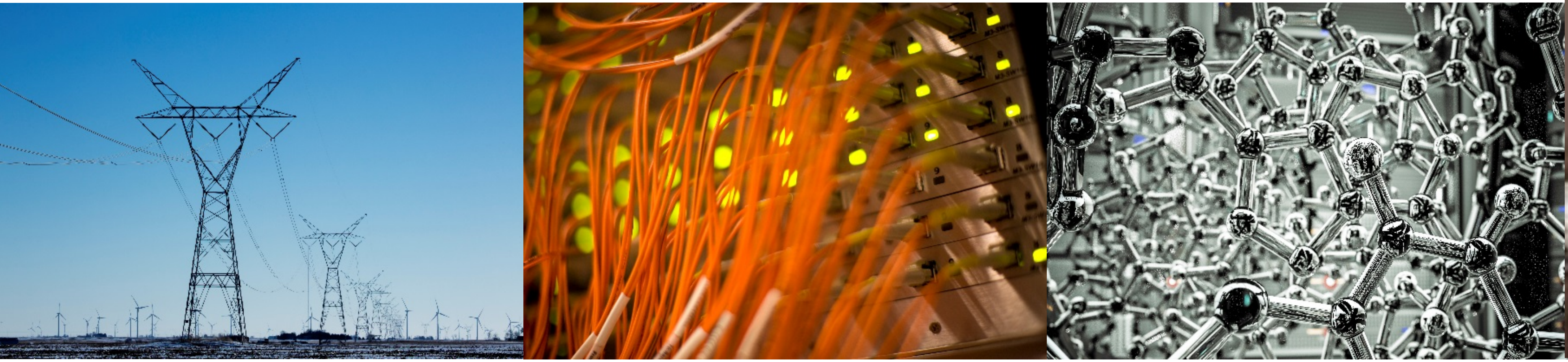
VGEM Student Day Tutorial: Magnetosphere-Ionosphere-Thermosphere Coupling

Mei-Yun Lin



ILLINOIS
Electrical & Computer Engineering
COLLEGE OF ENGINEERING

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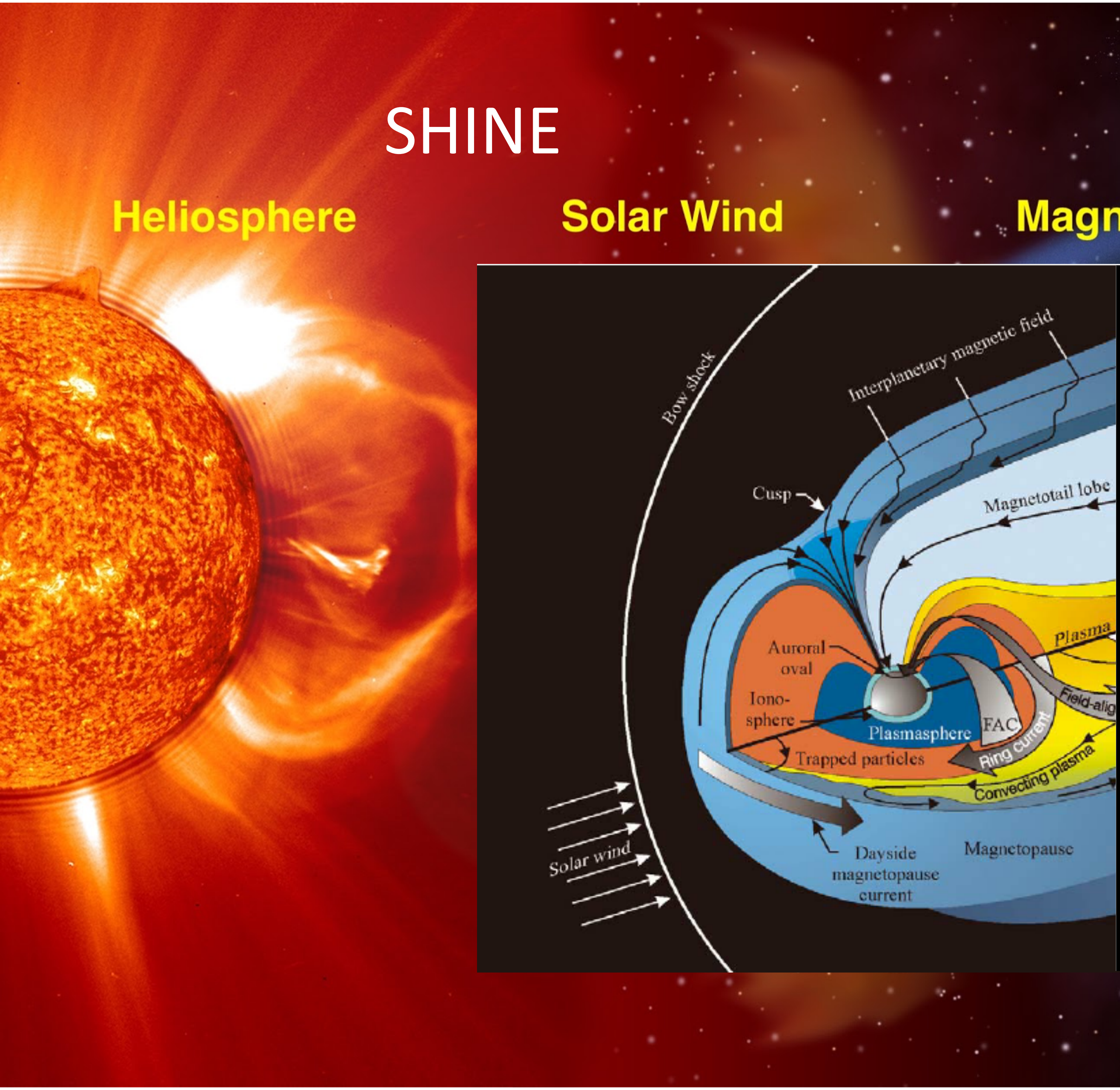
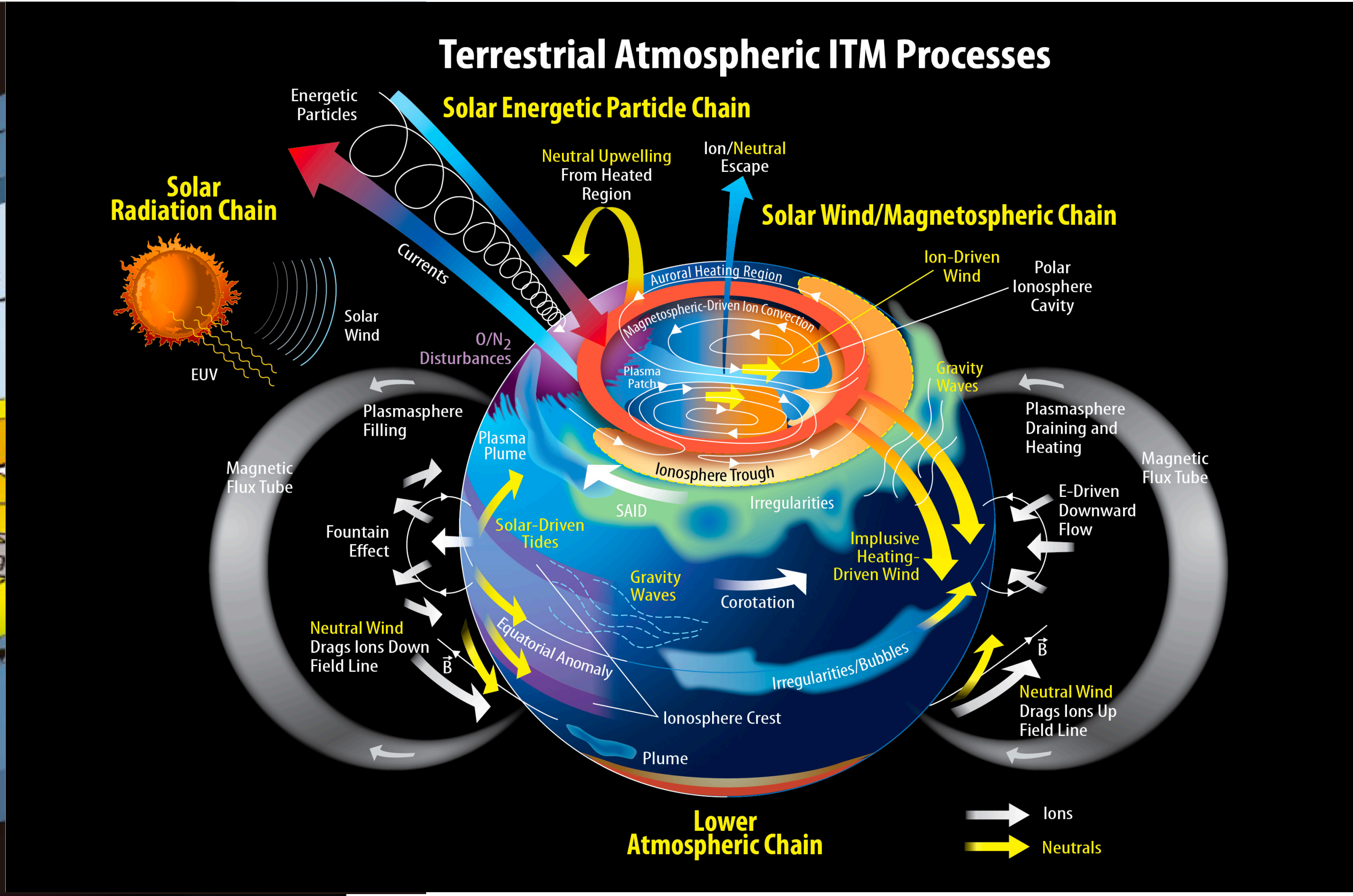
R. Ilie, M.-F. Bashir, J. Liu
Remote Sensing and Space Science group in the Department of Electrical and Computer Engineering, University of Illinois, Urbana-Champaign

