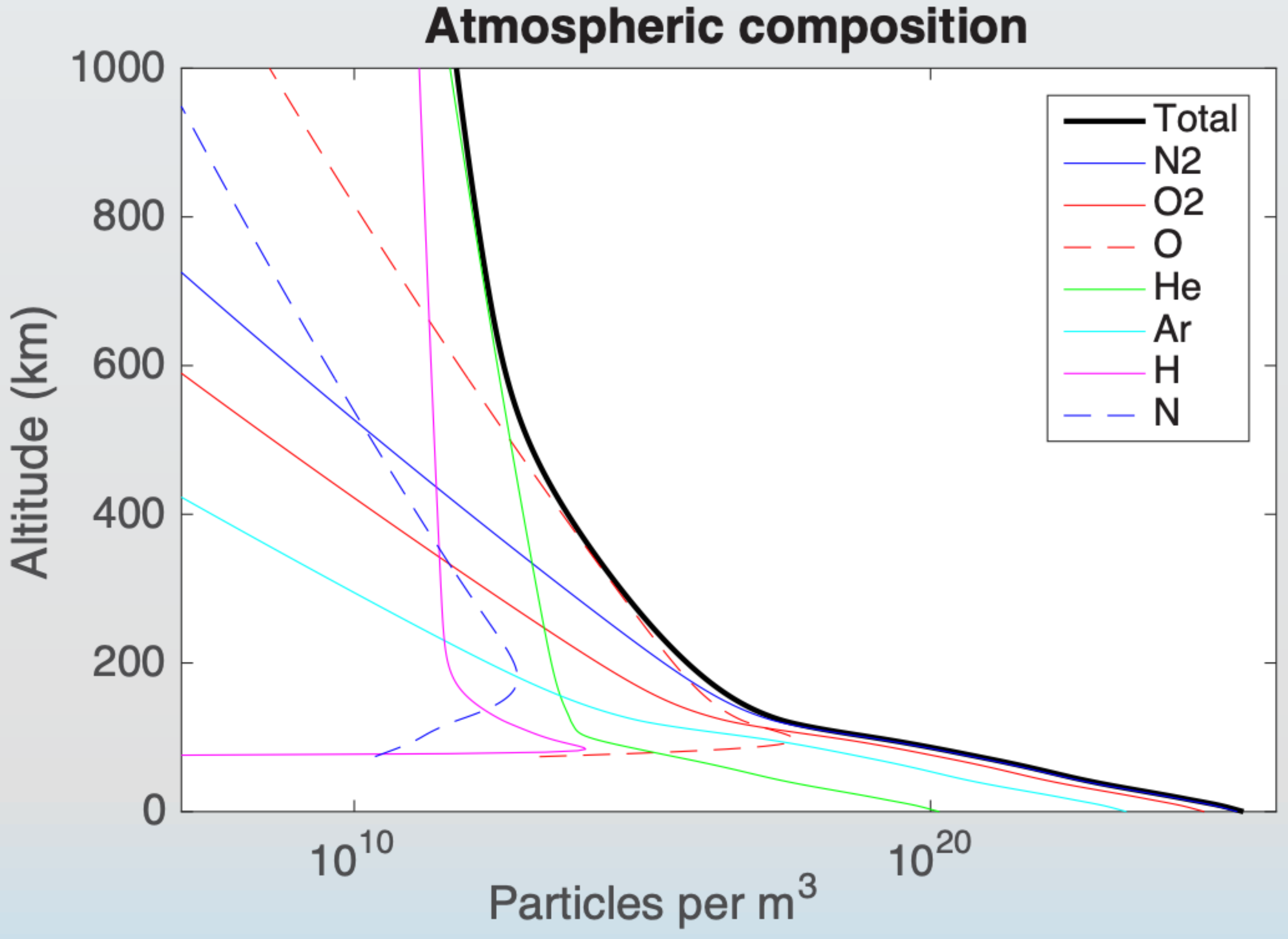
US Standard Atmosphere

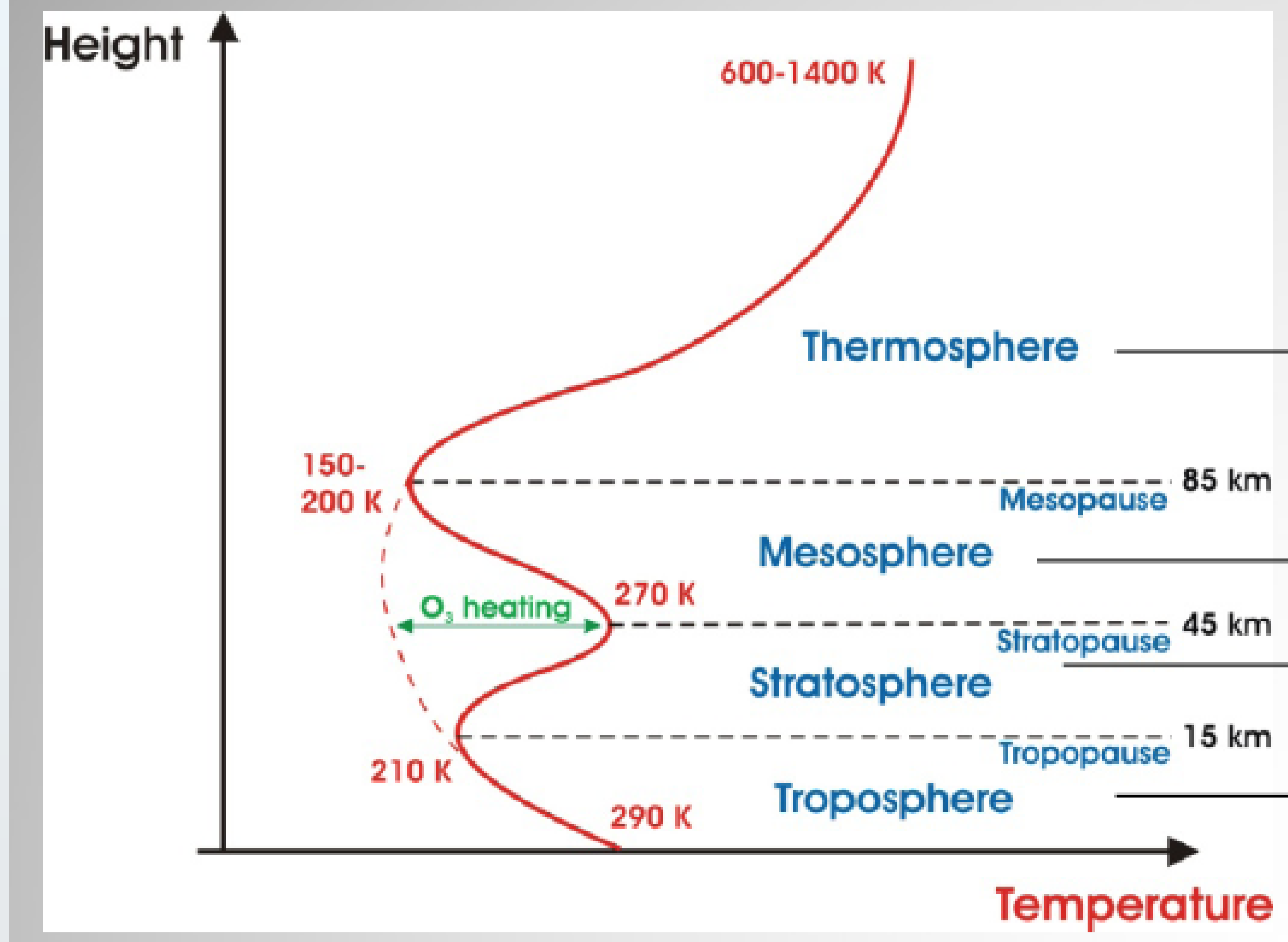


Origin of the Ionosphere

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







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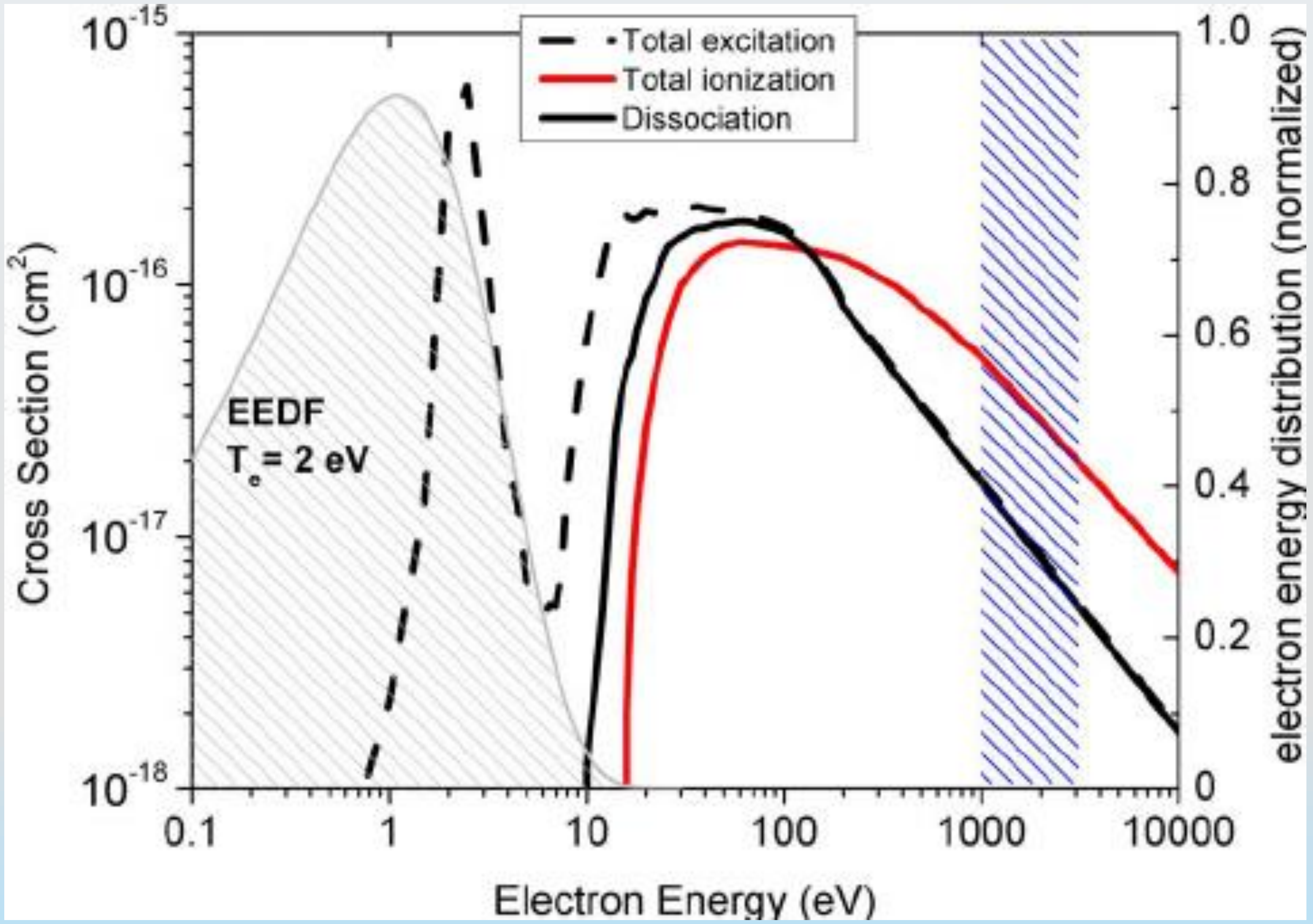
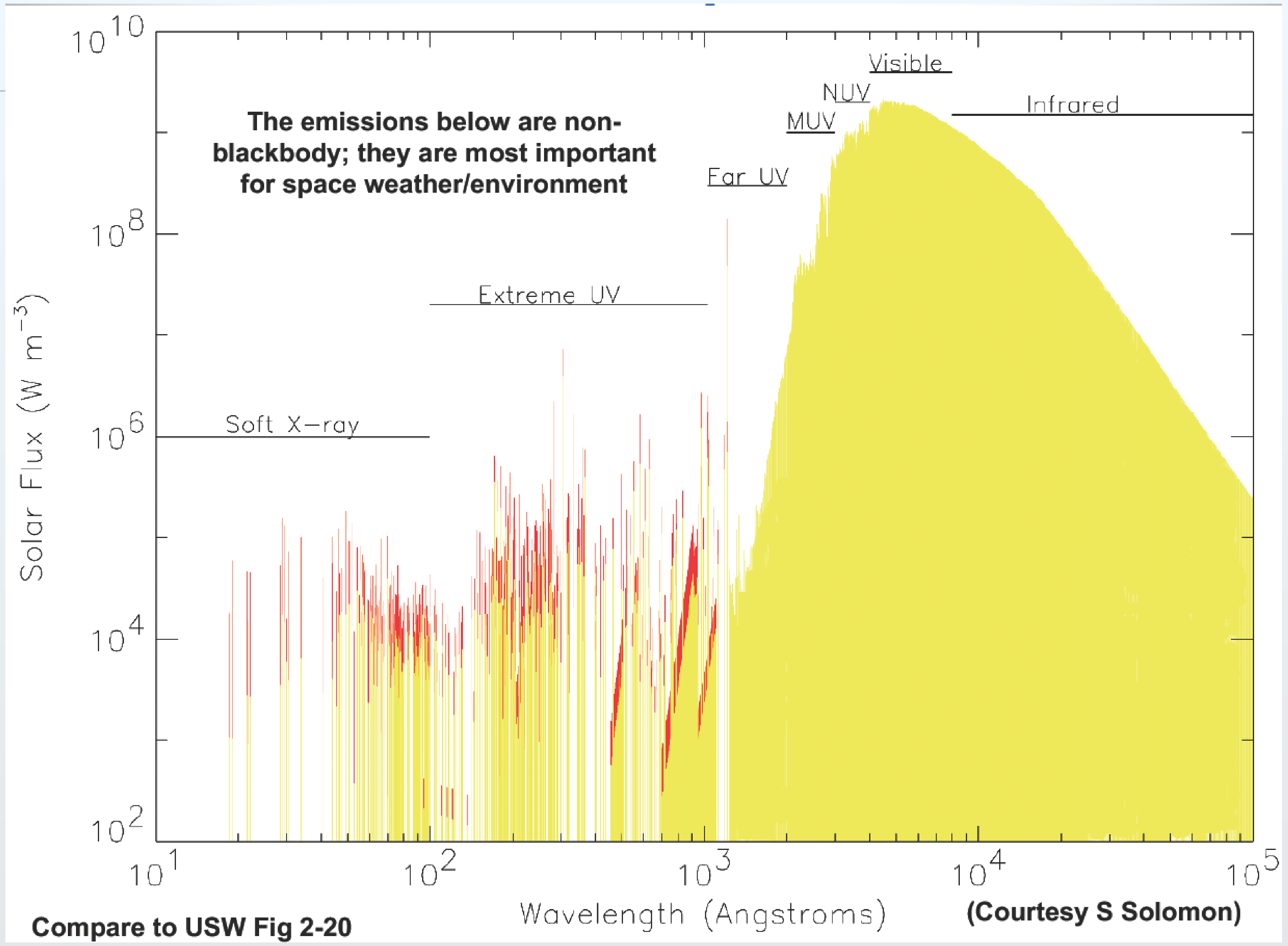
Ionization thresholds

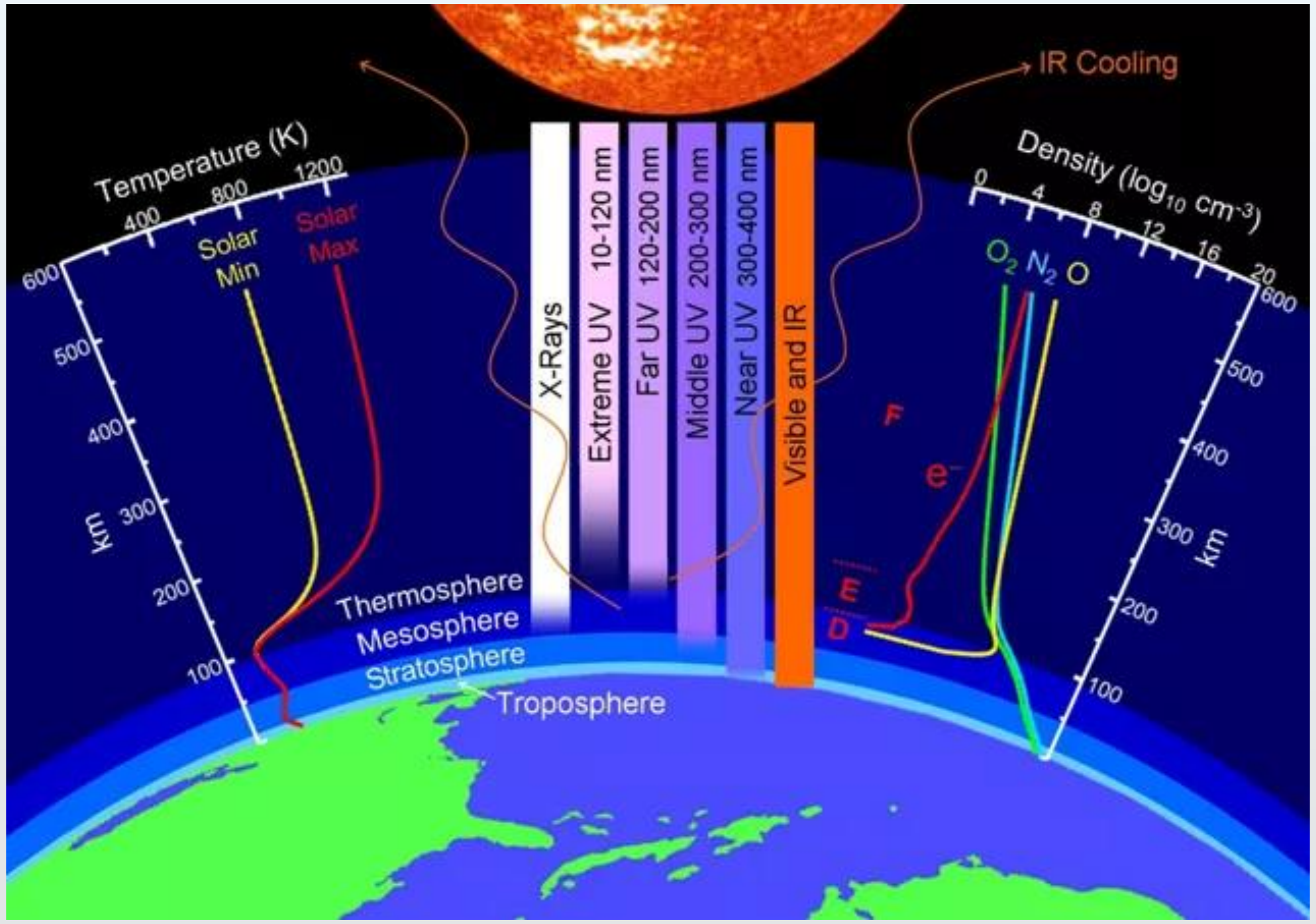
- Require a minimum energy to free an electron from an atom or molecule
- Require a photon with at least this minimum energy: "**ionizing radiation**" or sometimes just "**radiation**"
- **Ionization cross section** provides energy-dependent picture of ionization probability



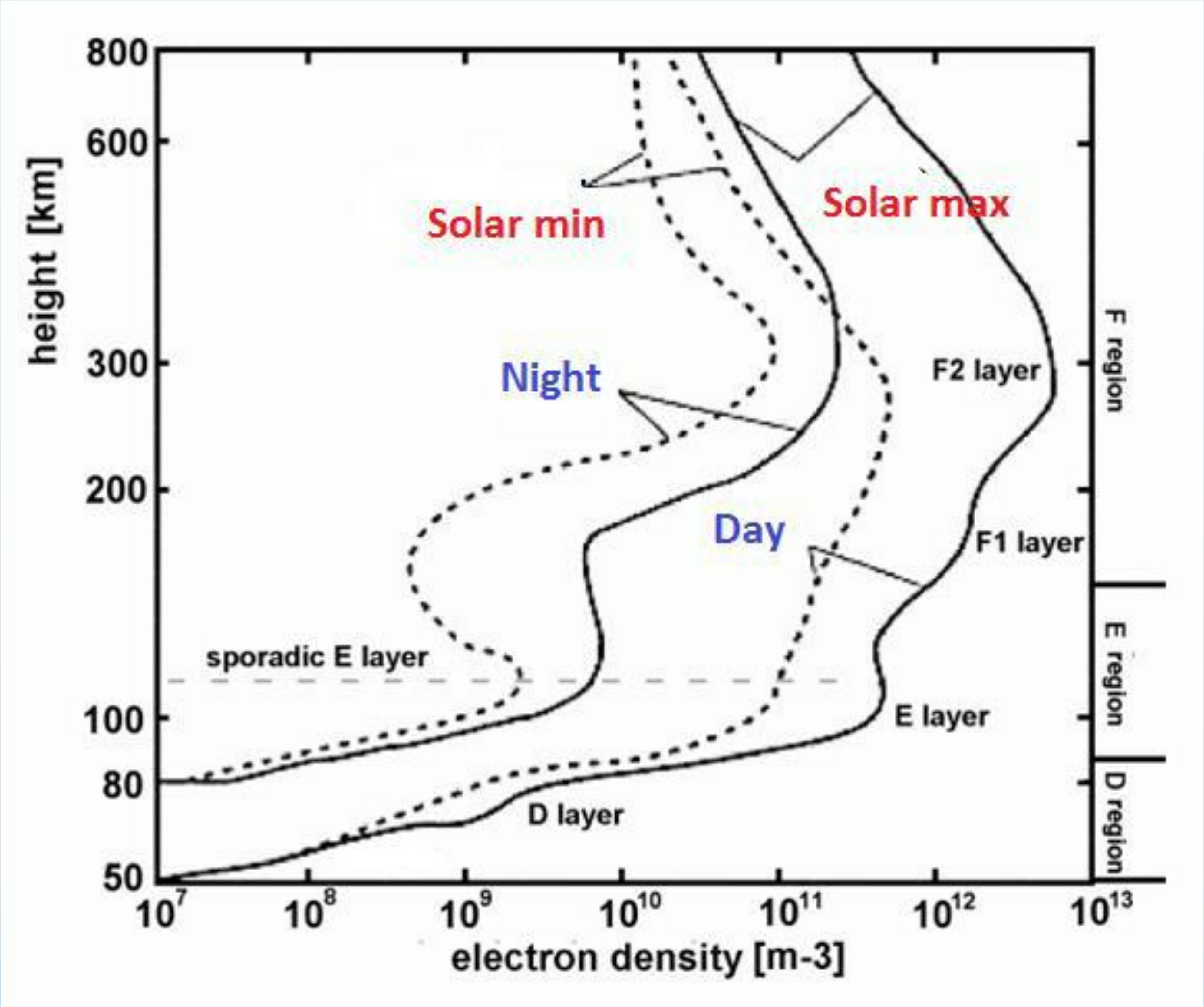


	Ionization Energy	Minimum photon wavelength
H	13.6 eV	91 nm (910 A)
He	24.6 eV	50 nm
O	13.62 eV	91 nm
Ar	15.76 eV	79 nm
N2	15.6 eV	80 nm
O2	12.1 eV	103 nm