SHINE

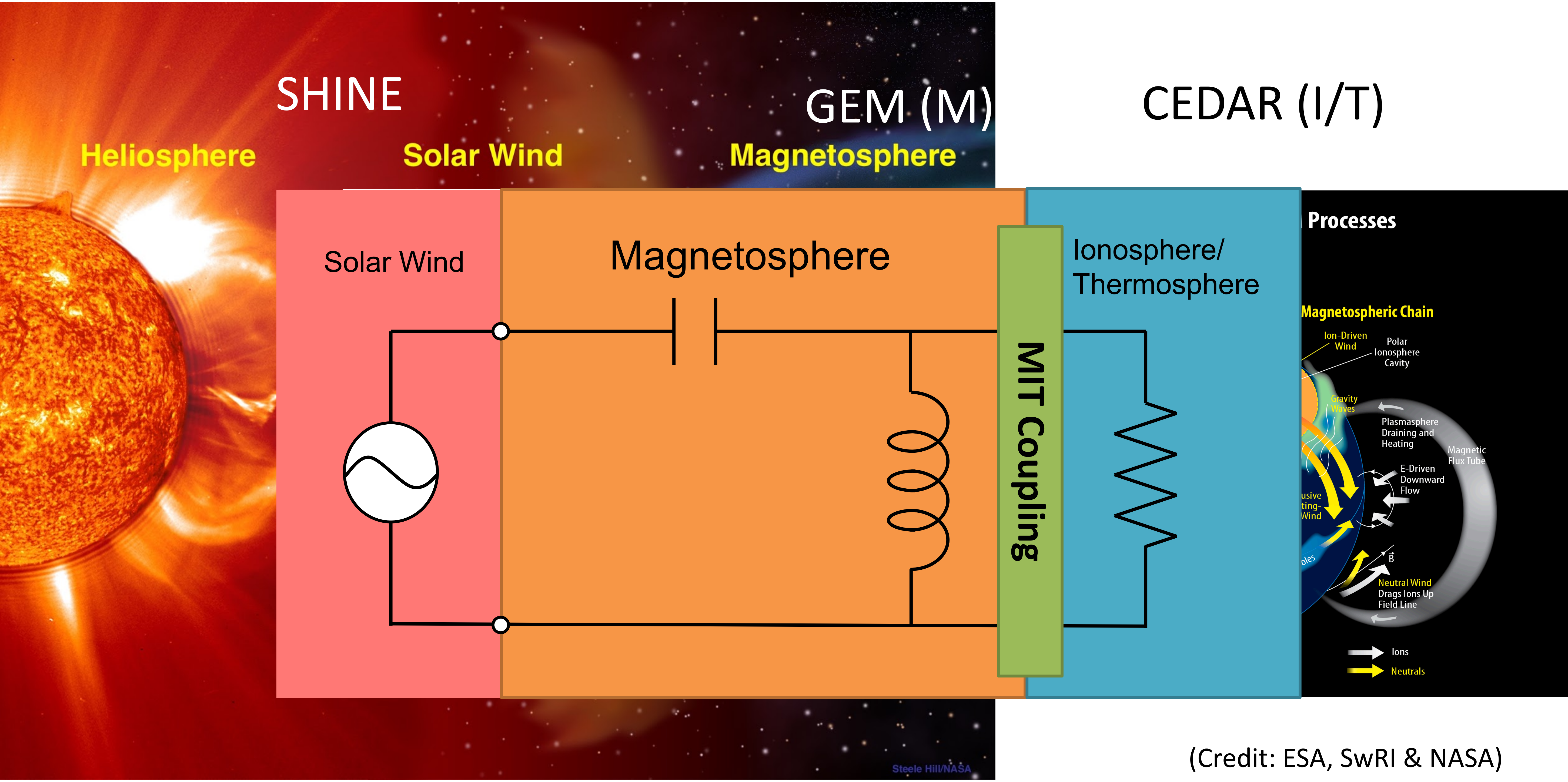
GEM (M)

CEDAR (I/T)





(Credit: ESA, SwRI & NASA)



SHINE

GEM (M)

CEDAR (I/T)