Earth’s Ionosphere

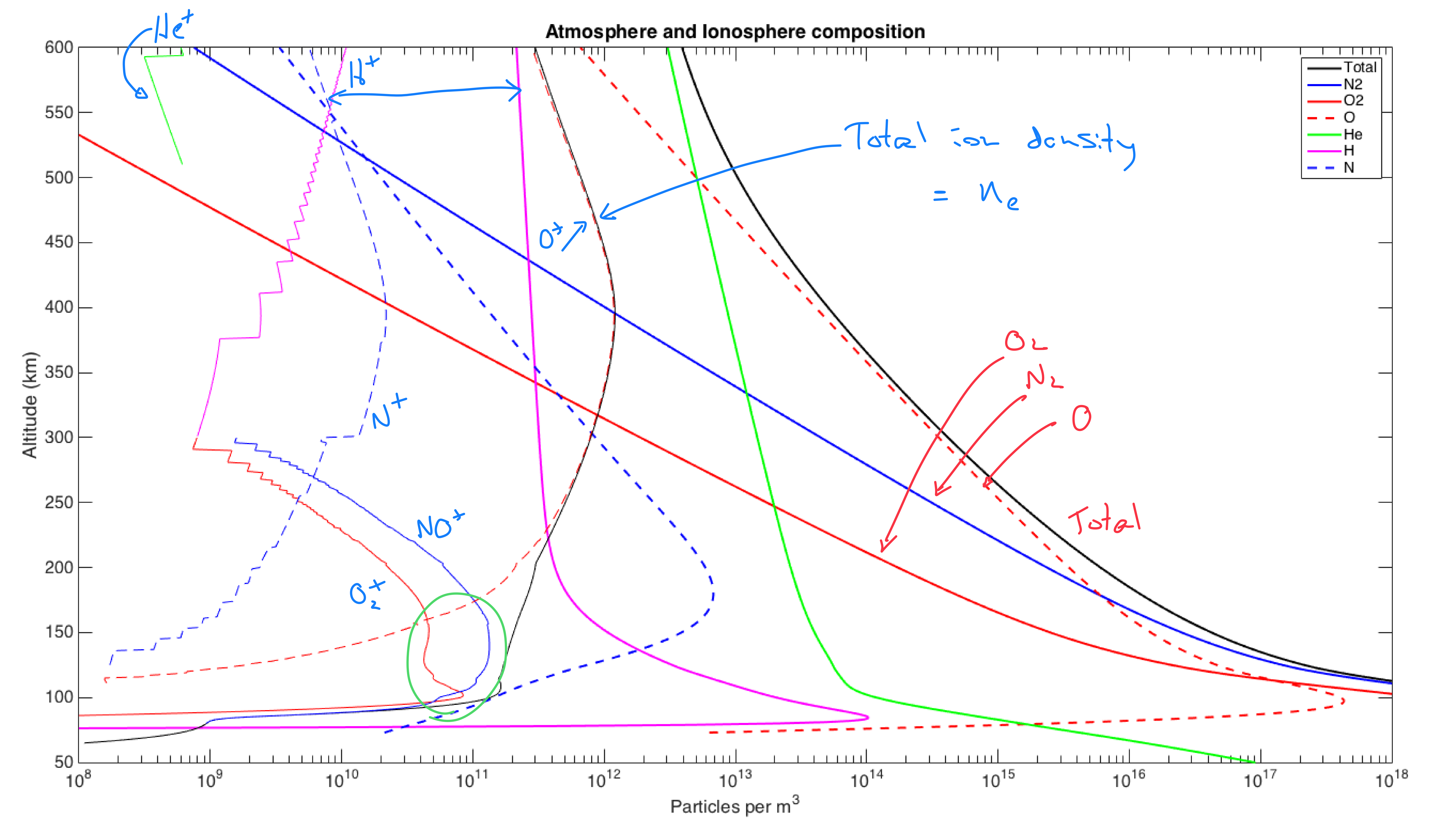


- Ionosphere altitudes and layers have a lot to do with where solar radiation is absorbed!



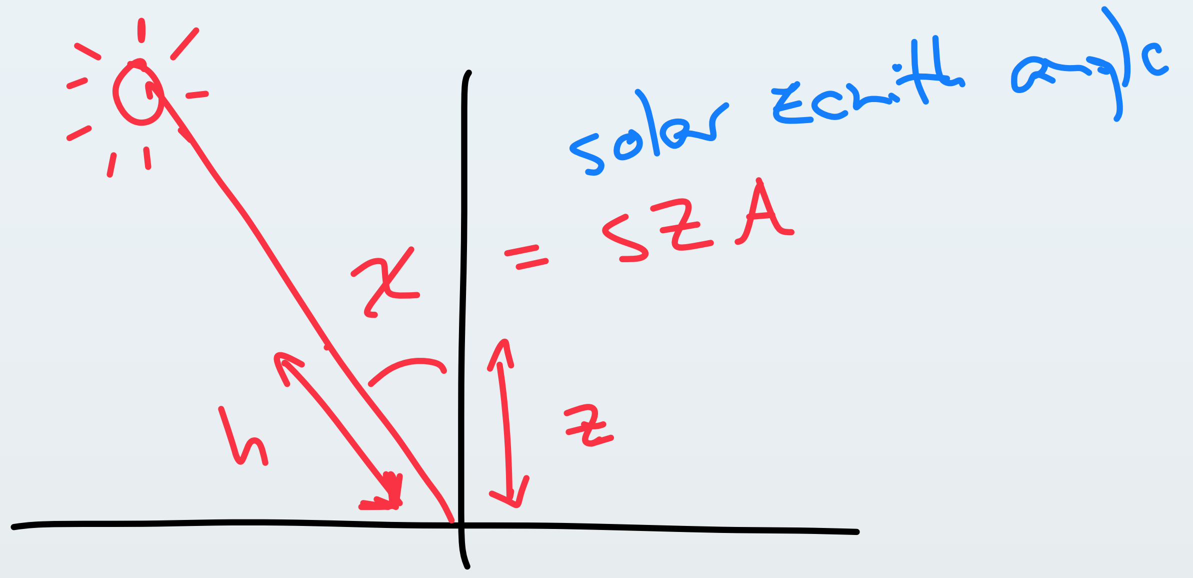
- Right: ionization density changes by 100x day vs night, and 10x or more with solar cycle

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?



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

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

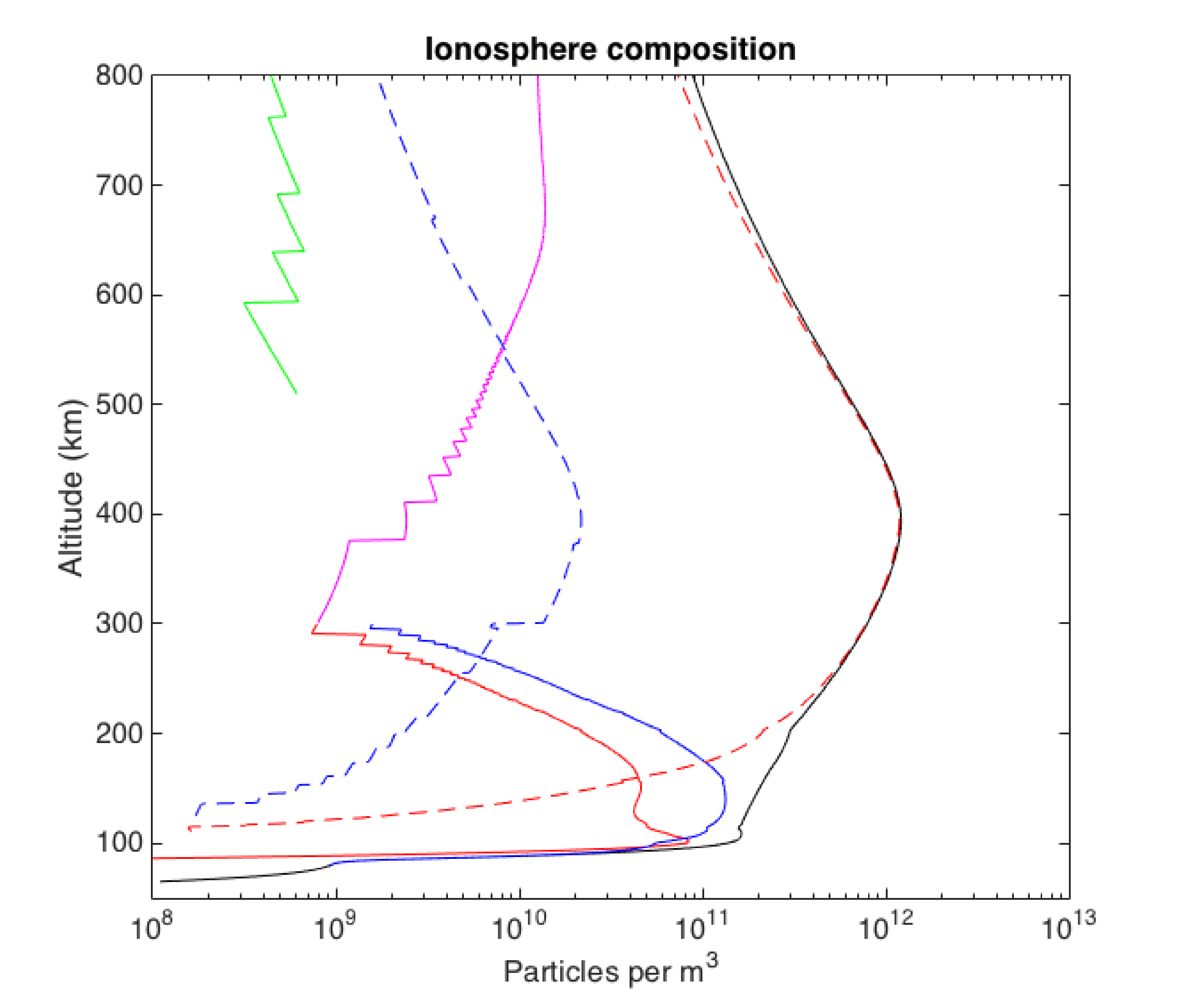
$$I(z) = I_\infty e^{-\int_\infty^z n(z)\sigma \sec\chi \, dz}$$

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

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

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

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



Chapman Layer

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

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

η_i: ionization efficiency, 0 – 1

$\sigma \cdot \eta_i$ → σ_i (cm^2), ioniz. cross section

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

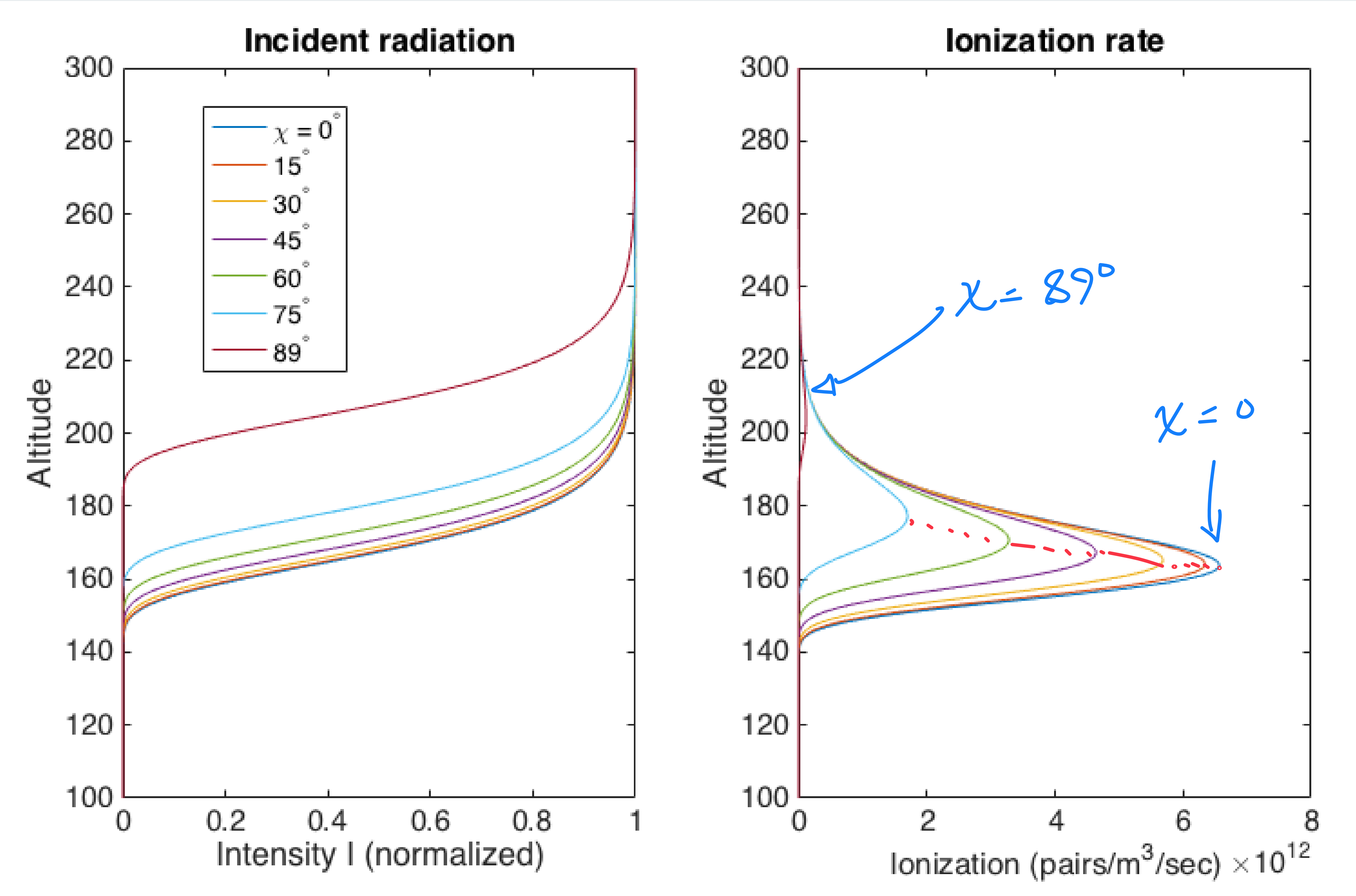
$n(z) = n_0 e^{-z/H}$

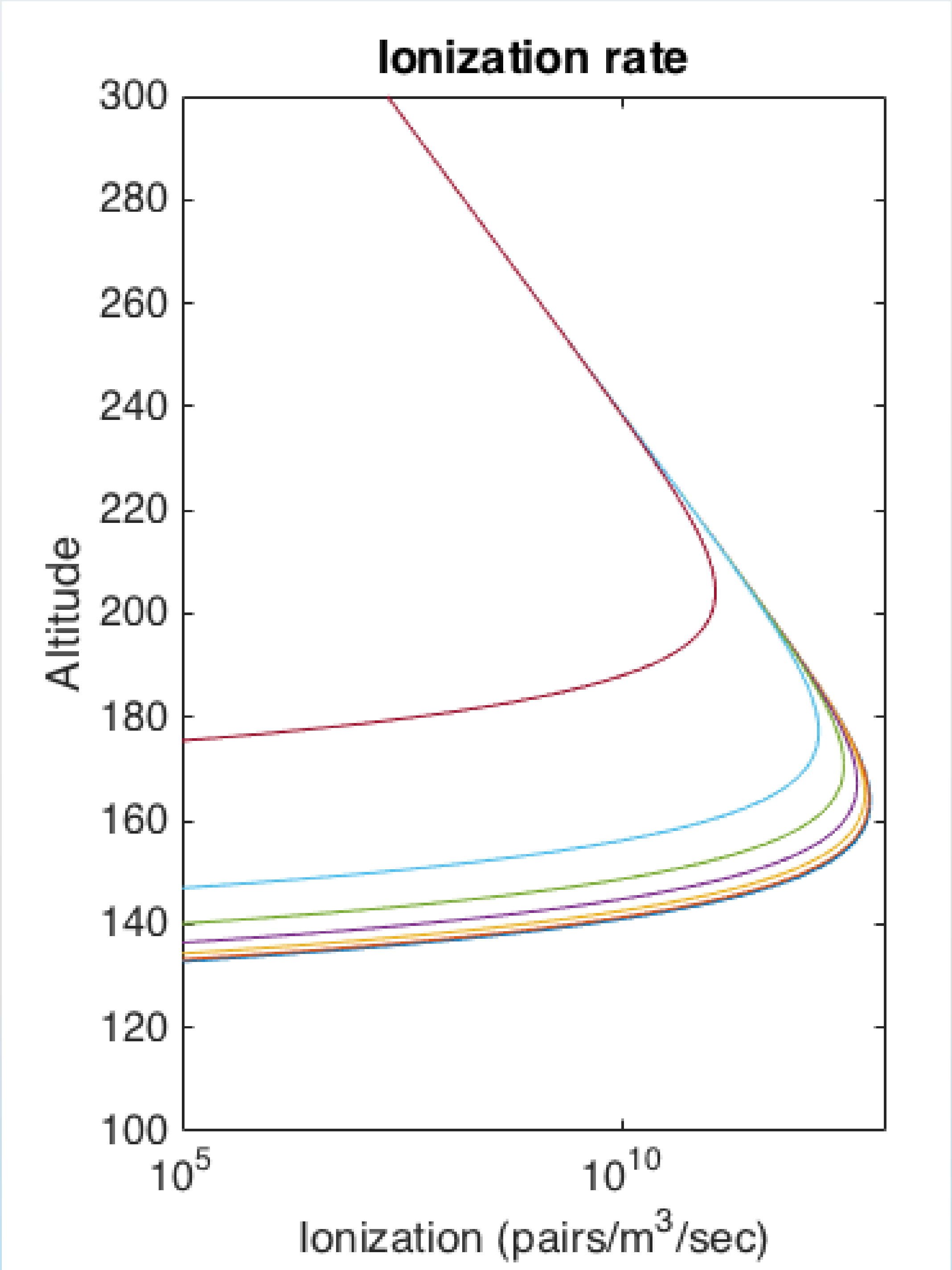
$$P = I_\infty \sigma \eta_i n_0 e^{-z/H} \exp\left(-H\sigma \sec\chi \, n_0 e^{-z/H}\right)$$

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

Continuity equation: $\frac{dn_e}{dt} = P - L$

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

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

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

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

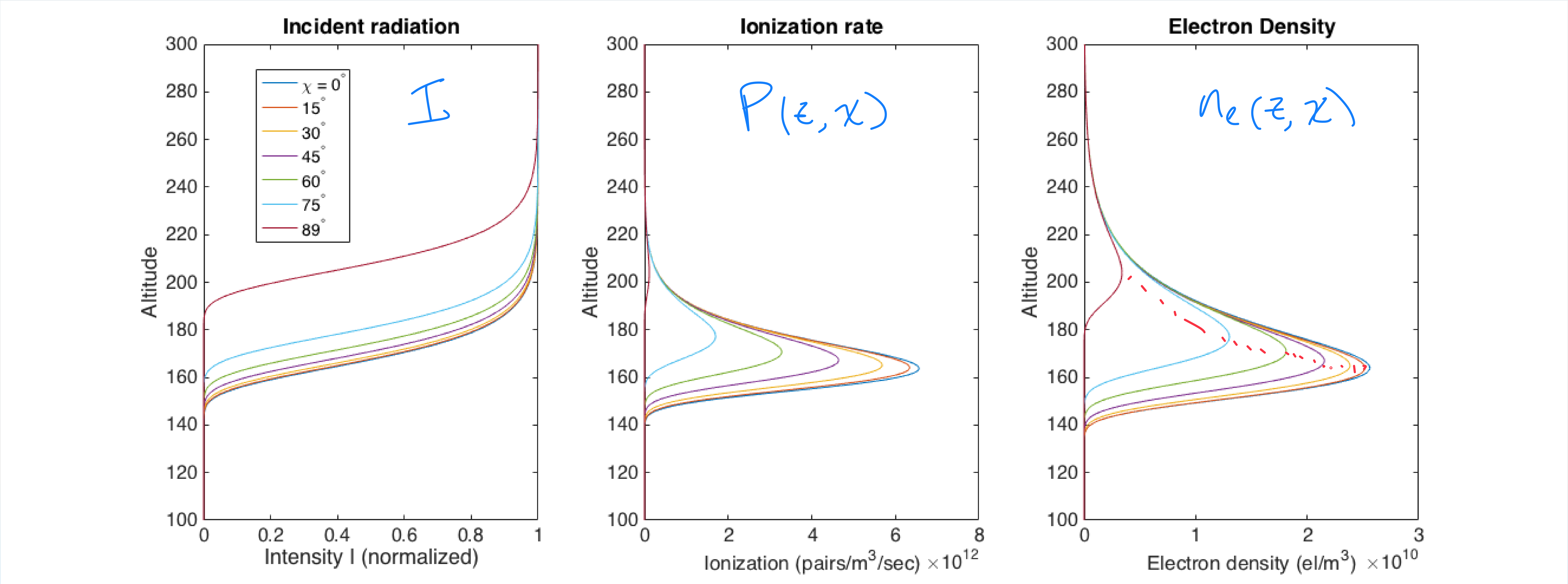
$$P = L \Rightarrow P = \alpha n_e^2 \Rightarrow n_e = \sqrt{\frac{P}{\alpha}}$$

Electron Density Profile

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

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

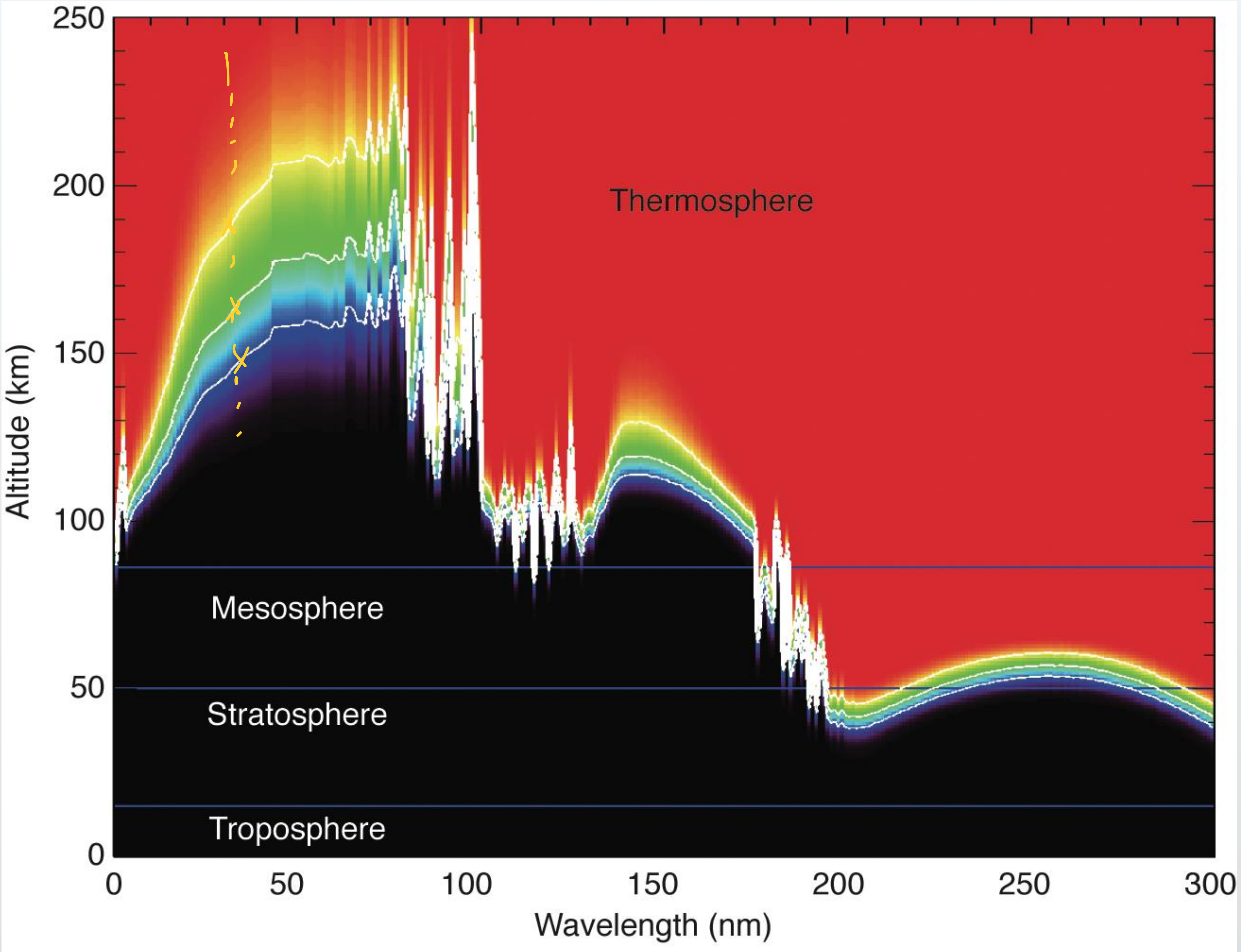
$$z_1 = \frac{z - z_{max}}{H}$$

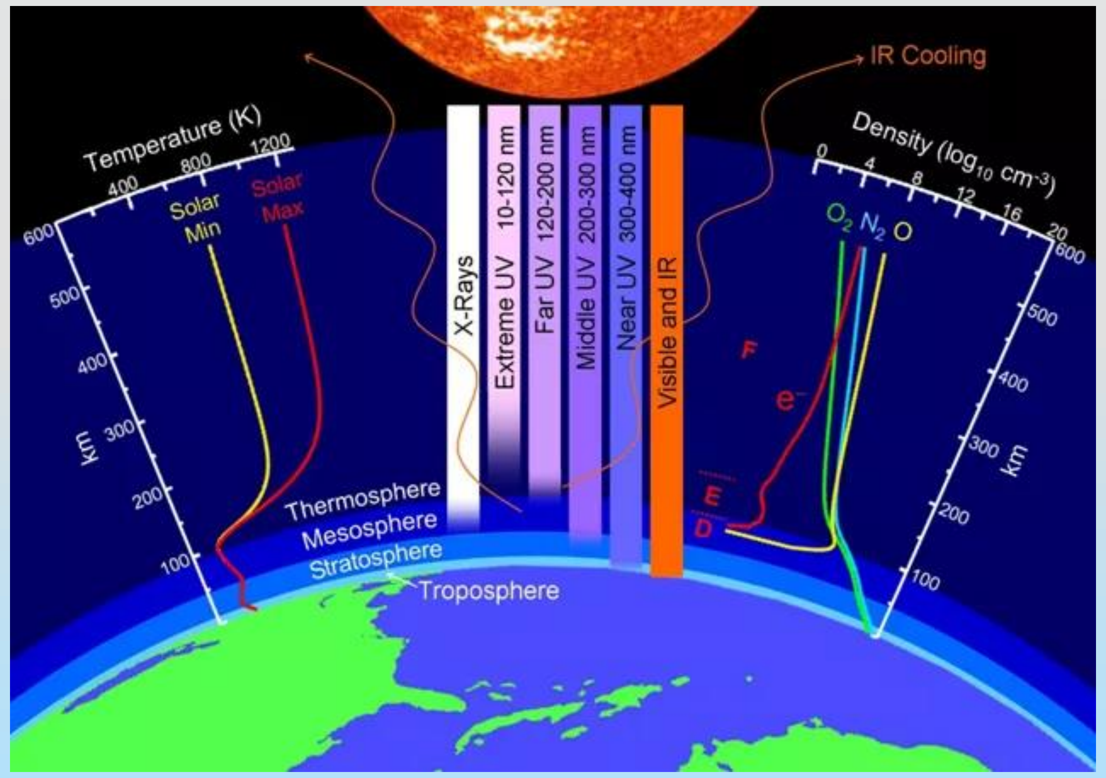


Ionosphere Layers

- 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





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

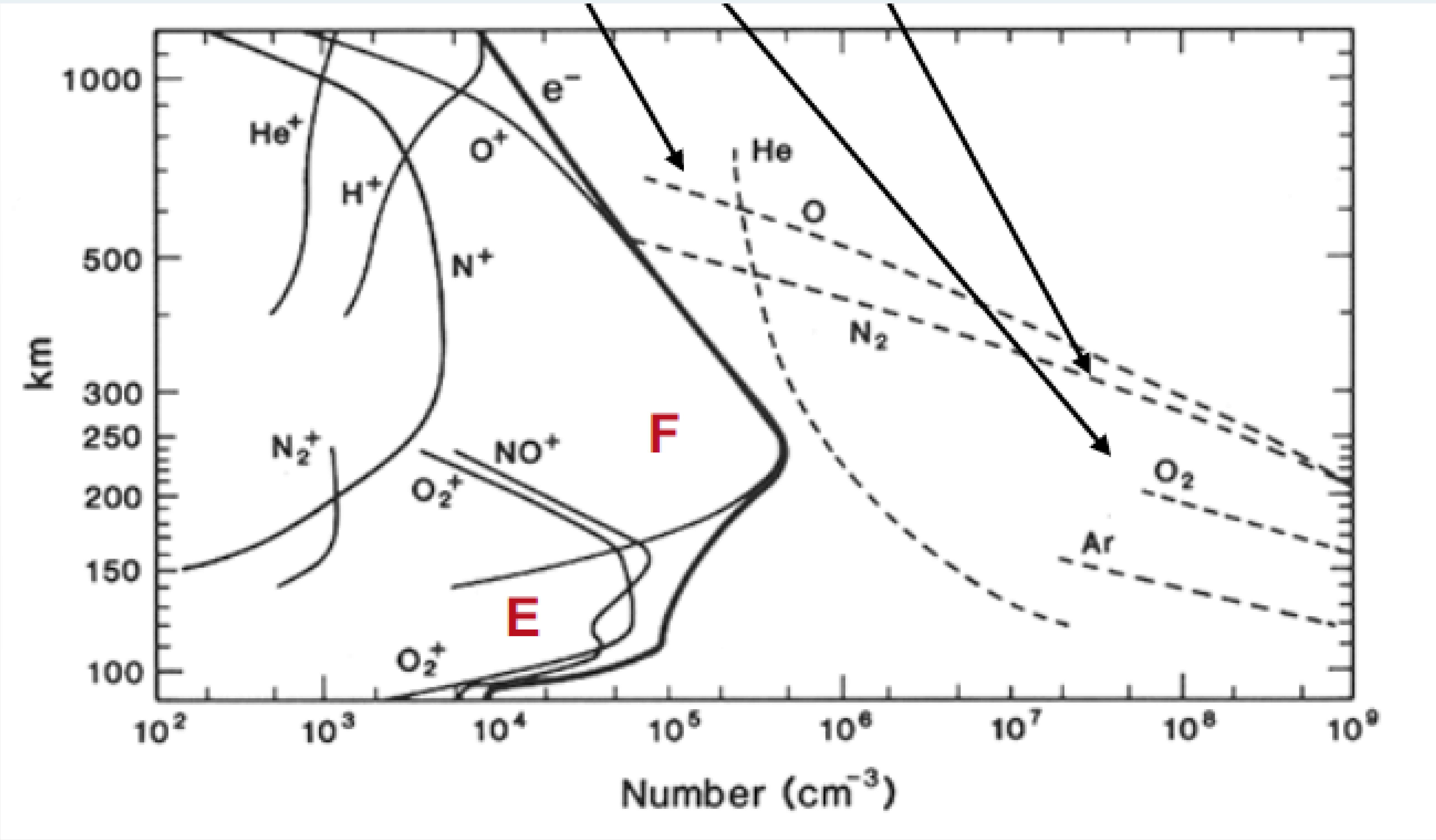
Recombination

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

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

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

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

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

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

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

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

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

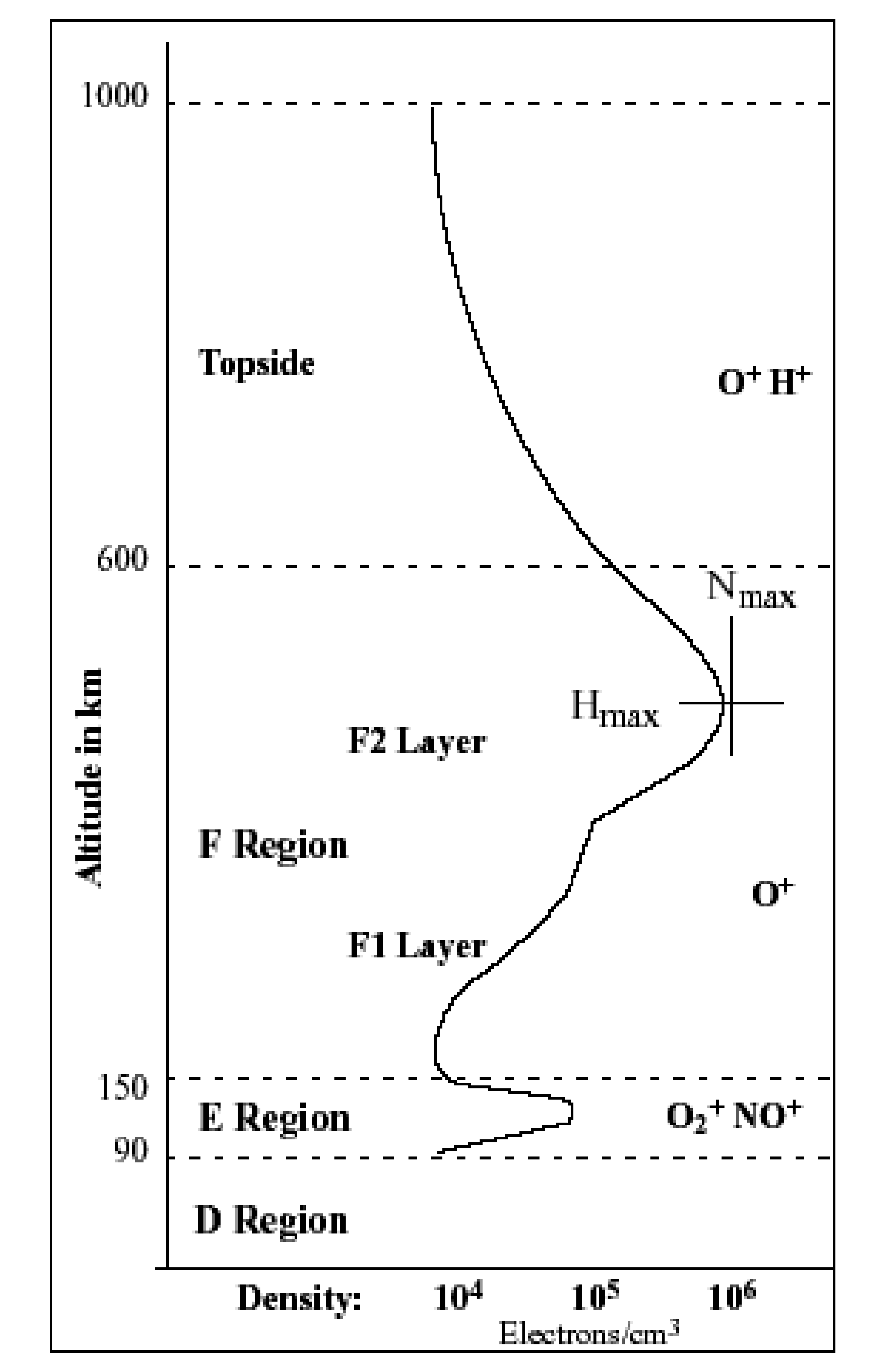
$O^+ + O_2 \rightarrow O_2^+ + O$

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

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

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

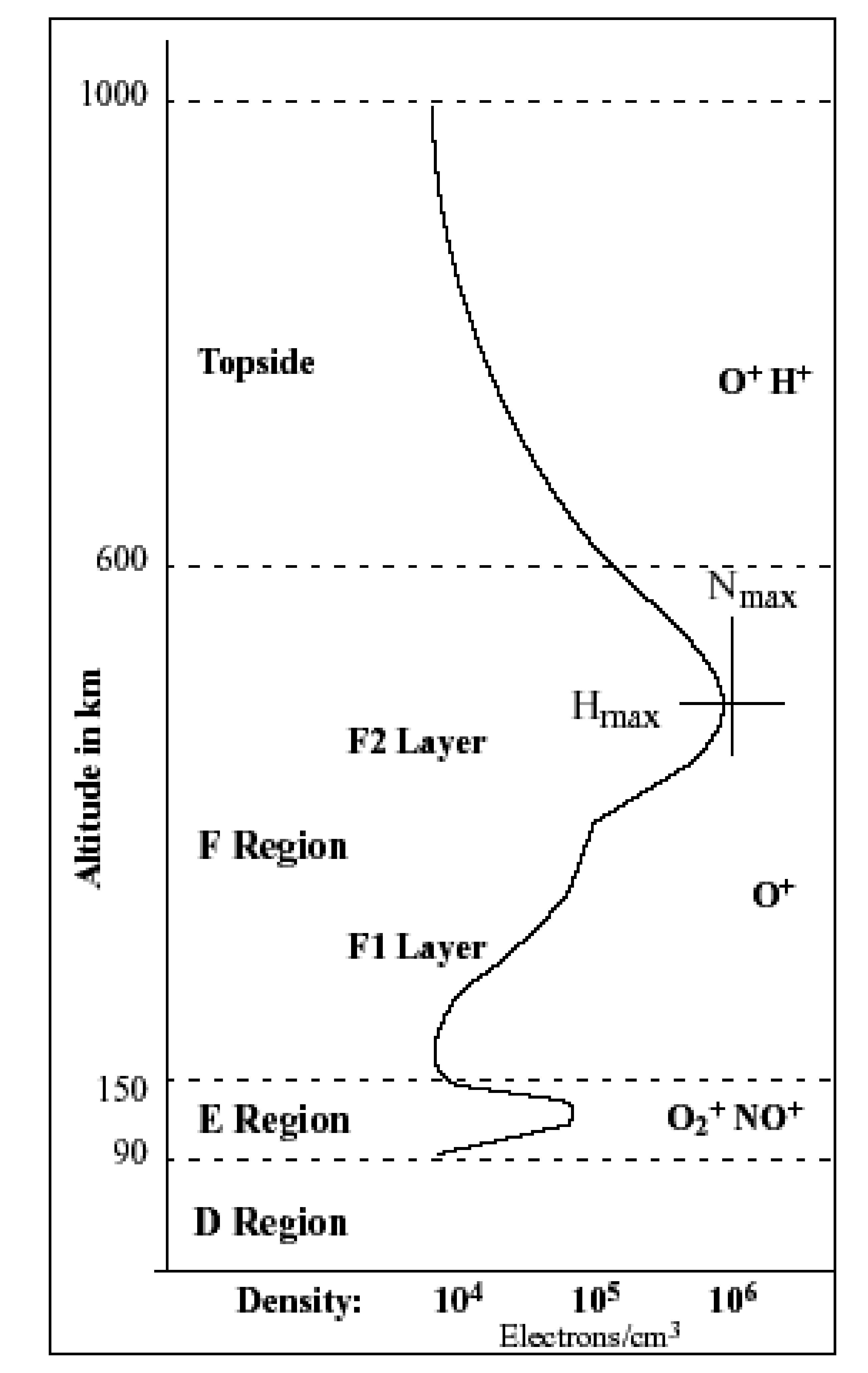
$O^+ + N_2 \rightarrow NO^+ + N$

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