Heliosphere

Solar Wind

Magnetosphere

Solar Wind

Magnetosphere

MIT Coupling

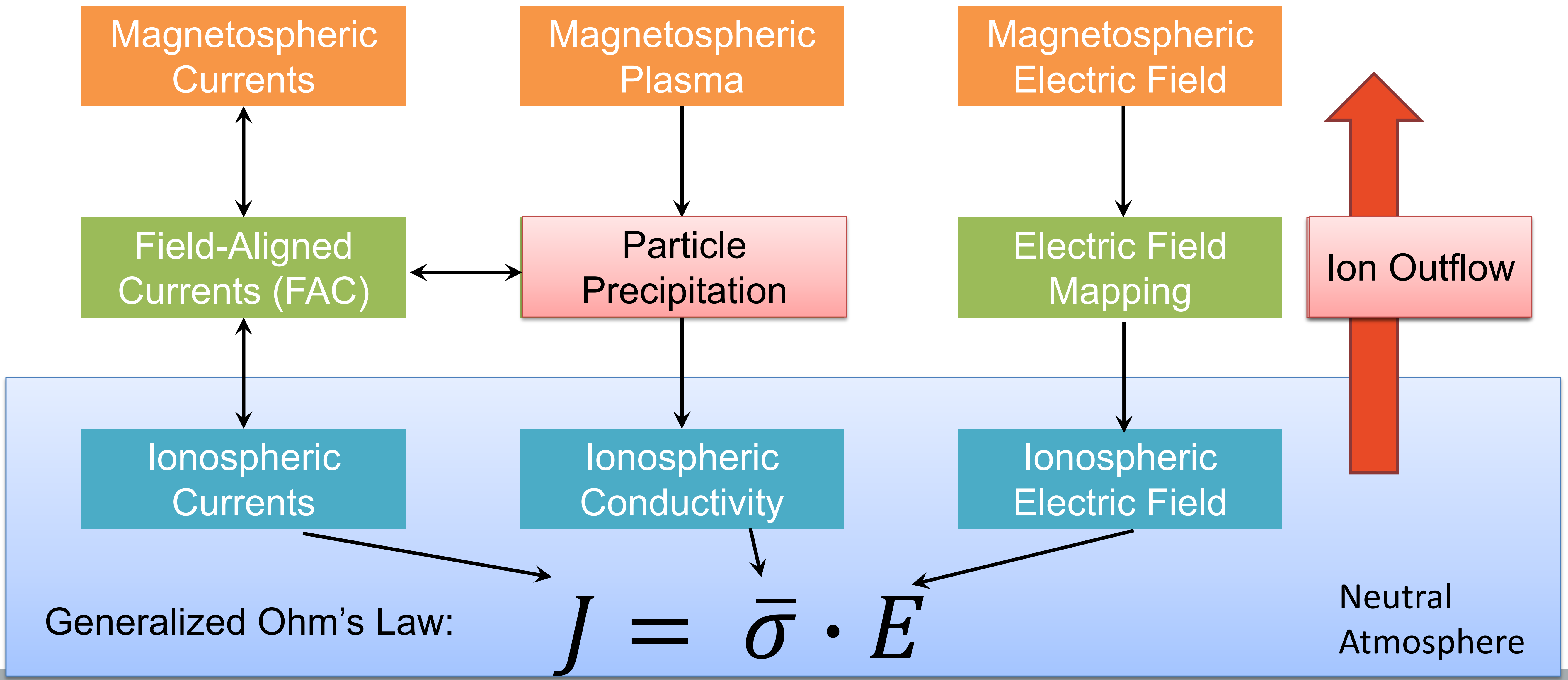
Ionosphere/ Thermosphere

(Credit: ESA, SwRI & NASA)

Magnetosphere-Ionosphere Coupling

🟥 Particle

🟩 Current



Magnetospheric Currents

Magnetospheric Plasma

Magnetospheric Electric Field

Field-Aligned Currents (FAC)

Particle Precipitation

Electric Field Mapping

Ion Outflow

Ionospheric Currents

Ionospheric Conductivity

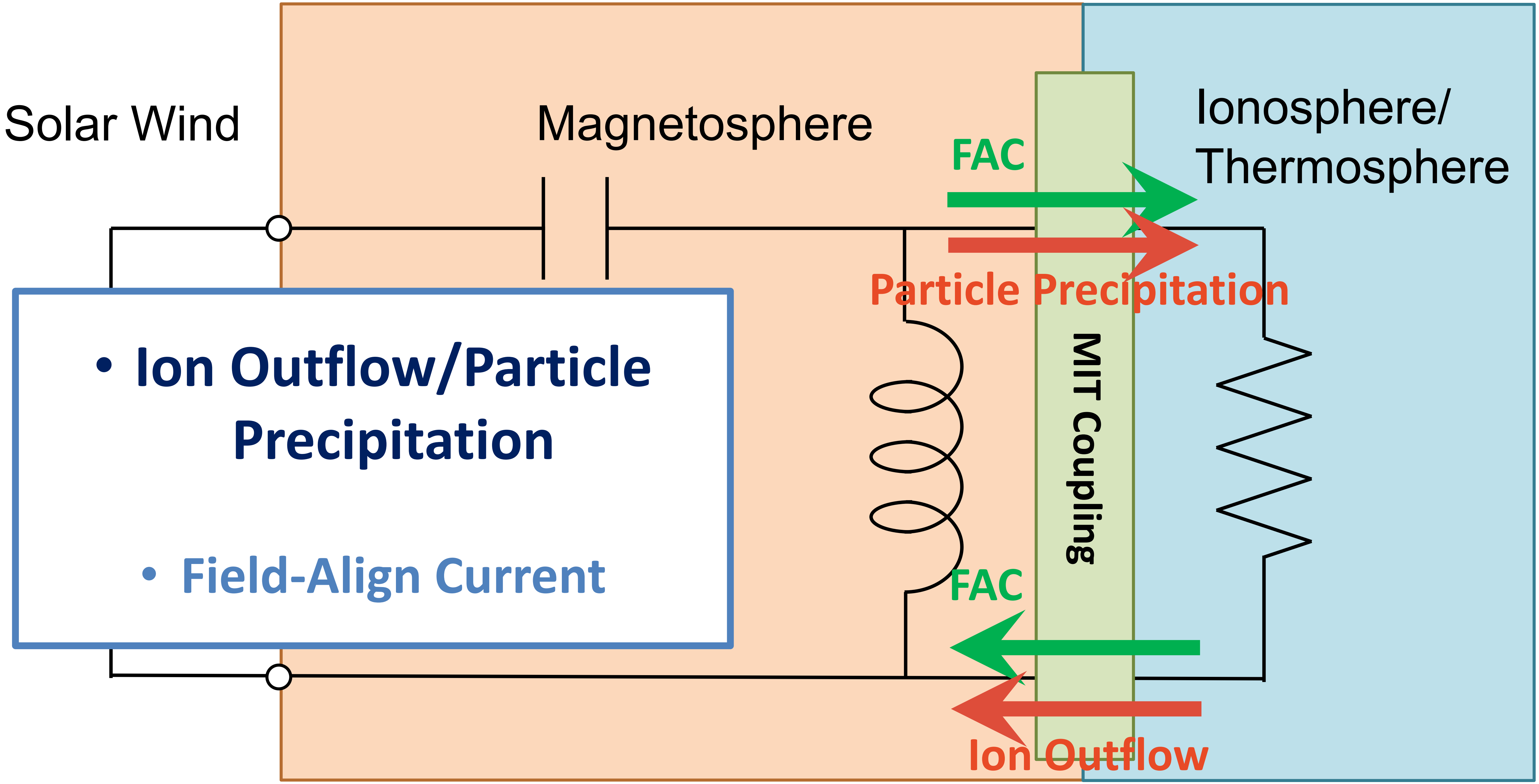
Ionospheric Electric Field

Generalized Ohm's Law:

$$J = \bar{\sigma} \cdot E$$

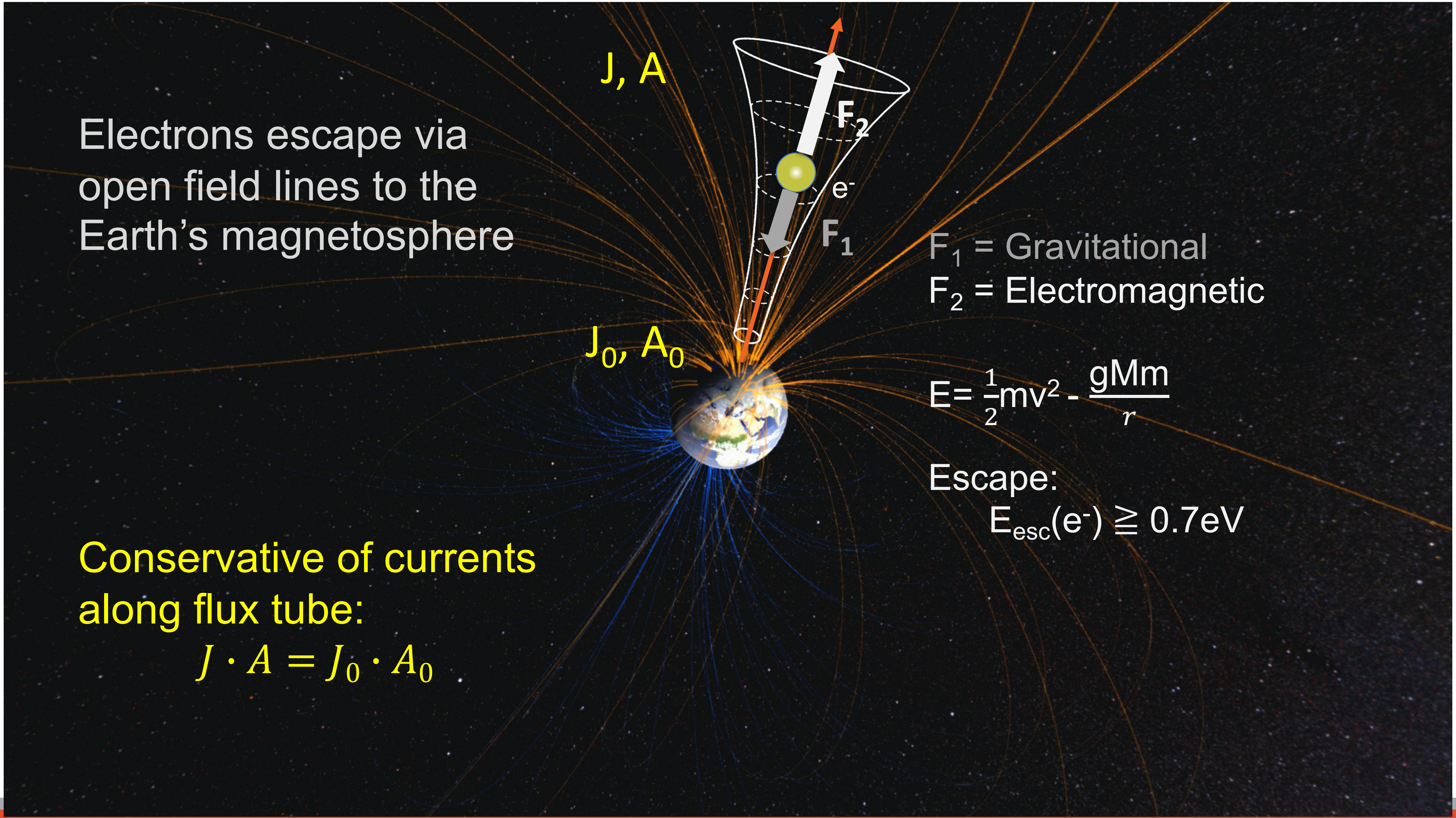
Neutral Atmosphere

(Credit: Baumjohann, 1983)



- **Ion Outflow/Particle Precipitation**
  - **Field-Align Current**

Electrons escape via open field lines to the Earth’s magnetosphere



F_1 = Gravitational
F_2 = Electromagnetic

$$E = \frac{1}{2}mv^2 - \frac{gMm}{r}$$

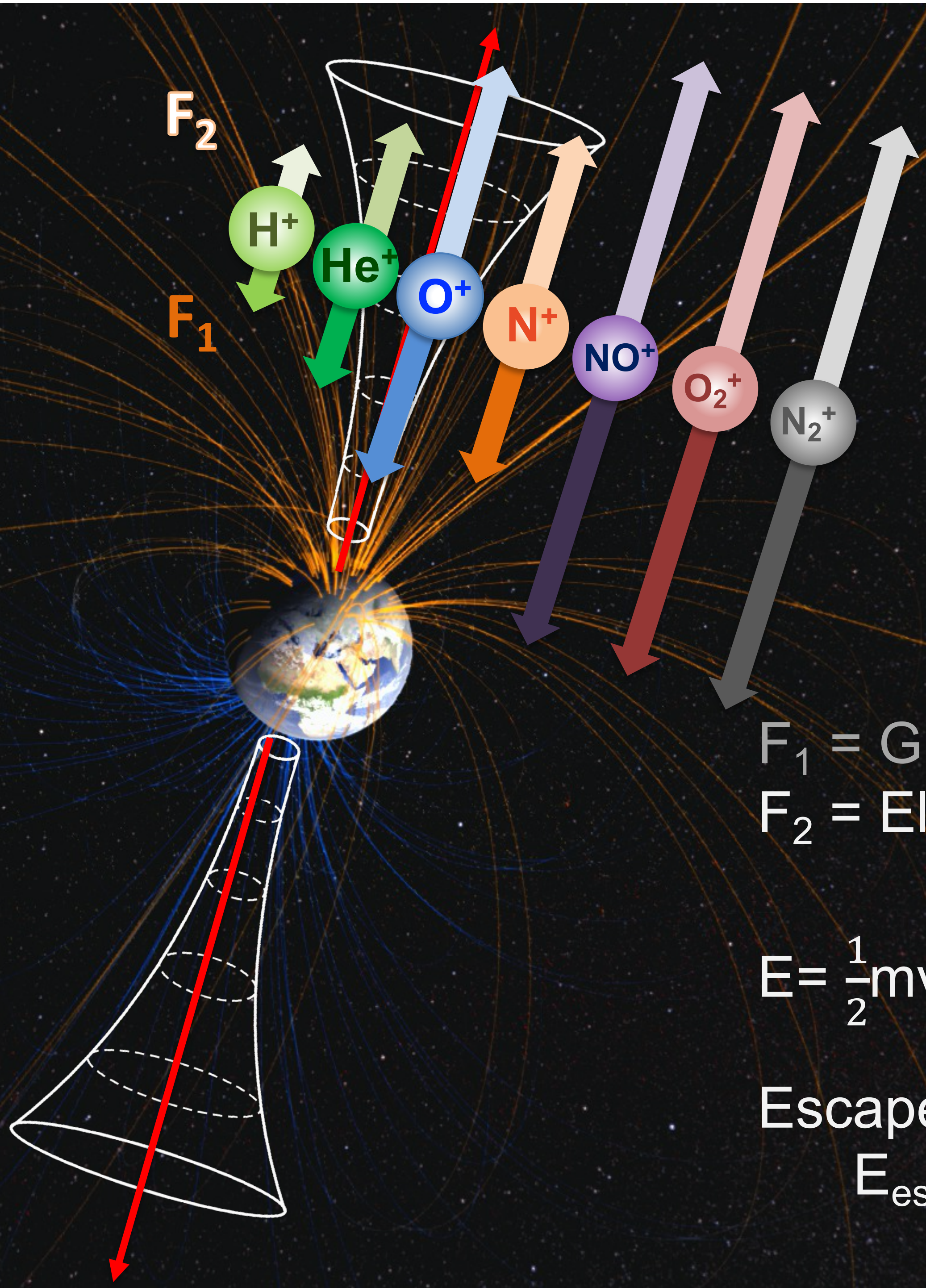
Escape:

$$E_{esc}(e^-) \geqq 0.7\text{eV}$$

Conservative of currents along flux tube:

$$J \cdot A = J_0 \cdot A_0$$

Ions escape via open field lines to the Earth's magnetosphere



F_1 = Gravitational
F_2 = Electromagnetic

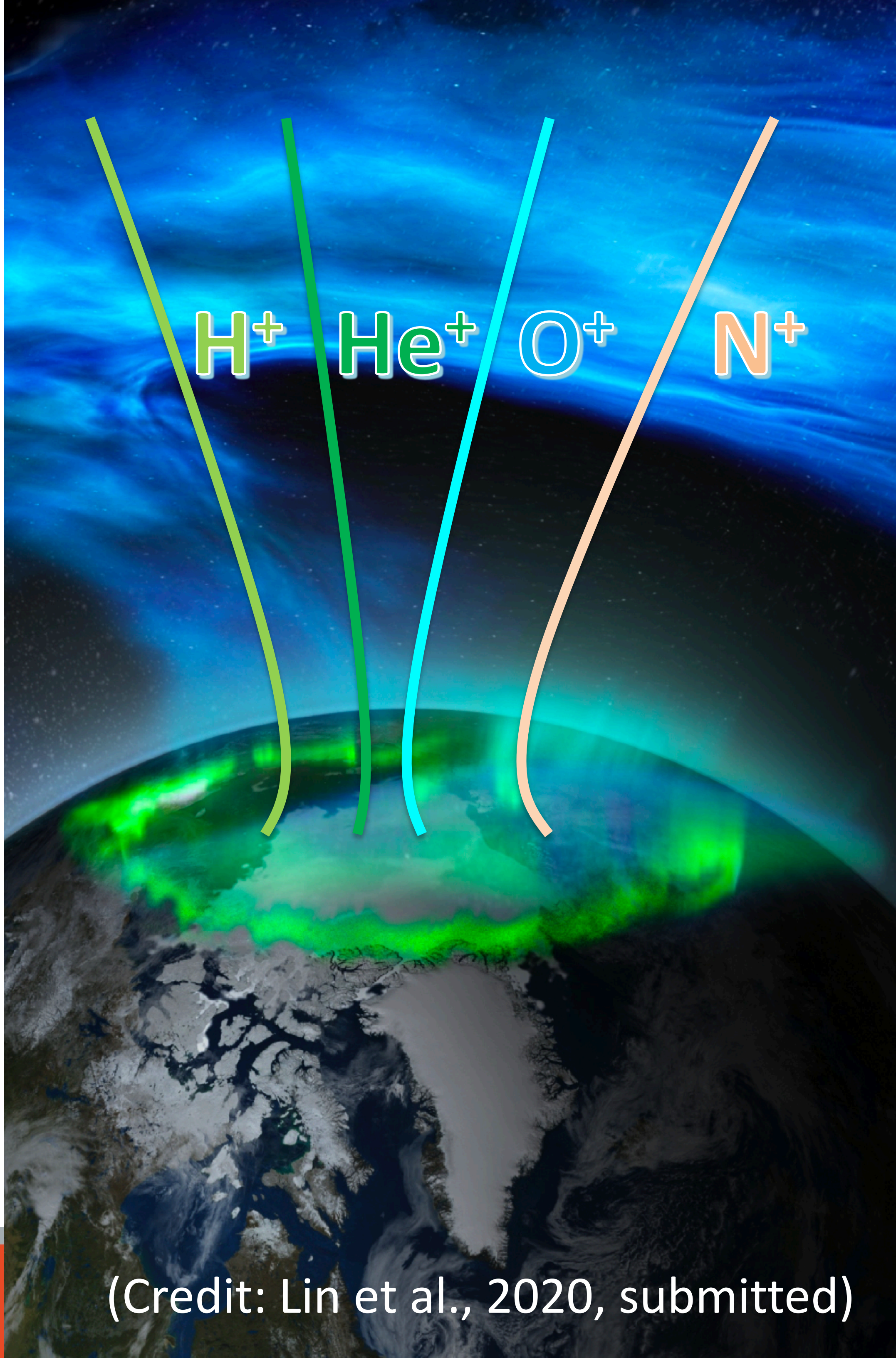
$$E = \frac{1}{2}mv^2 - \frac{gMm}{r}$$

Escape:
$E_{esc}(\text{Ions}) \geqq 10\text{eV}$

Polar wind is first suggested by Axford (1968) as an analogy to the solar wind.

The discovery (Shelley et al., 1972) of O^+ opens the discussion of cold plasma.

N+ were discovered in the Earth’s magnetosphere (Chappell et al., 1982)



(Credit: Lin et al., 2020, submitted)

Polar Wind Transport Equation

- Start with Boltzmann's equations,

$$\frac{\partial f_s}{\partial t} + \mathbf{v_s} \cdot \nabla f_s + \left[\mathbf{G} + \frac{e_s}{m_s}(\mathbf{E} + \mathbf{v} \times \mathbf{B})\right] \cdot \nabla_v f_s = \frac{\delta f_s}{\delta t}$$

$$\frac{\partial f_s}{\partial t} + \nabla \cdot (f_s \mathbf{v_s}) + \nabla_v \cdot (f_s \mathbf{a_s}) = \frac{\delta f_s}{\delta t}$$

$\frac{\delta f_s}{\delta t}$ { ≠ 0 @ low alt.; = 0 @ high alt.;

$$\mathbf{a_s} = \mathbf{G} + \frac{e_s}{m_s}(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

- f_s(**r**, **v**, t): velocity distribution function
- **r**, **v**, t: independent variables in the phase space

- Polar wind behaves as a hot fluid ⟹ Continuity Equation

$$\frac{\partial \rho_s}{\partial t} + \nabla \cdot (\rho_s \mathbf{u_s}) = P - L$$

$$\boxed{\frac{dp_e}{ds} = -e n_e E_\parallel = -e n_e(\mathbf{E} + \mathbf{u_e} \times \mathbf{B})}$$

$$\cancel{\rho_e u_e \frac{du_e}{ds}} + \frac{dp_e}{ds} - \cancel{\rho_e g_\parallel} + e n_e E_\parallel = \cancel{\Sigma \rho_e \nu_{et}(u_t - u_e)}$$