$\neq$

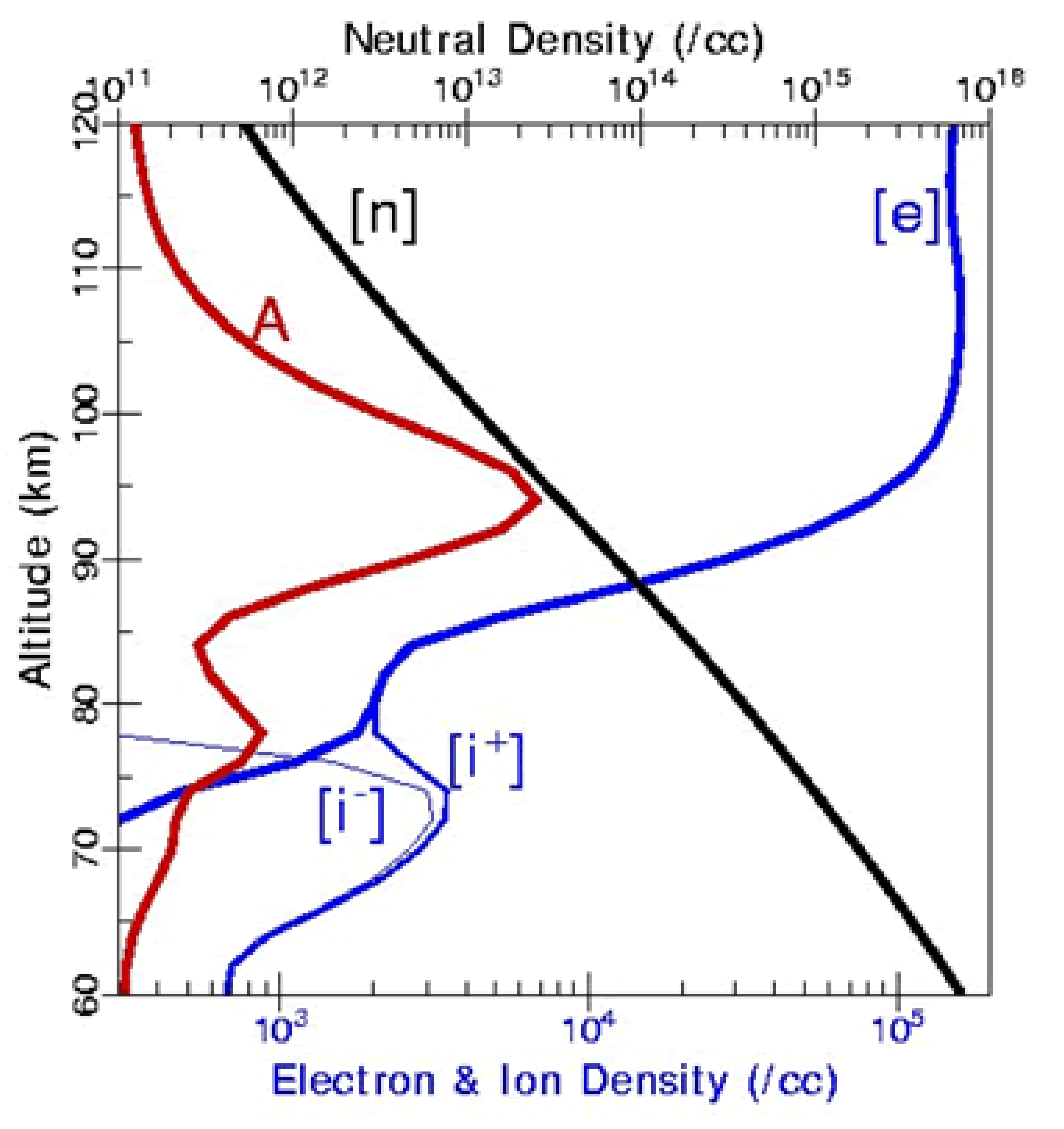
other factors

* dynamics : vertical transport
  - diffusion
* electrostatic forces



D-region

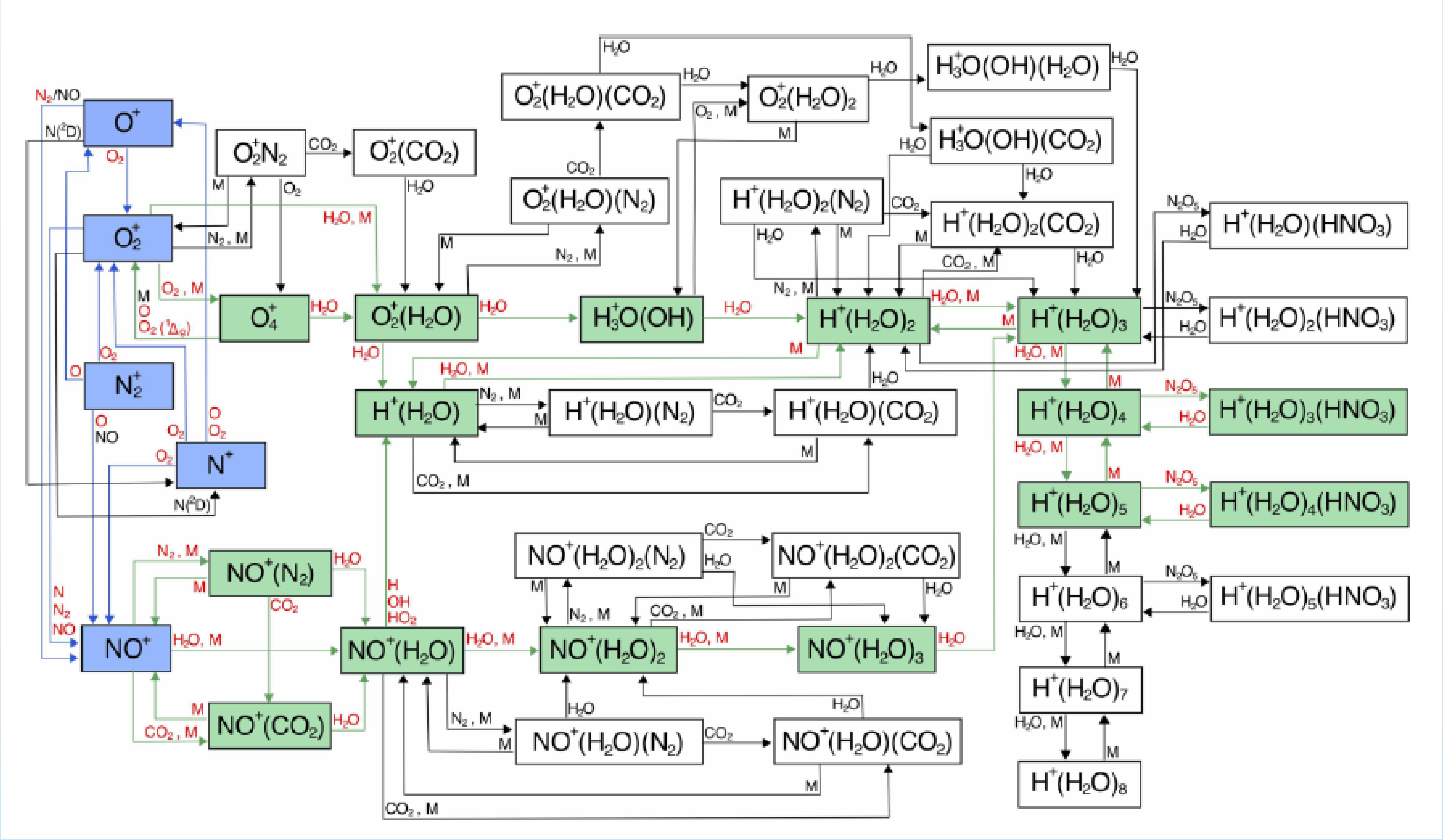
- D-region is known for low electron densities, light and heavy positive and negative ions, and complex chemistry.
- **Production:**
  - $N_2 + \gamma \longrightarrow N_2^+ + e^-$
  - $O_2 + \gamma$ —> $O_2^+ + e^-$
  - $NO + \gamma$ —> $NO^+ + e^-$
- **Negative ions formed by attachment processes:**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

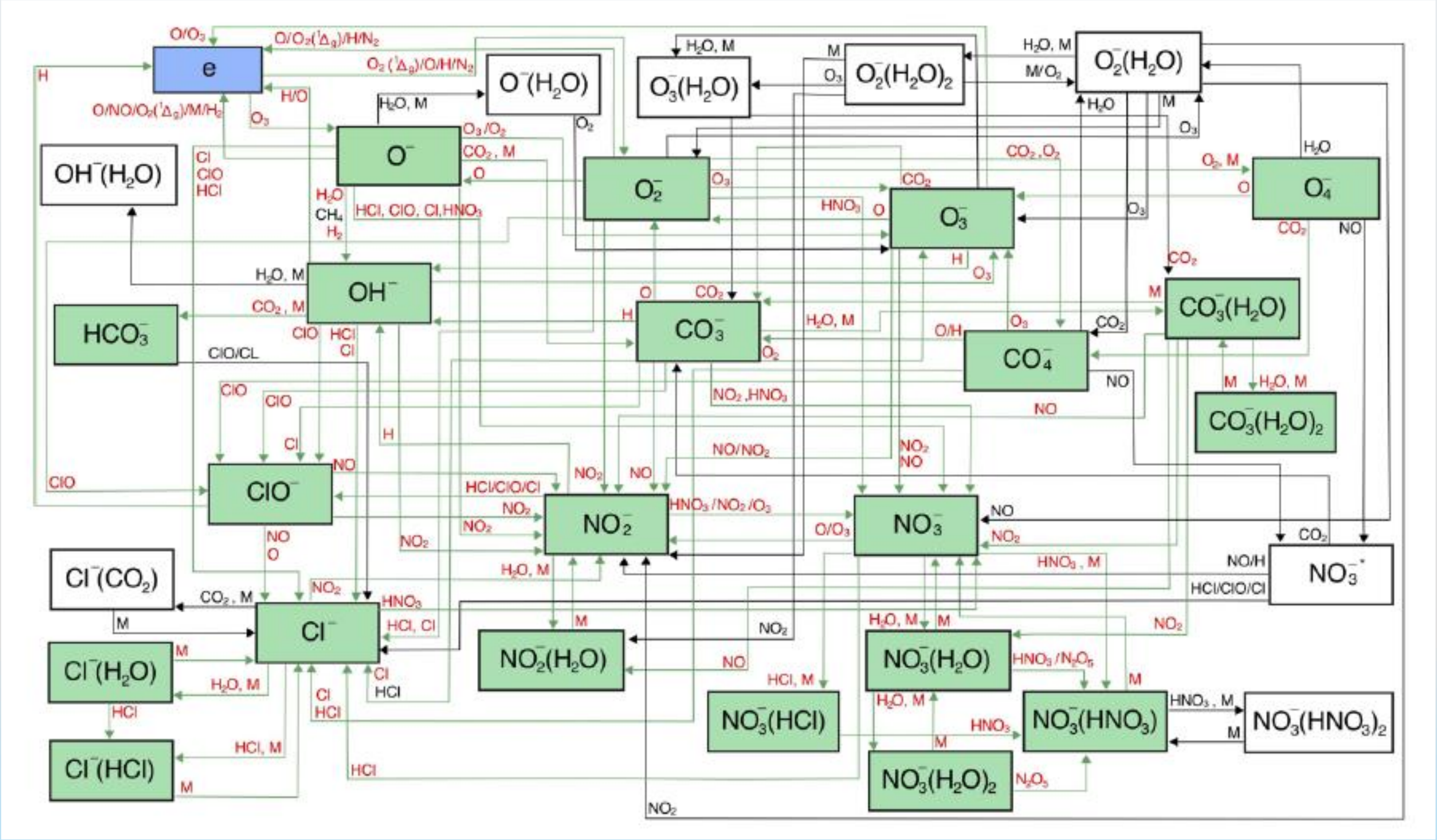


D-region chemistry and "cluster ions"

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

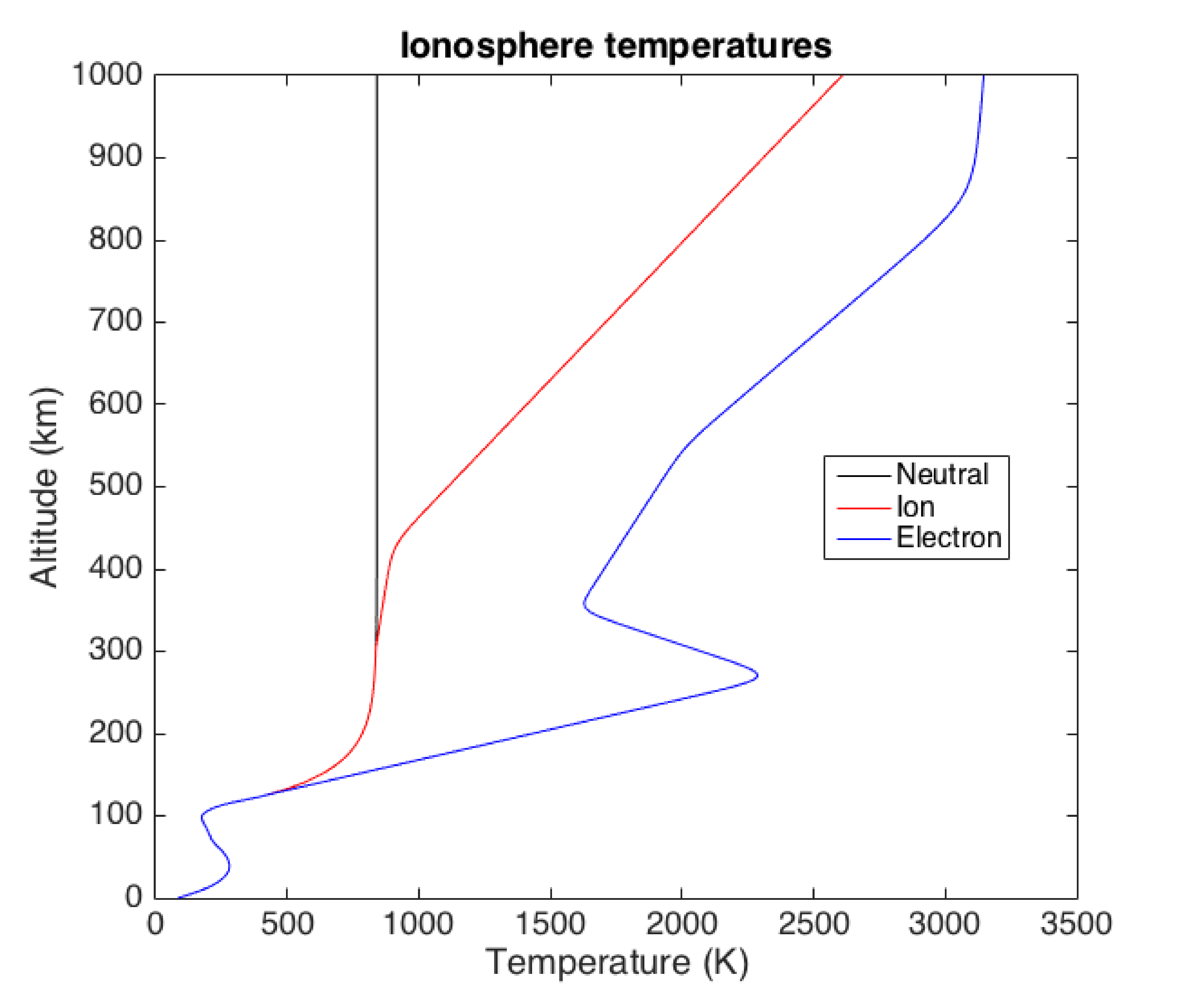
Sodankyla Ion and Neutral Chemistry (SIC) model:





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



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**

New continuity equation:

$$\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \mathbf{v}_e) = P - L$$

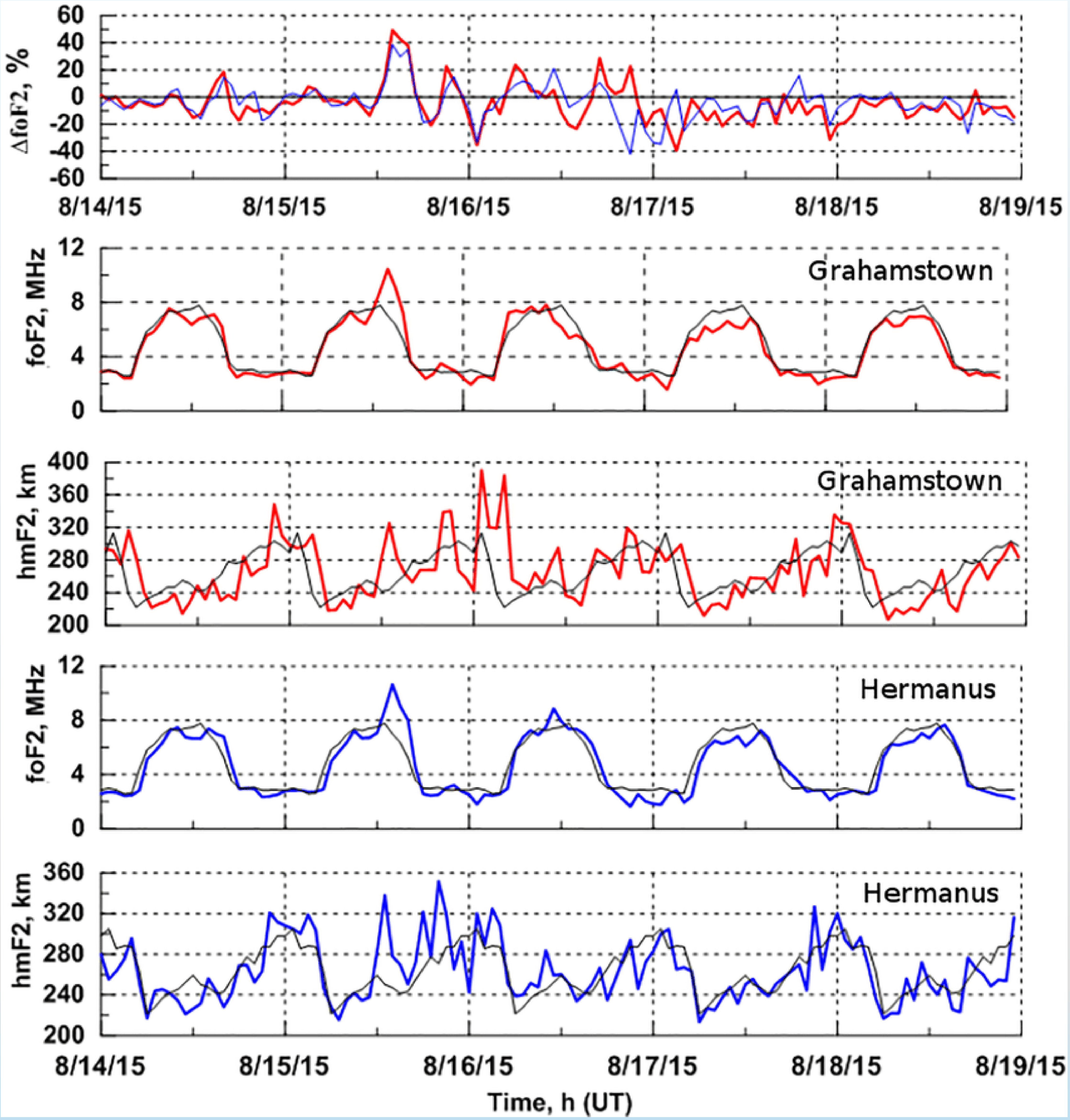
foF2 and hmF2

- 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:

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

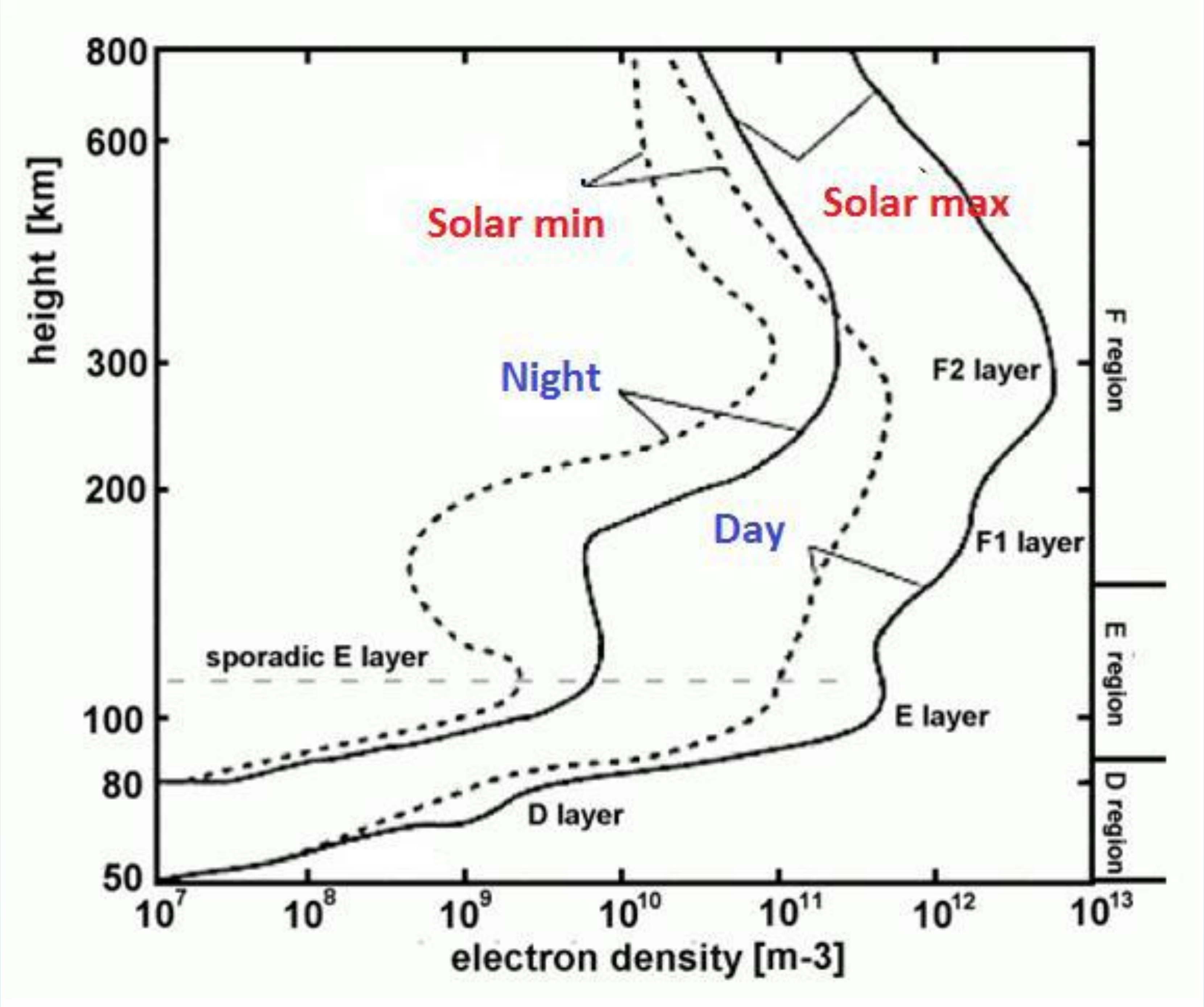
$$f_{pe} = \frac{\omega_{pe}}{2\pi} \simeq 9\sqrt{n_e\,(cm^{-3})} \quad (kHz)$$