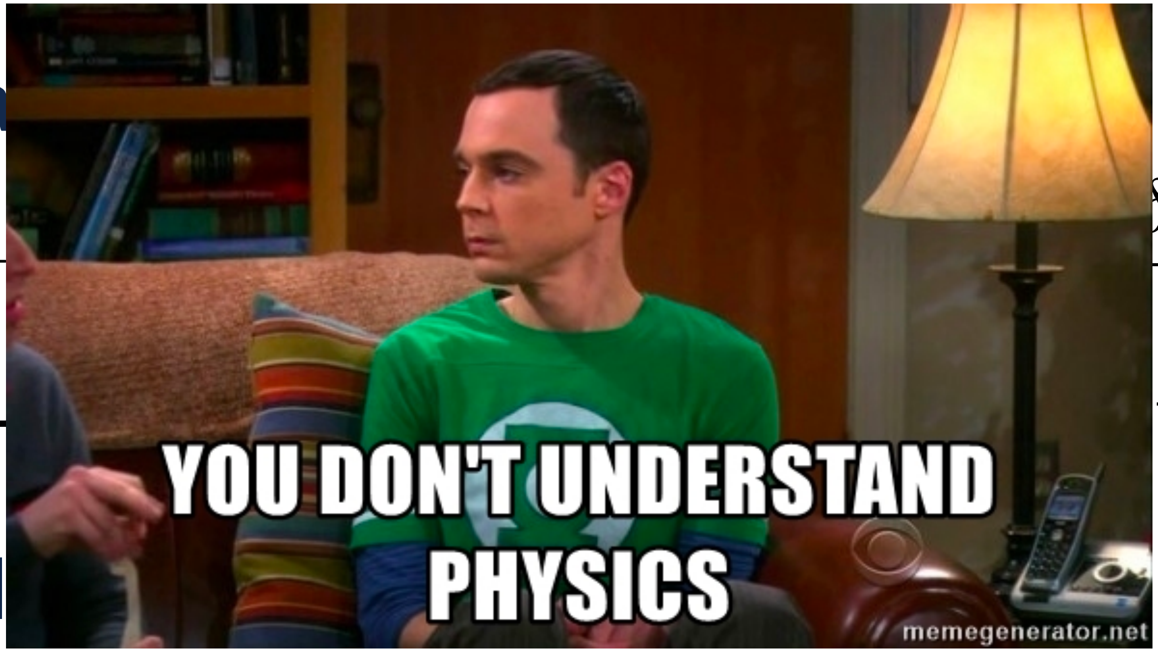
Ambipolar Electric Field explains transport of e⁻

Polar Wind Transport Equation

- Sta

$$\frac{\partial f_s}{\partial t} + \quad \frac{\delta f_s}{\delta t} = \frac{\delta f_s}{\delta t}$$

$$\frac{\delta f_s}{\delta t} \quad \mathbf{v} \times \mathbf{B})$$



- f_s(**r**, **v**, t): velocity distribution function
- **r**, **v**, t: independent variables in the phase space

- Pol $\Longrightarrow$ Continuity Equation

$$\frac{\partial}{\partial t}([\chi Density]) + \nabla\cdot([\chi Flux]) = S$$

$$\frac{\partial \rho_s}{\partial t} + \nabla\cdot(\rho_s \mathbf{u_s}) = S$$

χ is the conserved quantity

Transport agent of χ

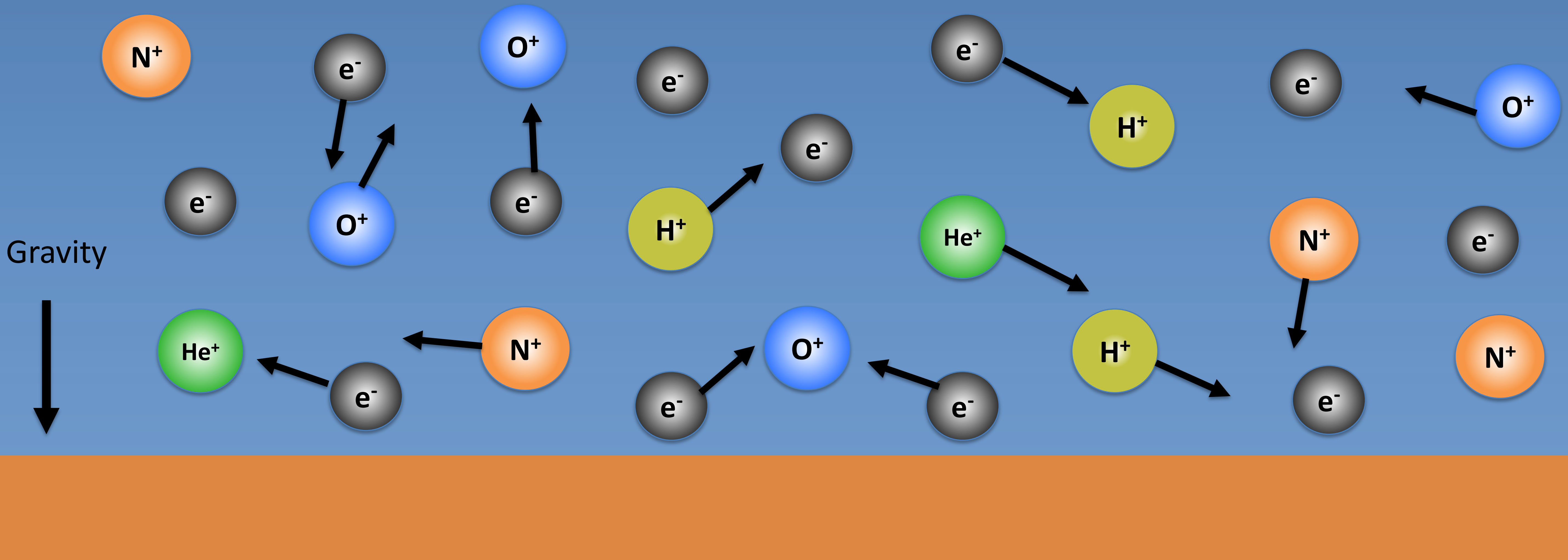
$$\cancel{\rho_e u_e \frac{du_e}{ds}} + \frac{dp_e}{ds} - \cancel{\rho_e g_\parallel} + en_e E_\parallel = \cancel{\Sigma\rho_e \nu_{et}(u_t - u_e)}$$

$$\boxed{\frac{dp_e}{ds} = -en_e E_\parallel = -en_e(\mathbf{E} + \mathbf{u_e} \times \mathbf{B})}$$