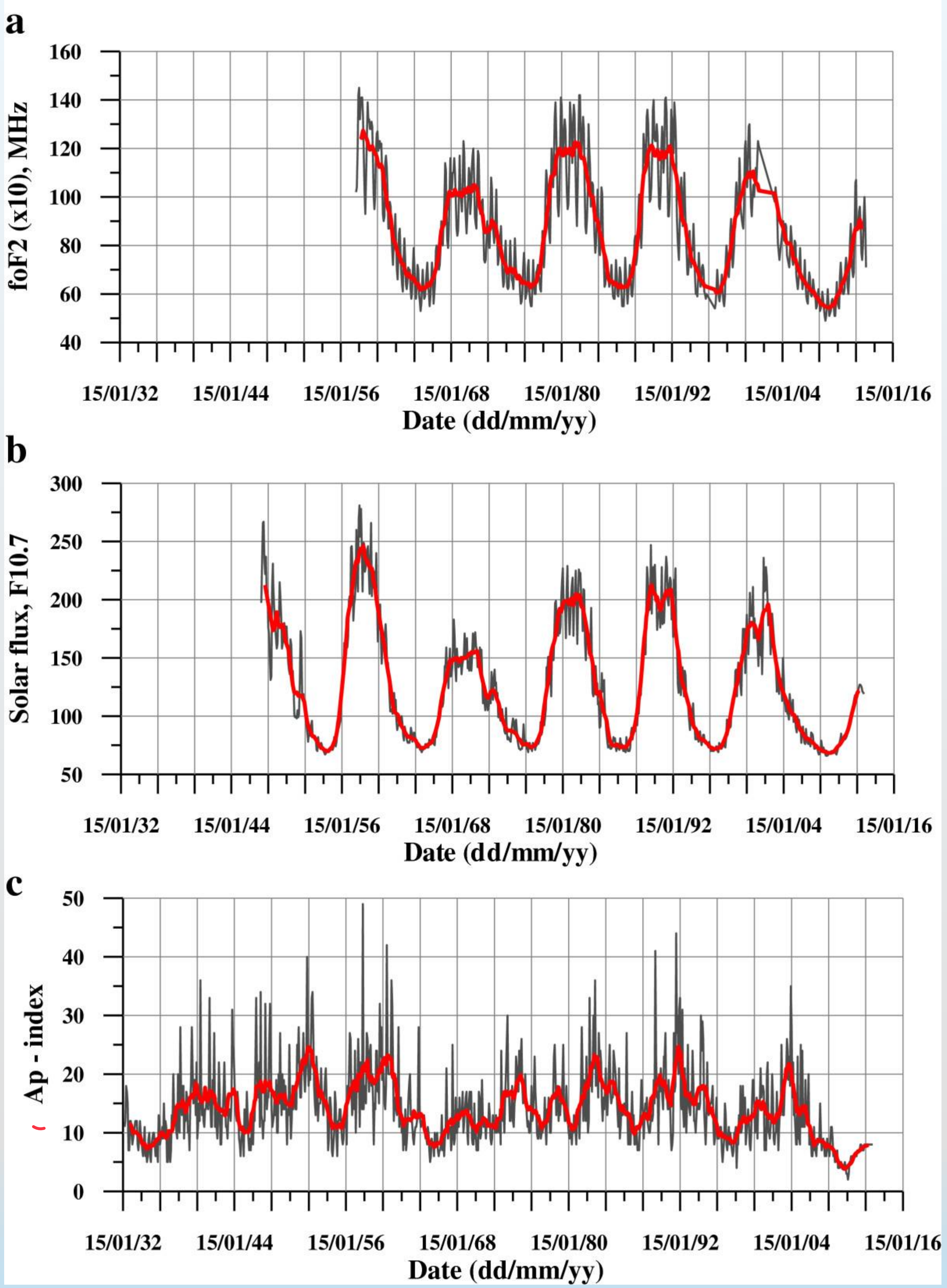
- hmF2 is simply altitude in km



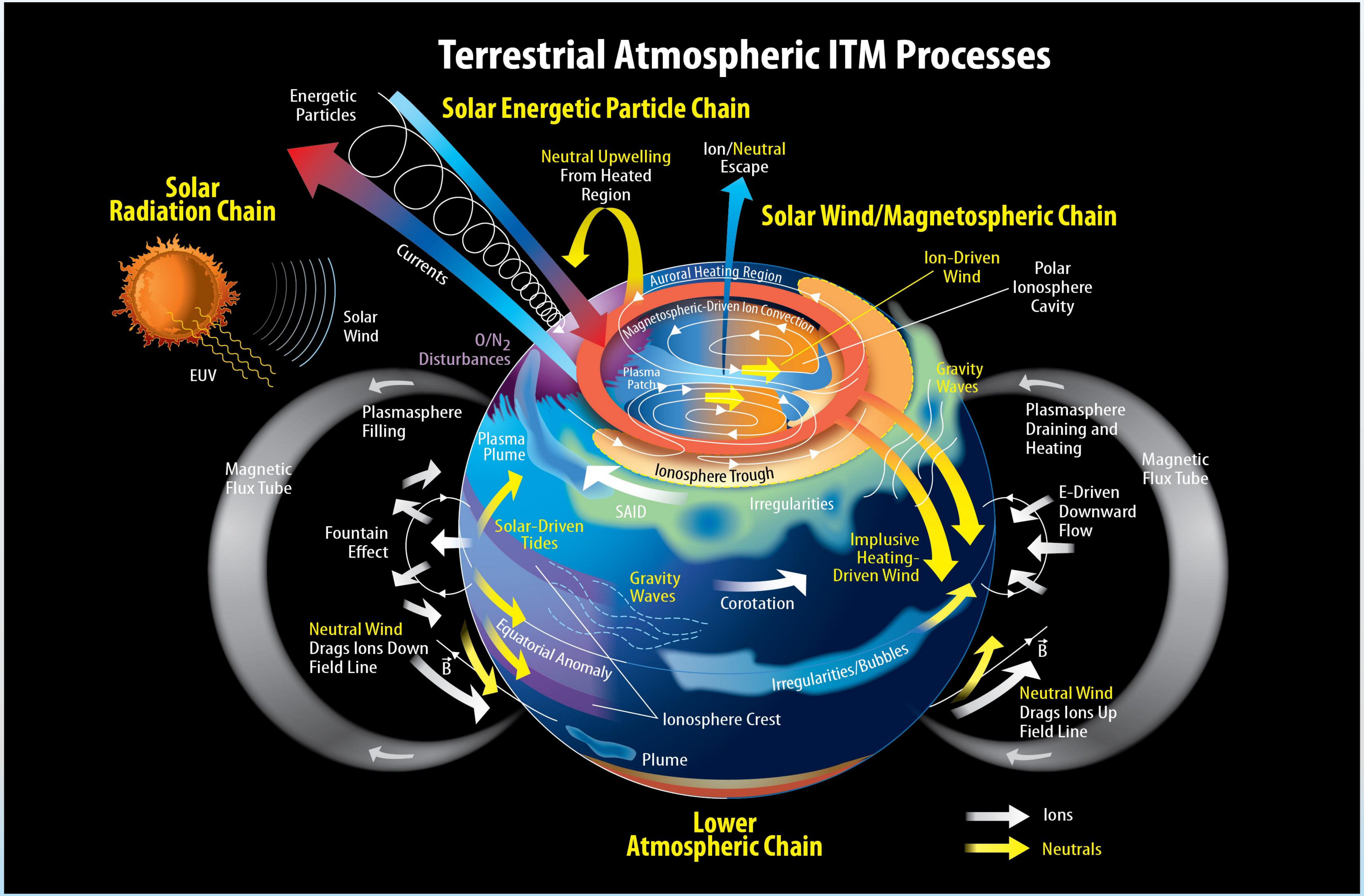
Solar Cycle Variation

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

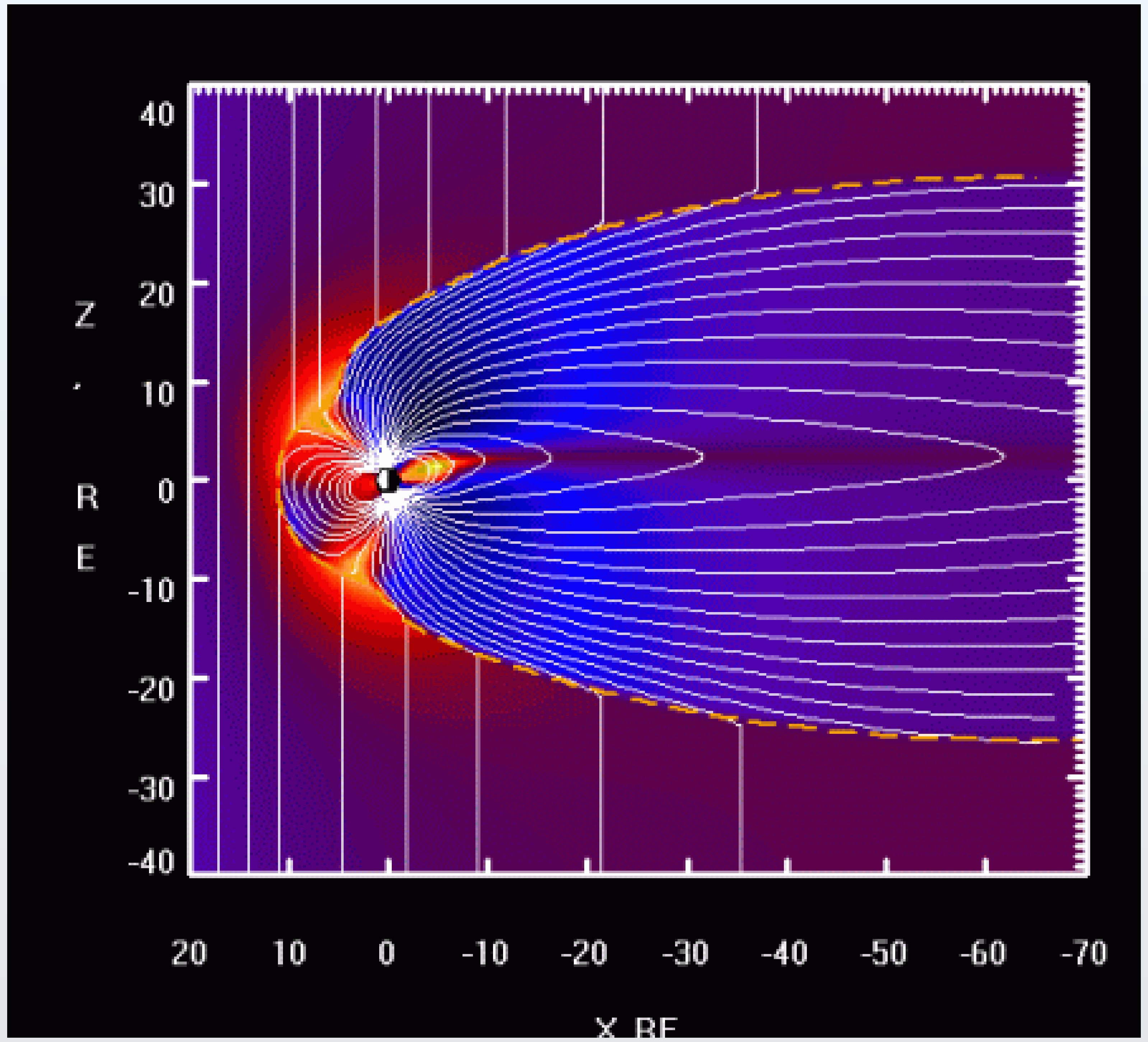




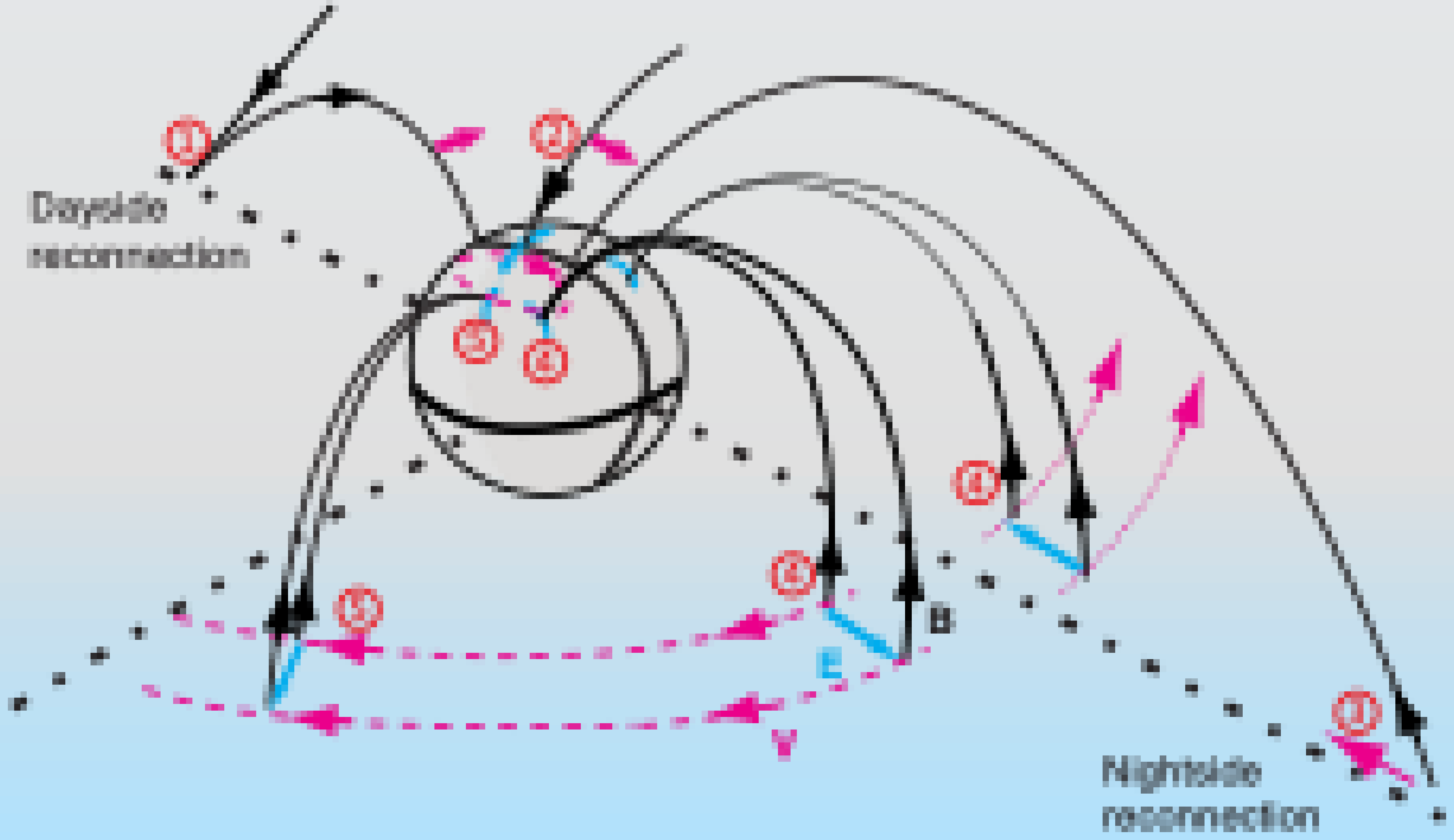
Lots more to the Ionosphere / Atmosphere system…



Ionosphere-Thermosphere Coupling

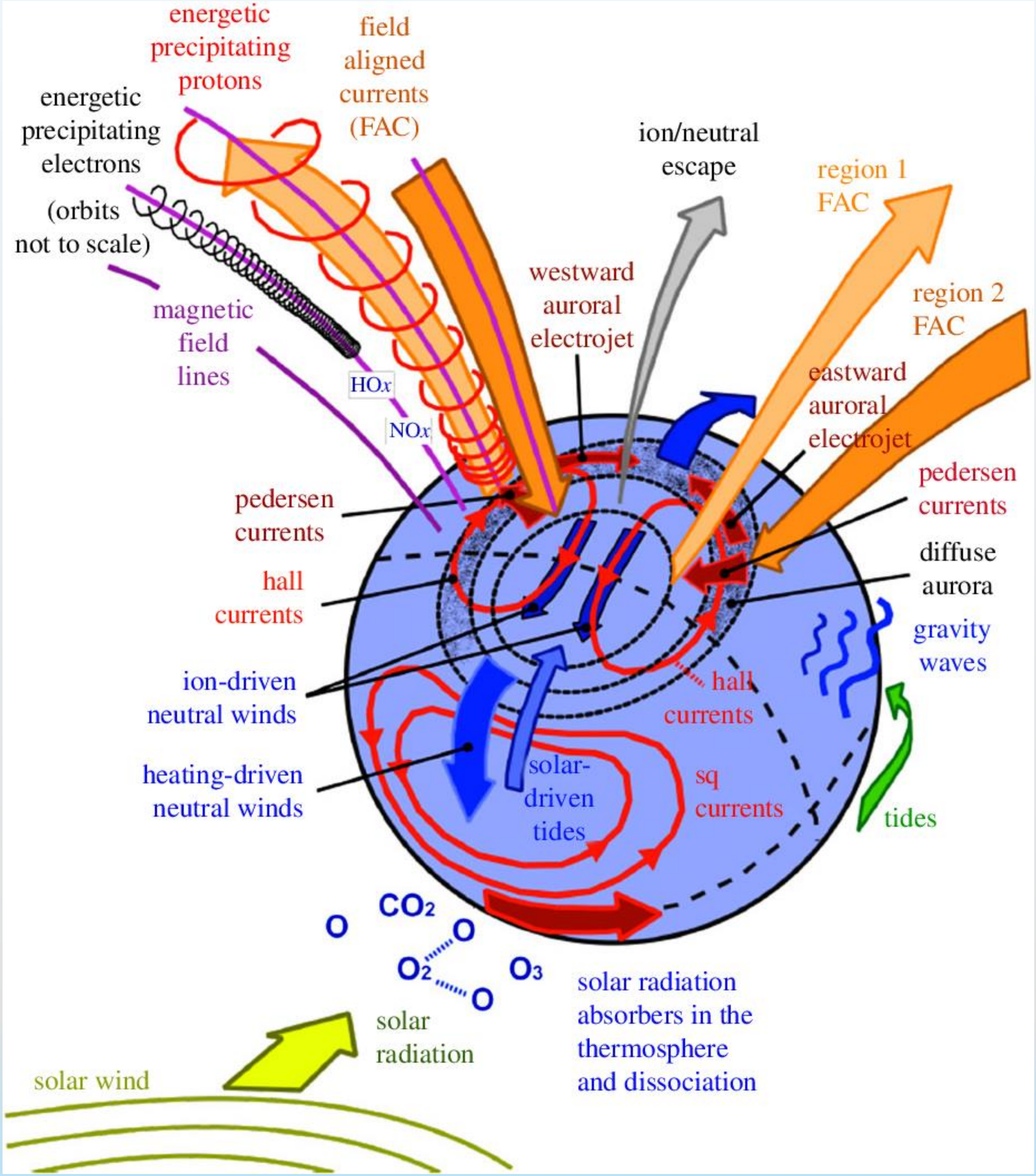


- Conductivity and the E-region dynamo
- Equatorial Anomaly and the F-region dynamo
- Traveling ionospheric disturbances (TIDs)
- Conductivity and Current Systems (R1 / R2)
- Radio wave absorption



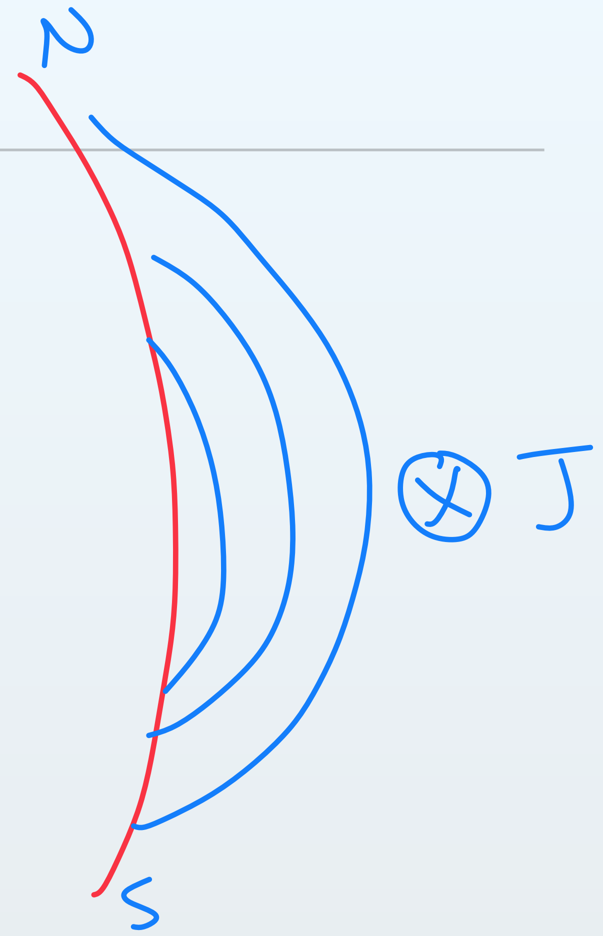
E-region Dynamo

- Solar EUV ionizes and heats the dayside thermosphere; additional heat leads to tides and neutral winds
- **Neutral wind drags ions across magnetic field lines** thanks to large collision frequency.
  - Electrons stay behind (tied to field lines); thus a **current** is generated (Sq currents)
- V x B is balanced by an electric field (E = -v x B). If v is horizontal (both E/W and N/S), it crosses the vertical component of B, producing E that is horizontal

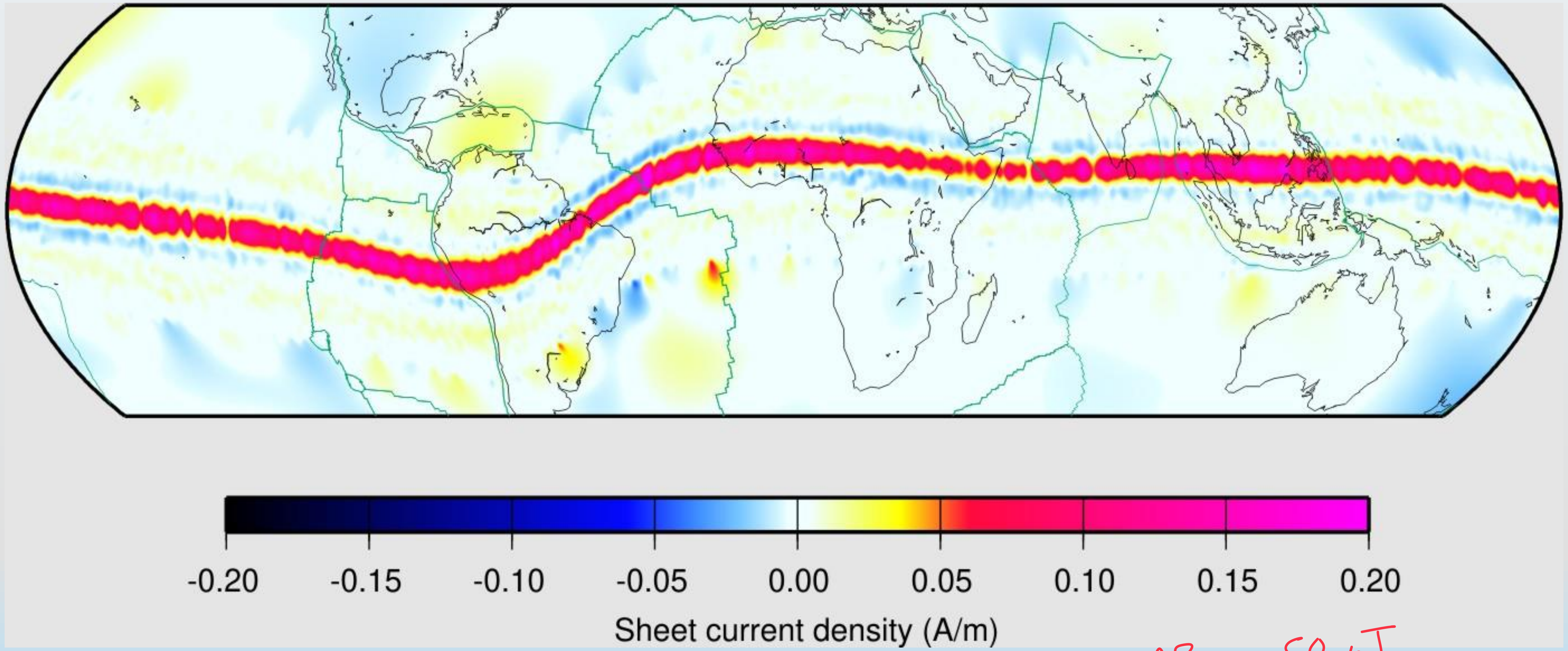


Equatorial Electrojet

- 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



$J = \sigma E$

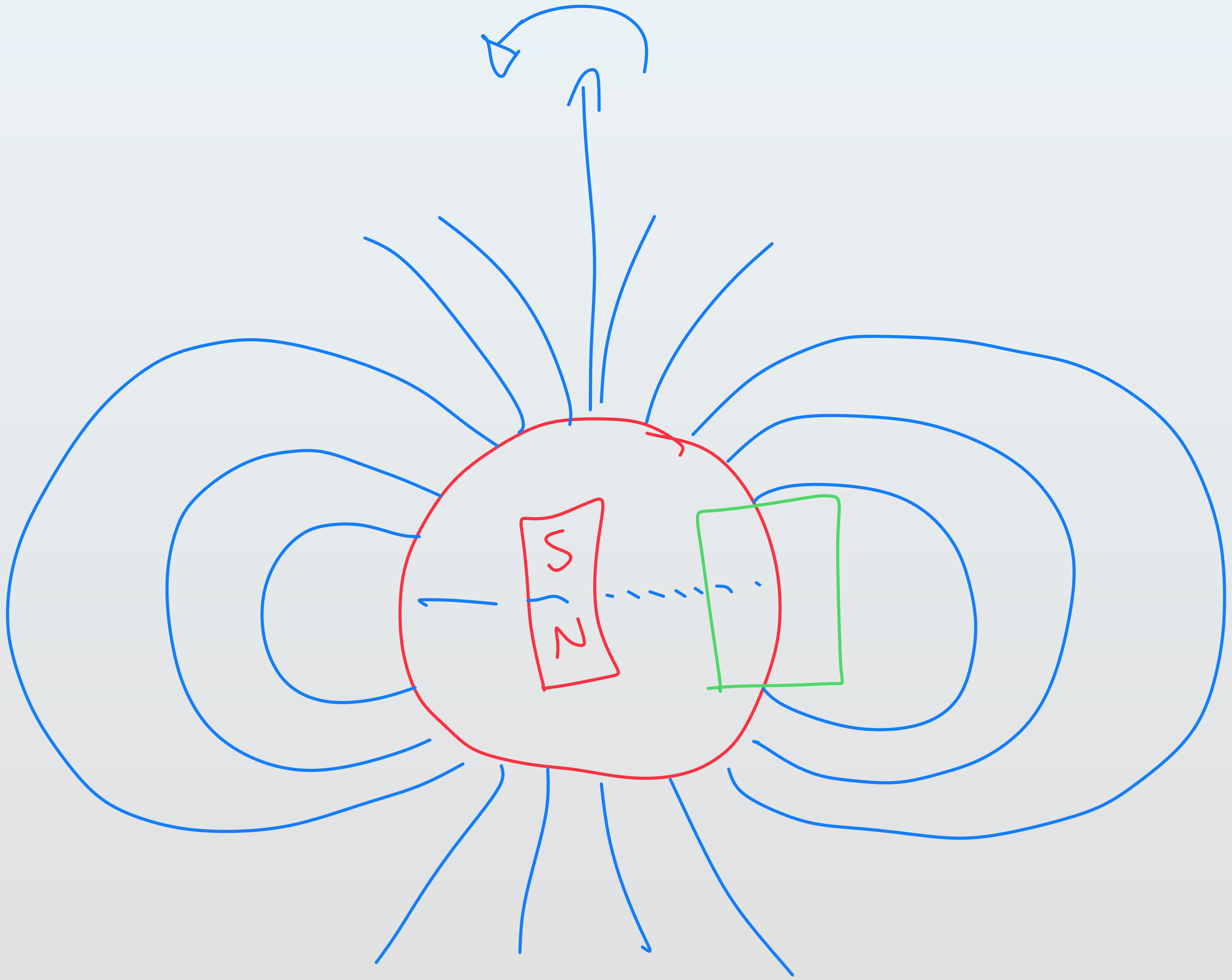


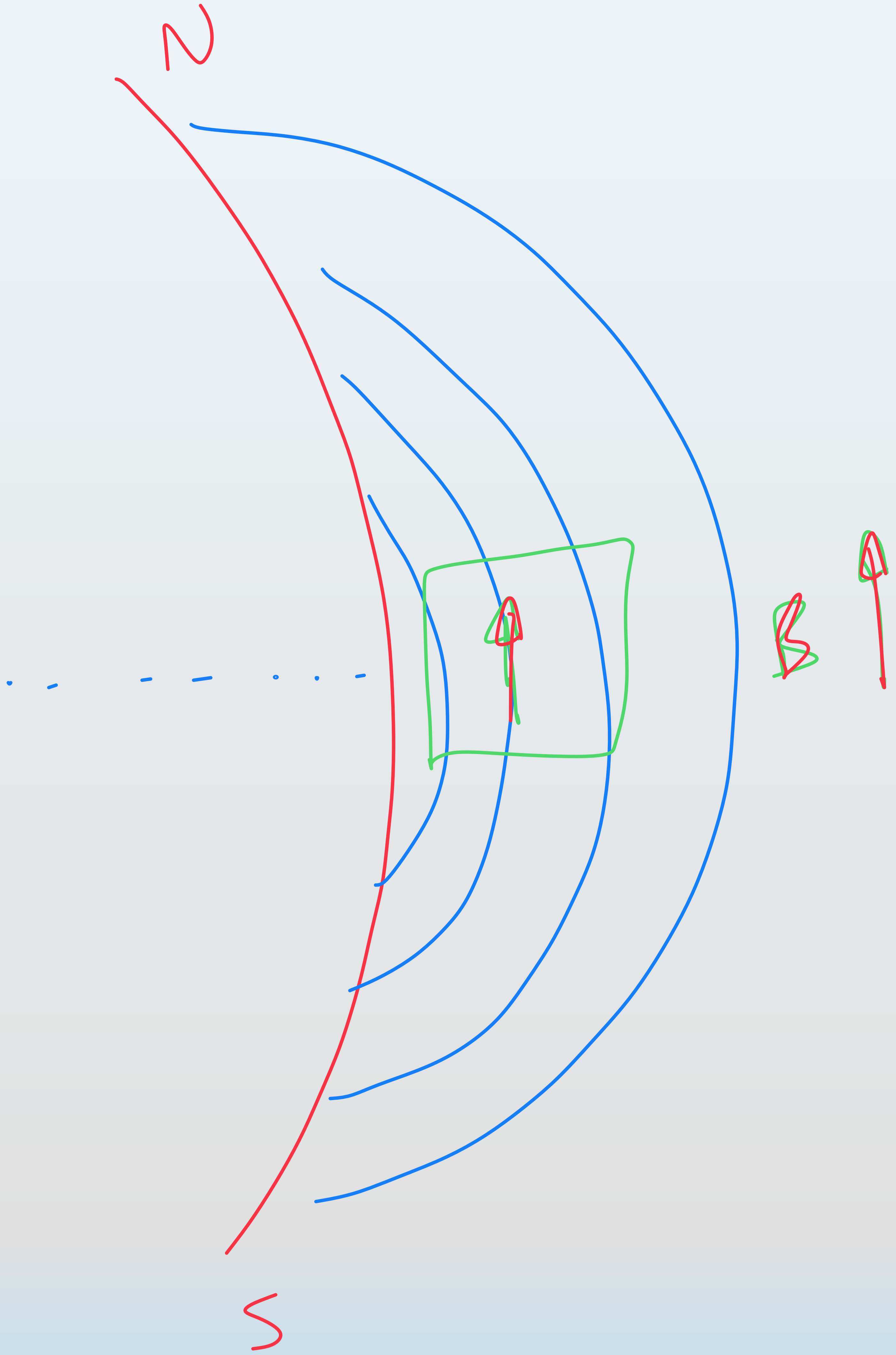
J
E

~ 100 kA

$\Delta B \sim 50$ nT

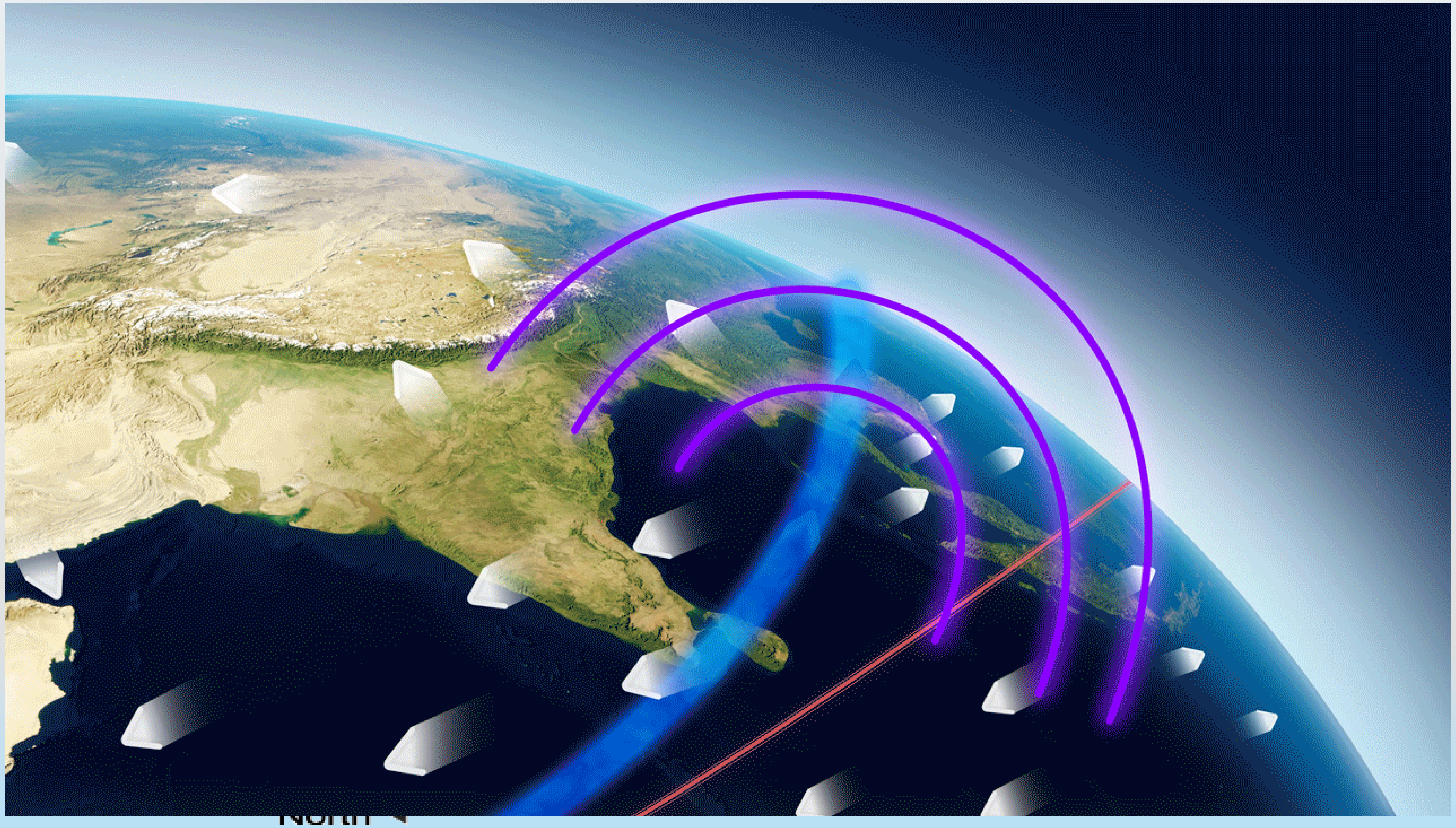
Magnetic field





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"

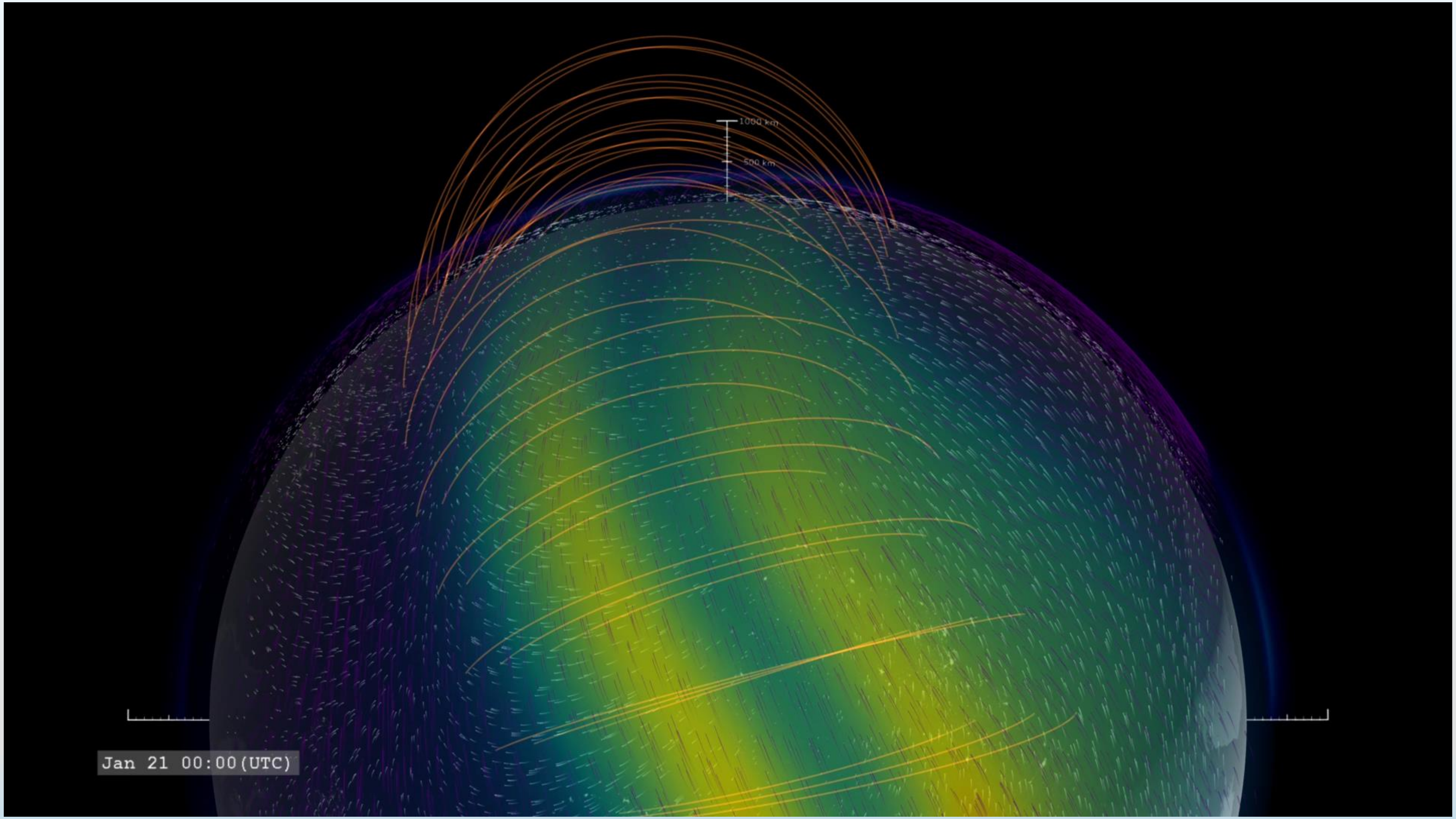


$$\bar{V}_d = \frac{\bar{F} \times \bar{B}}{qB^2}$$

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

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

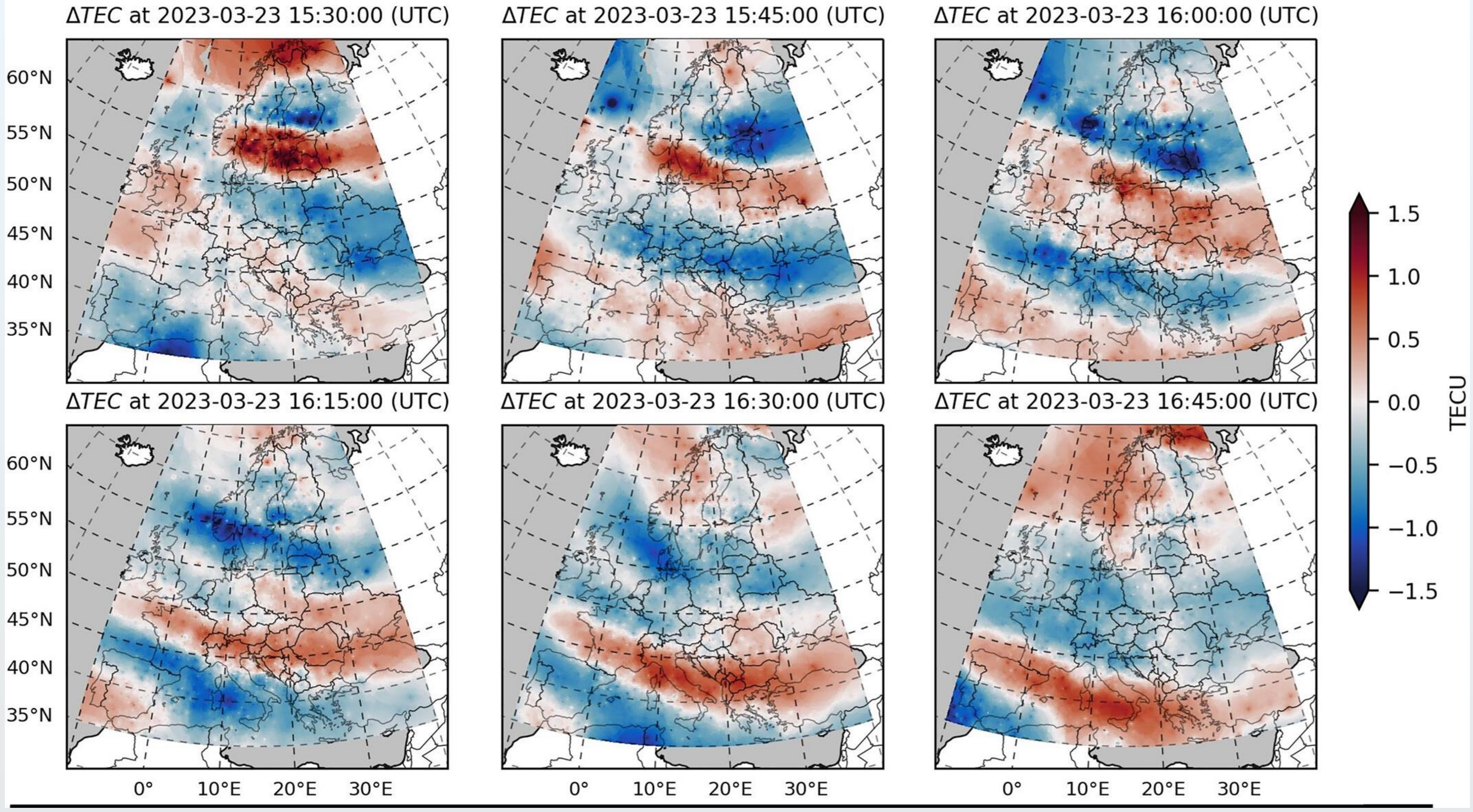
Equatorial Anomaly

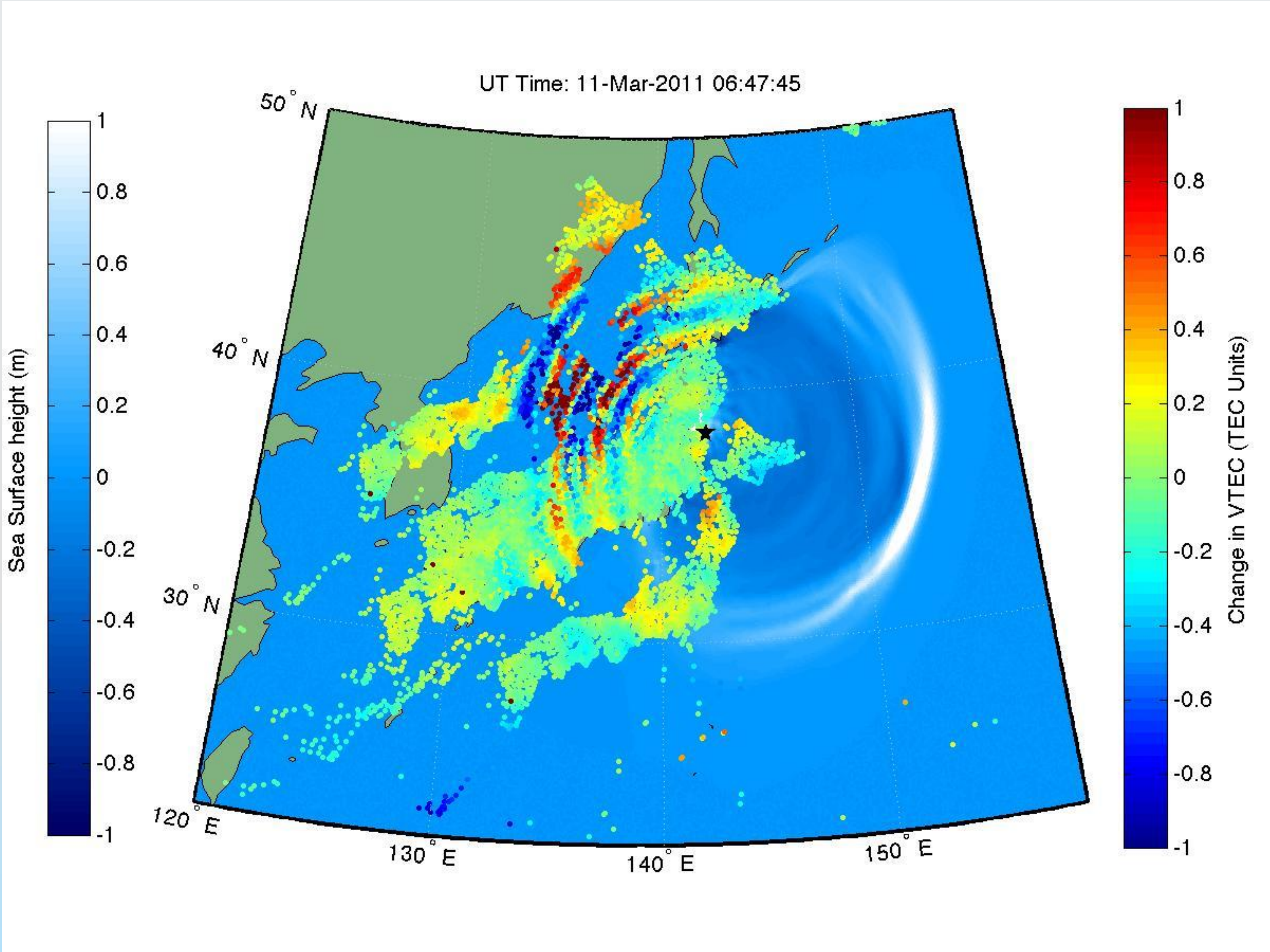


Traveling Ionospheric Disturbances

- Triggered by gravity waves, which propagate from lower altitudes to higher, and **grow in amplitude** as they climb in altitude
- Perturb the ionosphere electron density in the vertical direction
- When they reach the F-region, they create cause the electron density to oscillate up and down
- That oscillation propagates horizontally with a period of tens of minutes, speeds of 0.1 - 1 km/s
- **Large Scale (LSTIDs):** triggered by geomagnetic storms through auroral heating
- **Medium Scale (MSTIDs):** triggered by thunderstorms, volcanic eruptions, earthquake / tsunami, wind shears