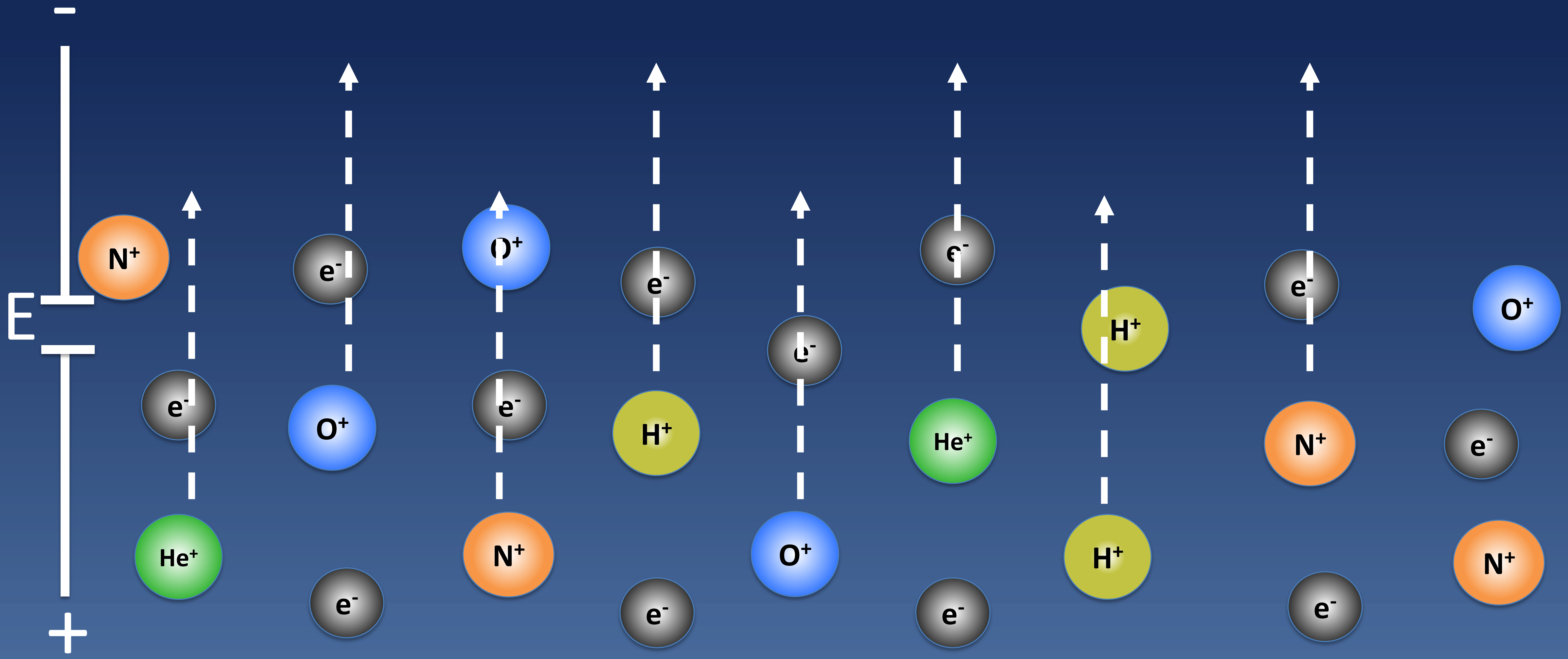
Ambipolar Electric Field explains transport of e^-

Low altitude – collisions dominate

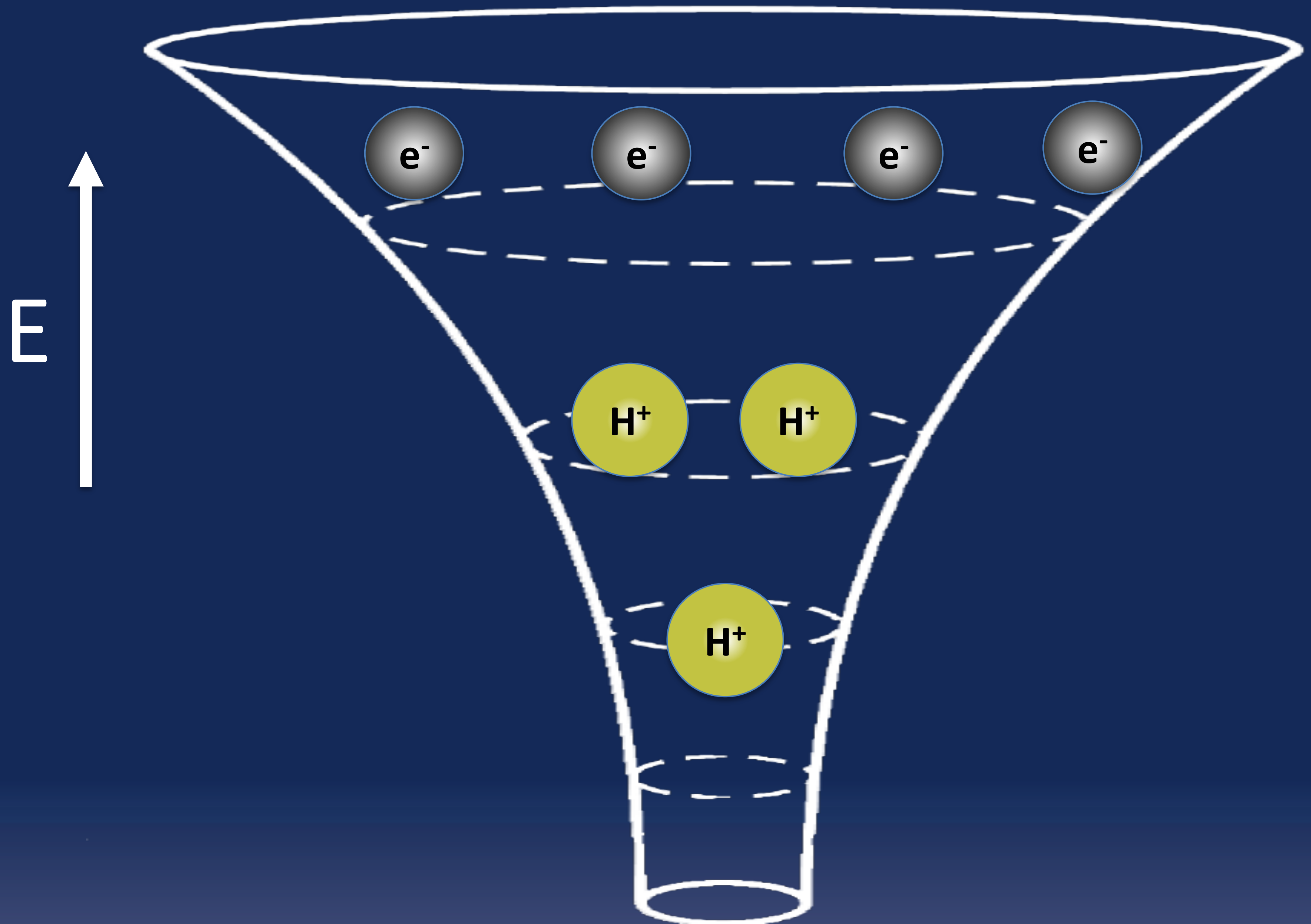
All species are coupled through friction-like action