From Nykiel et al (2024)





NASA JPL

High-Latitude Current Systems

- Ionospheric current systems connect the ionosphere to the magnetosphere
- Currents in the magnetosphere (cross-tail current, magnetopause current, and ring current) connect to ionosphere
- Region 1 (upward) and Region 2 (downward) currents must close in the ionosphere:

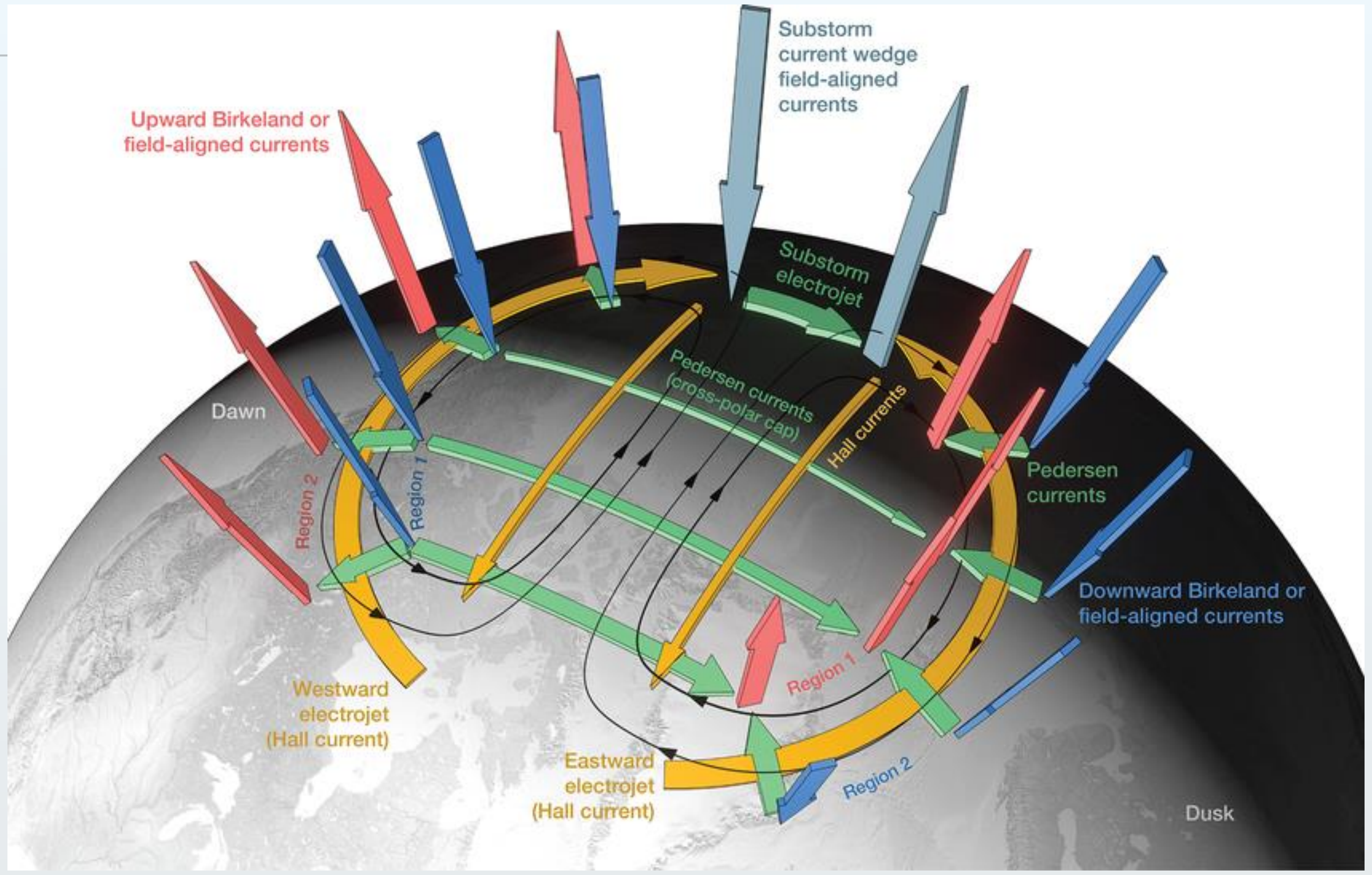
  Pedersen currents (cross B, parallel to E)
  and **Hall currents** (cross B and E)
- **Ionosphere conductivity** play a major role in controlling these current systems

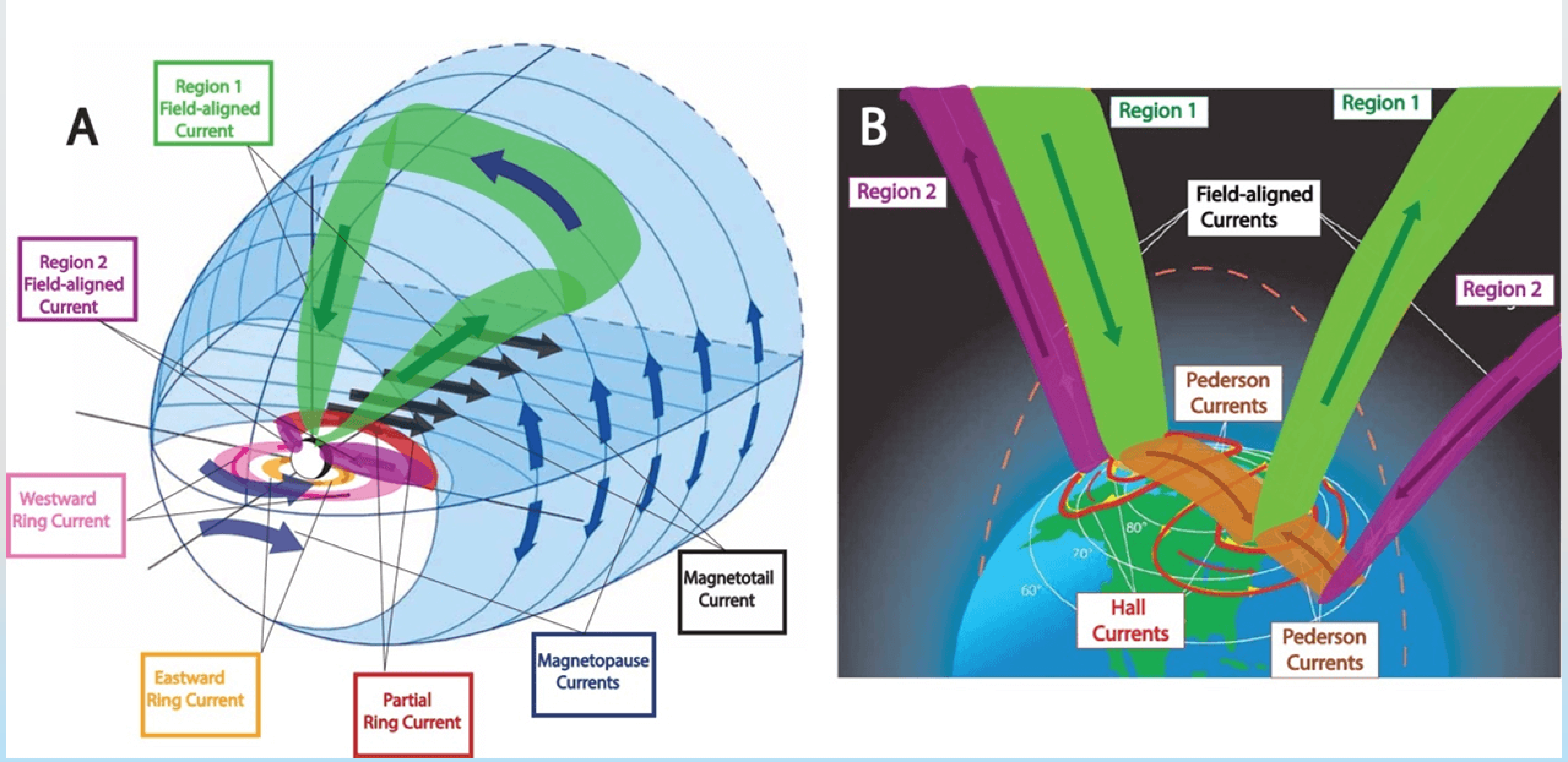
$$\boldsymbol{\sigma} = \begin{pmatrix} \sigma_P & -\sigma_H & 0 \\ \sigma_H & \sigma_P & 0 \\ 0 & 0 & \sigma_0 \end{pmatrix}$$

$$\sigma_0 = \sum_s \frac{n_s e_s^2}{m_s \nu_s}$$

$$\sigma_P = \sum_s \frac{n_s e_s^2}{m_s} \frac{\nu_s}{\nu_s^2 + \Omega_s^2}$$

$$\sigma_H = \sum_s \frac{n_s e_s^2}{m_s} \frac{\Omega_s}{\nu_s^2 + \Omega_s^2}$$



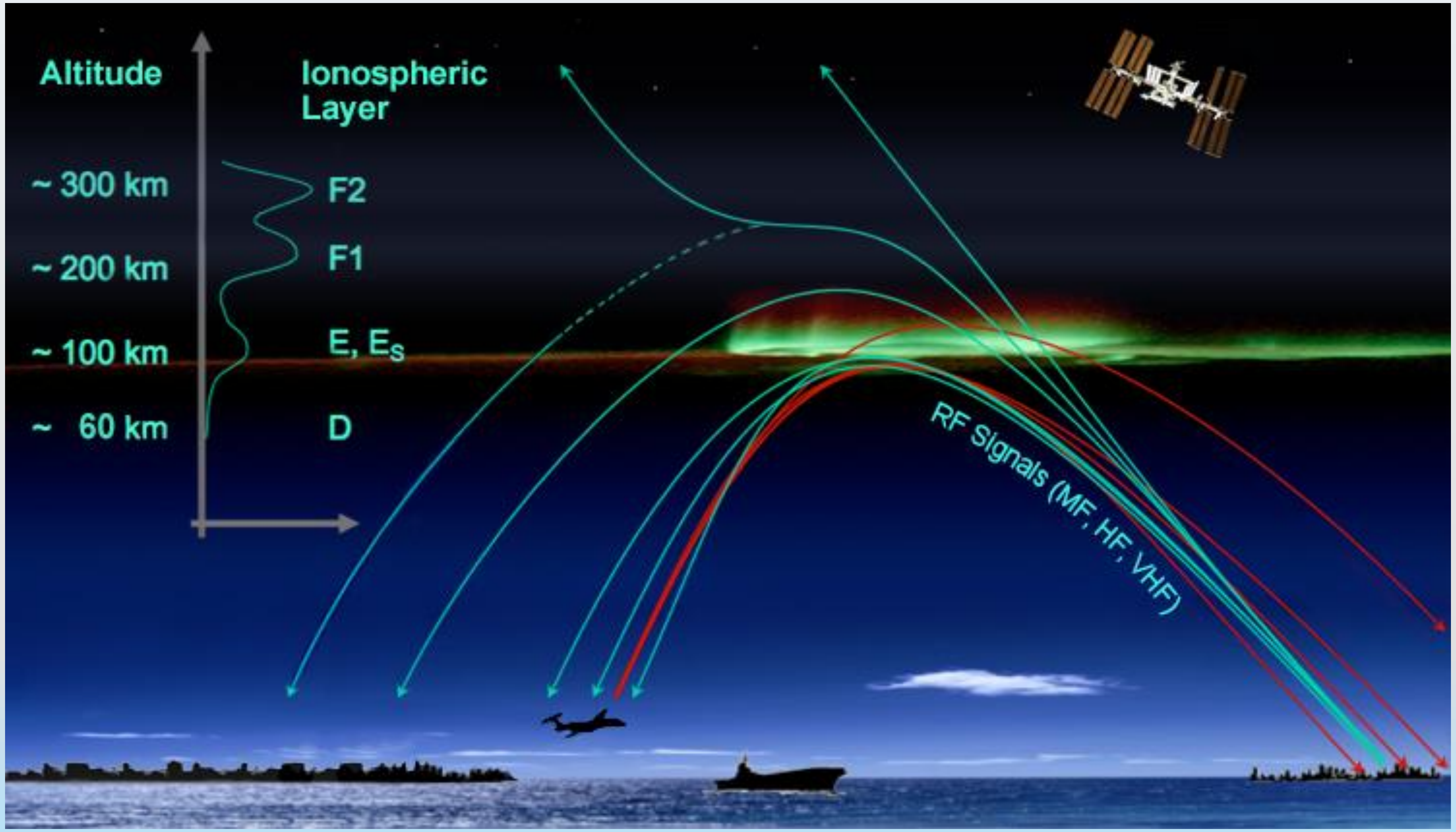


Reflection and Absorption of Radio Waves

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

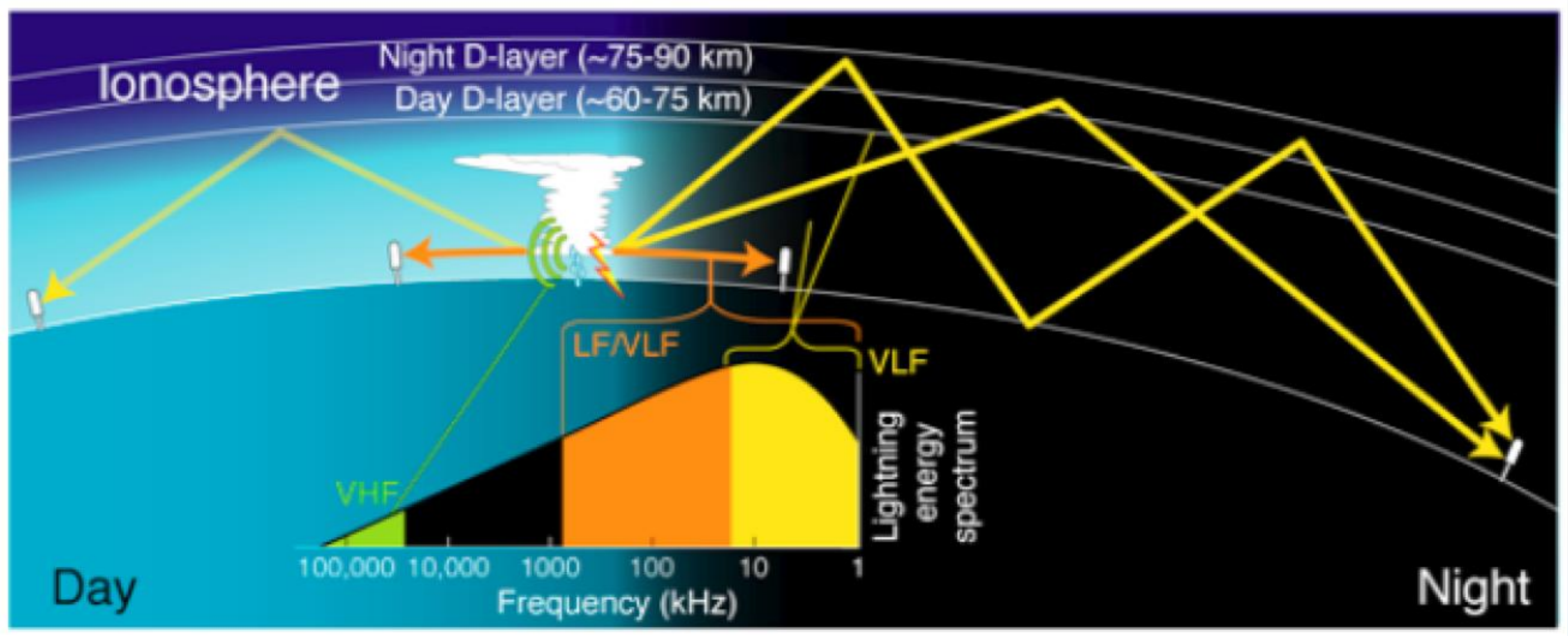
- Plasma frequency ω_p directly related to electron density
- Radio waves above ω_p pass through the ionosphere; electrons cannot respond fast enough
- Radio waves below ω_p are reflected; electrons are “shaken” and re-radiate

- **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

- **The critical frequency is the maximum plasma frequency in the ionosphere. That obviously depends on the state of 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



Index of refraction in a cold plasma

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

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

θ: angle between $\bar{B}_0$ and $\bar{k}$

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

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

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

$n = \alpha + j\beta$

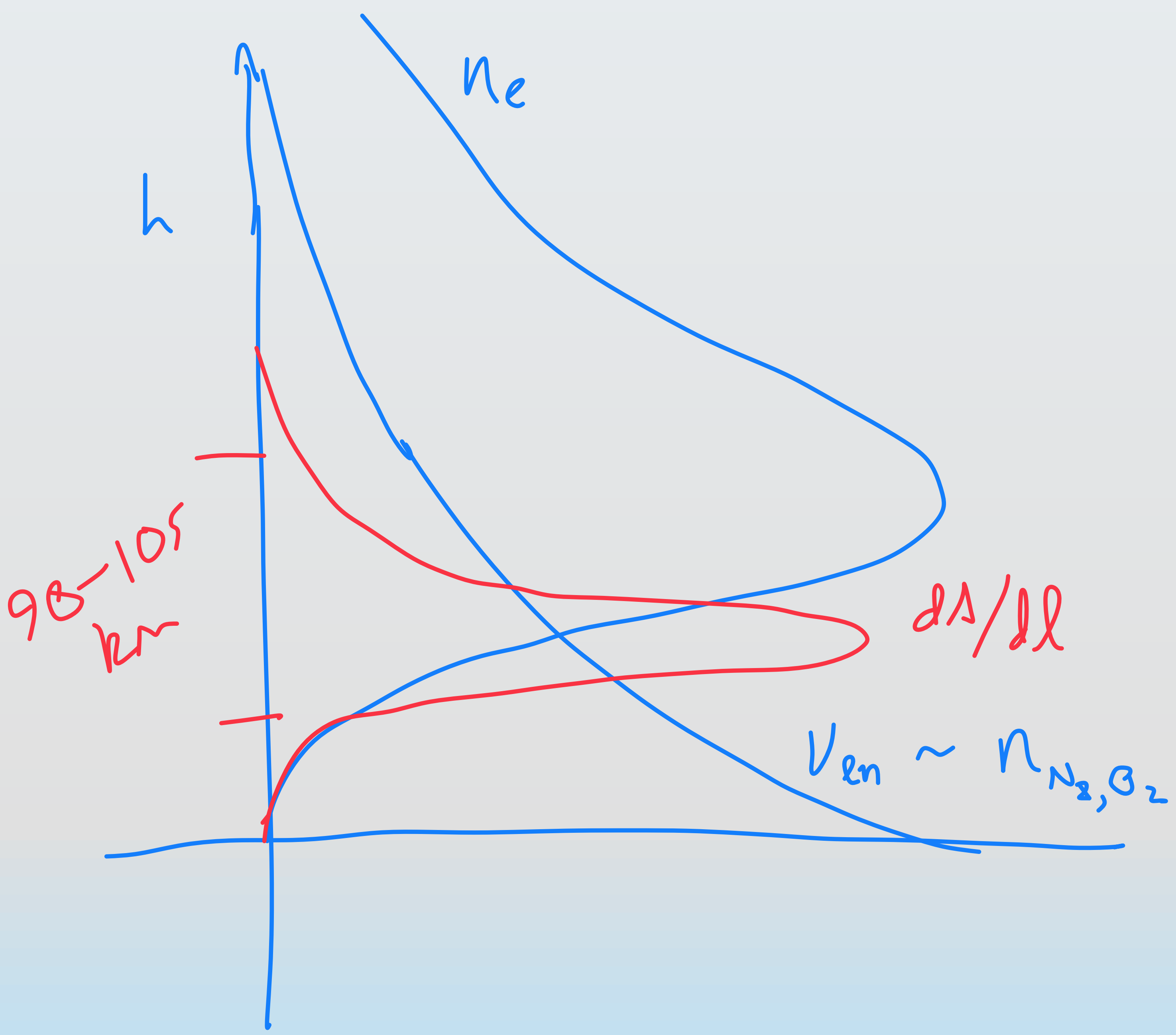
D-region absorption

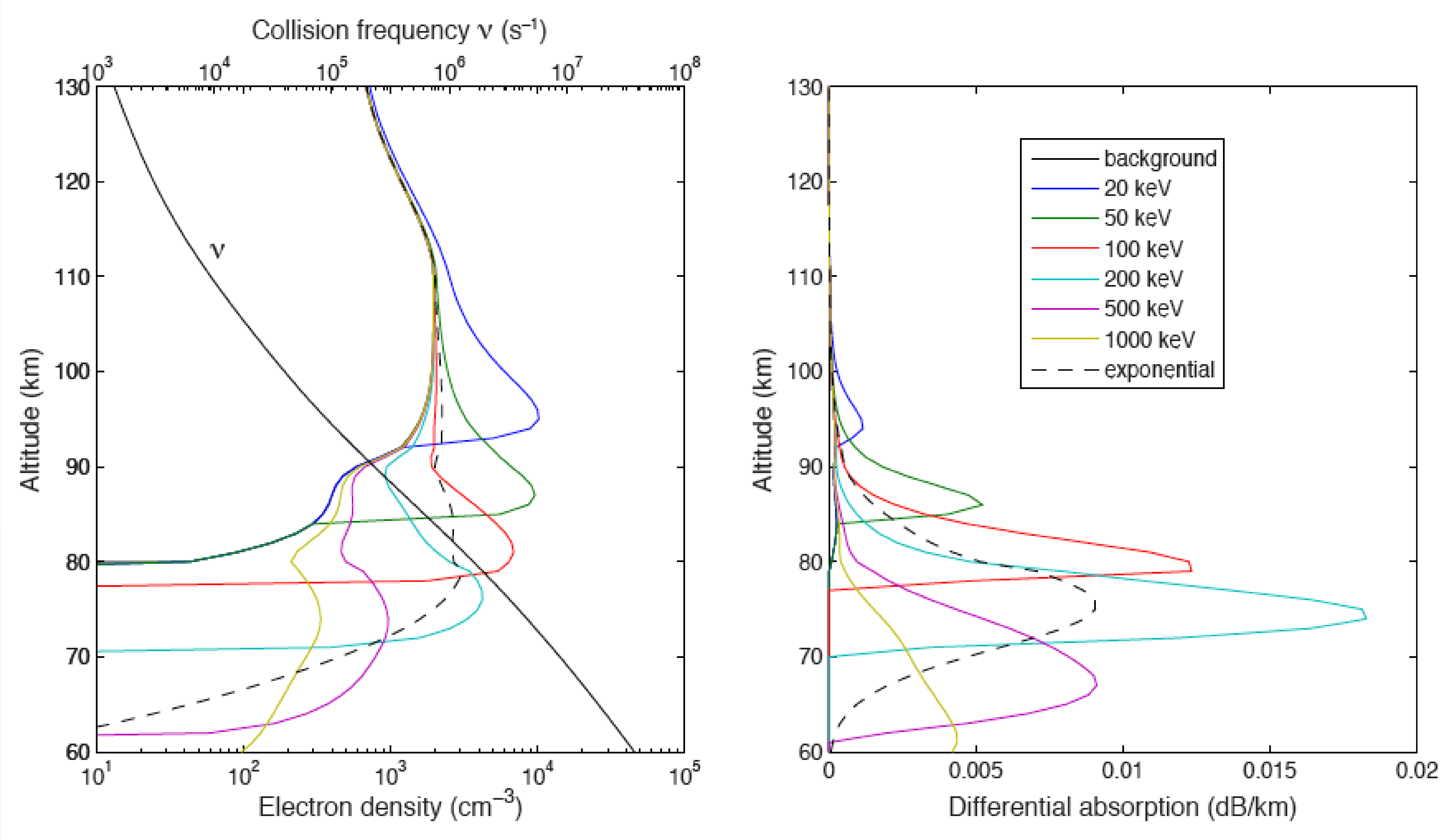
- As electrons get excited by waves with f < fc, the collide with neutrals
- Some of the EM wave energy gets transferred to heat; radio waves suffers absorption
- How much absorption?

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

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

$\downarrow f_c \sim 1\text{–}2$ 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**?

$$\nu_{\text{av}}(e, \text{N}_2) = 2.33 \times 10^{-17} N_{\text{N}_2} (1 - 1.21 \times 10^{-4}\, T_e)\, T_e$$

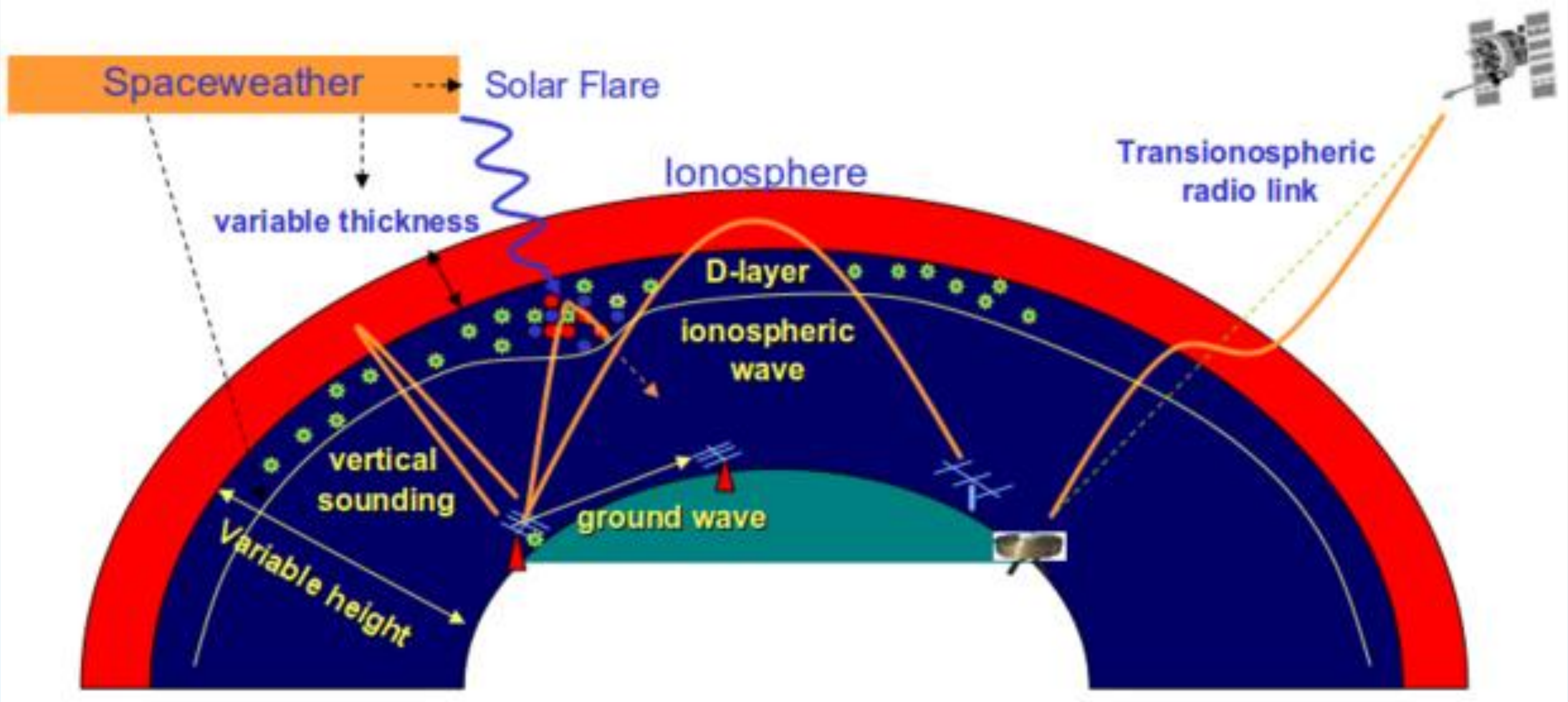
$$\nu_{\text{av}}(e, \text{O}_2) = 1.82 \times 10^{-16} N_{\text{O}_2} (1 + 0.036\, T_e^{1/2})\, T_e^{1/2}$$

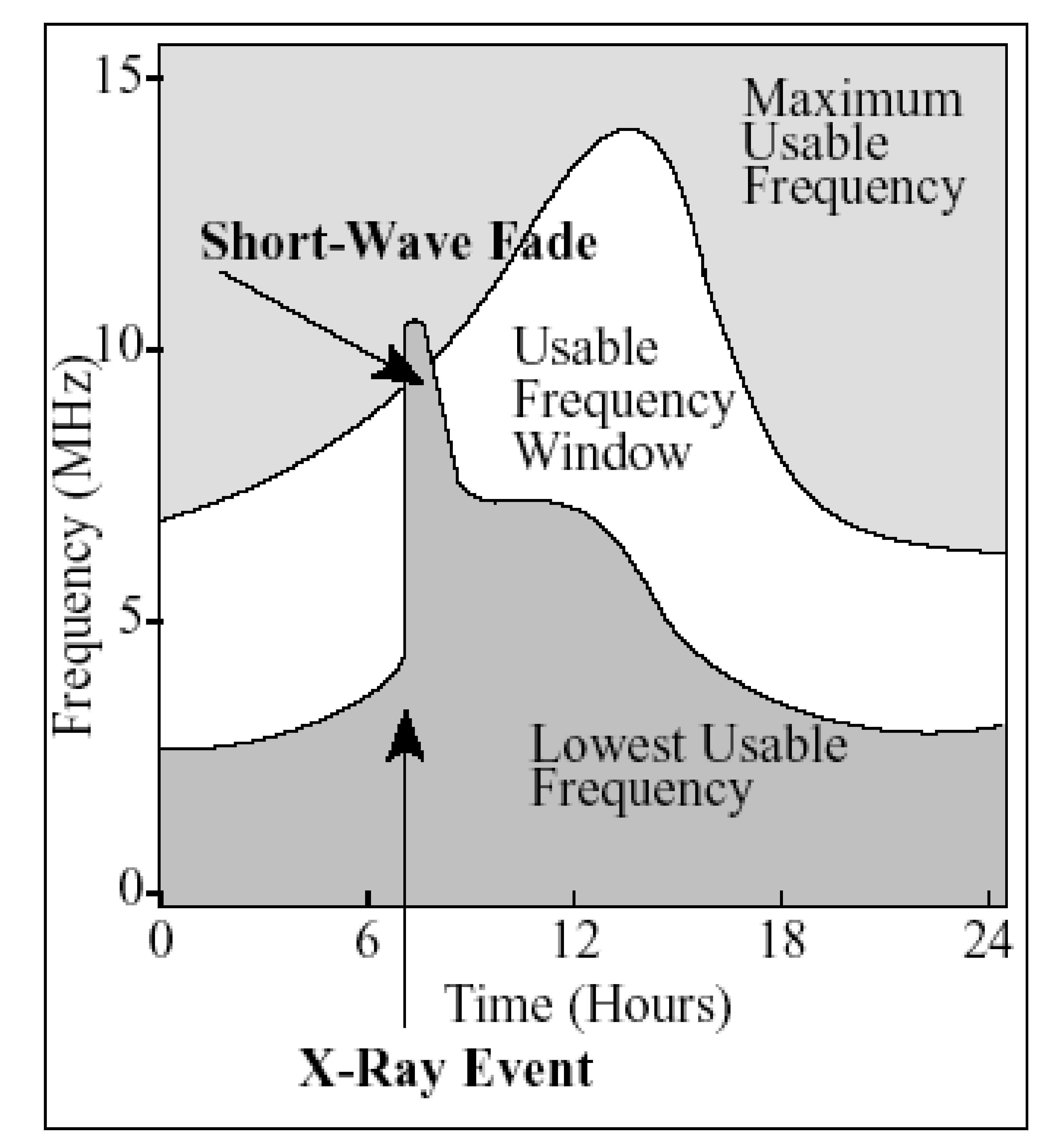
$$\nu_{\text{en}} = \nu_{\text{av}}(e, \text{N}_2) + \nu_{\text{av}}(e, \text{O}_2)$$

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**: when the LUF, set by absorption, rises to exceed the MUF, determined by peak F-region density, communication is blocked!



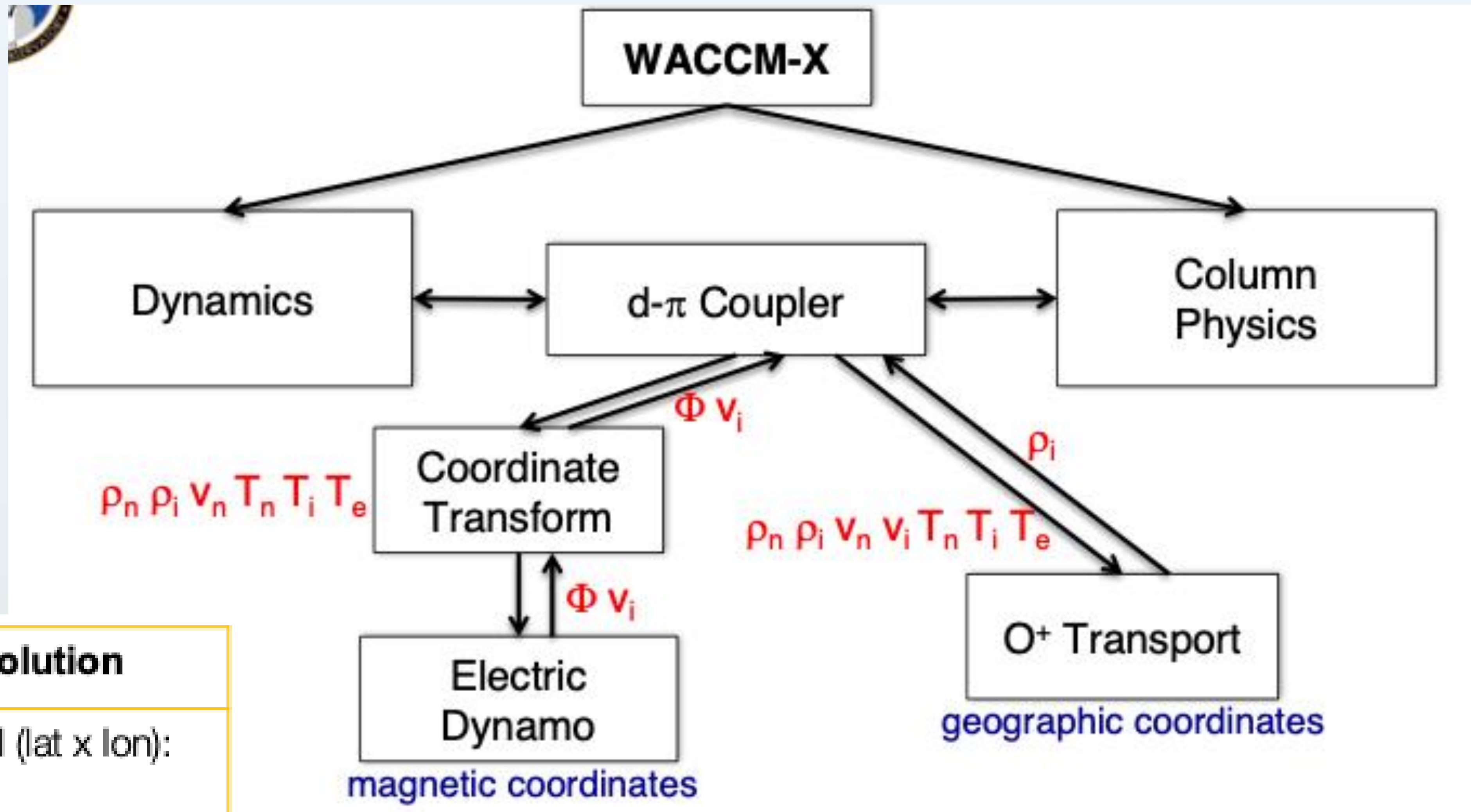


Modeling the M-I-T system

- https://cgs.jhuapl.edu/MAGE/

Modeling the I-T system: WACCM-X

- Developed by NCAR HAO over many years!
- Regular improvements, updates, new physics, etc.
- WACCM-X extends WACCM from ~150 km to 600 km altitude

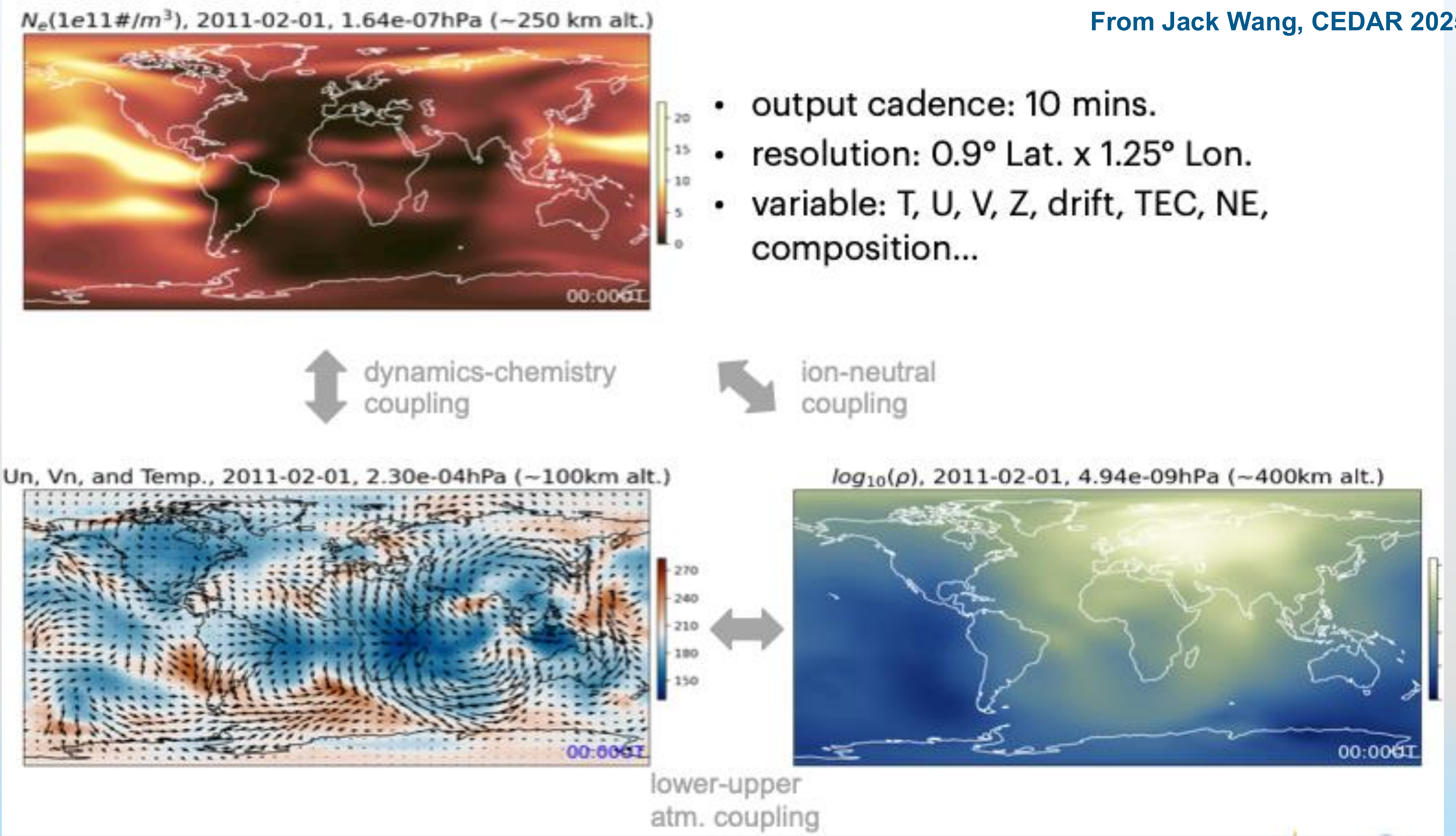


From Pedatella et al, CEDAR 2025

Model Framework	Chemistry	Neutral Atm. Physics	Ionosphere Physics	Resolution
Atmosphere component of NCAR CESM Extension of the NCAR Community Atmosphere Model (CAM) Finite Volume Dynamical Core (modified to consider species dependent Cp, R, m)	MA/Ion Chemistry (~100 species) Fully-interactive with dynamics	Long wave/short wave/EUV RRTMG IR cooling (LTE/non-LTE) Modal Aerosol Model (MAM) CARMA Convection, precip., and cloud parameterization (CLUBB) Parameterized GW Major/minor species diffusion (+UBC) Horizontal/Vertical molecular viscosity and thermal conductivity (+UBC) Species dependent Cp, R, and m	Parameterized electric field at high latitudes. IGRF geomagnetic field Auroral processes, ion drag and Joule heating Ion/electron energy equations Ambipolar diffusion Ionospheric dynamo Coupling with plasmasphere/magnetosphere	Horizontal (lat x lon): 1.9 x 2.5 0.9 x 1.25 0.47 x 0.625 Vertical: 130, 145 levels (0 - ~600 km)

Coupling ionosphere and thermosphere processes

From Jack Wang, CEDAR 2025 tutorial



Summary

- **Thermosphere**
  - Tenuous atmosphere above ~100 km; heated by solar EUV absorption
  - Primarily atomic oxygen, He / H at higher altitudes
  - Highly variable with geomagnetic activity and other forcing
- **Ionosphere**
  - Generated through ionization by solar EUV; balanced by chemistry and transport
  - Also highly variable based on solar EUV and X-ray fluxes
- **I-T (and M-I-T) Coupling**
  - Earth’s magnetic field plays a big role! But so do collisions in the atmosphere
  - Lead to complex effects that create significant I-T perturbations, making state prediction very difficult; global modeling necessary!