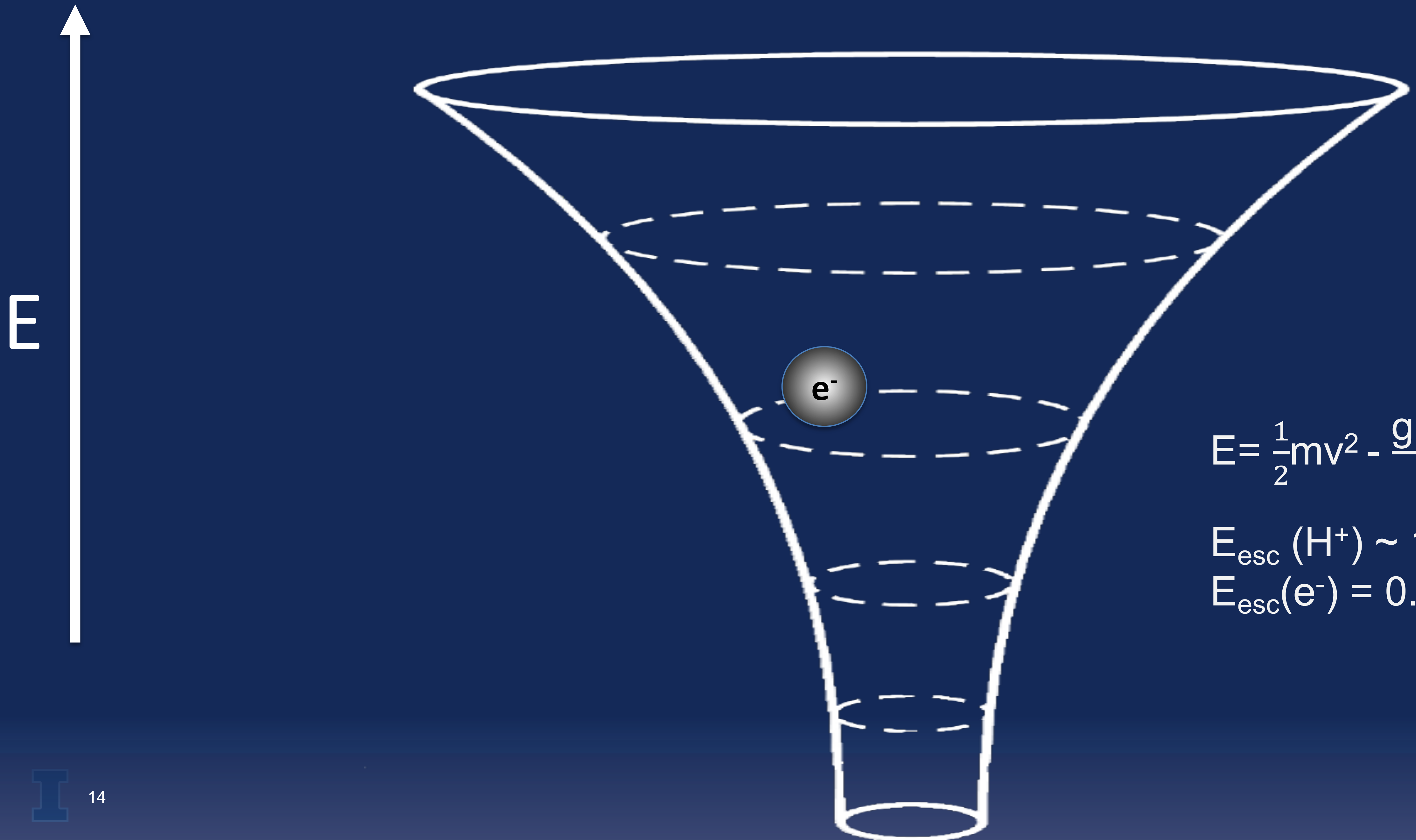
Higher altitude – less density - collisionless



Ambipolar electric field - created by charge separation of particles of equal charges but different masses



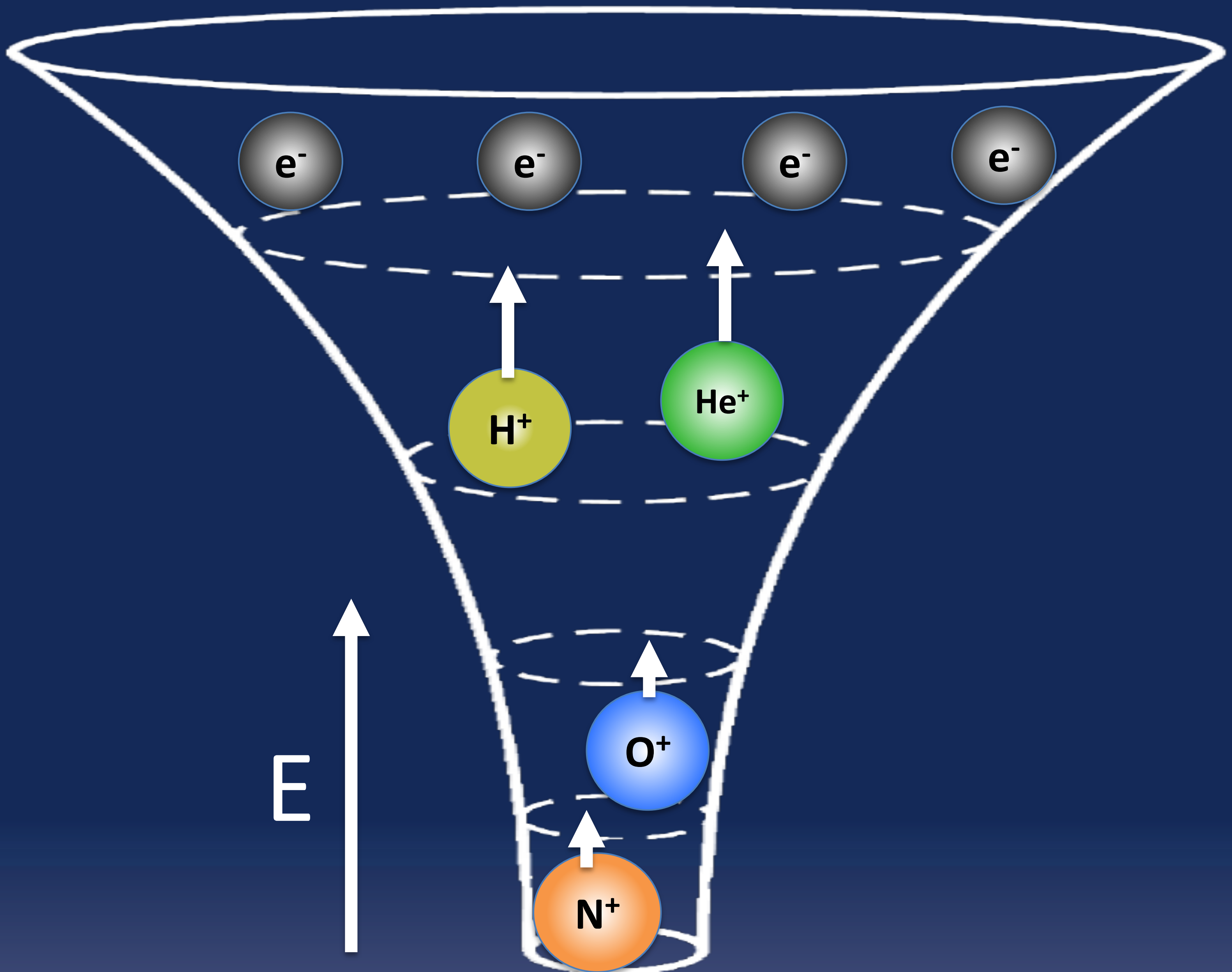
Ambipolar electric field – classical outflow



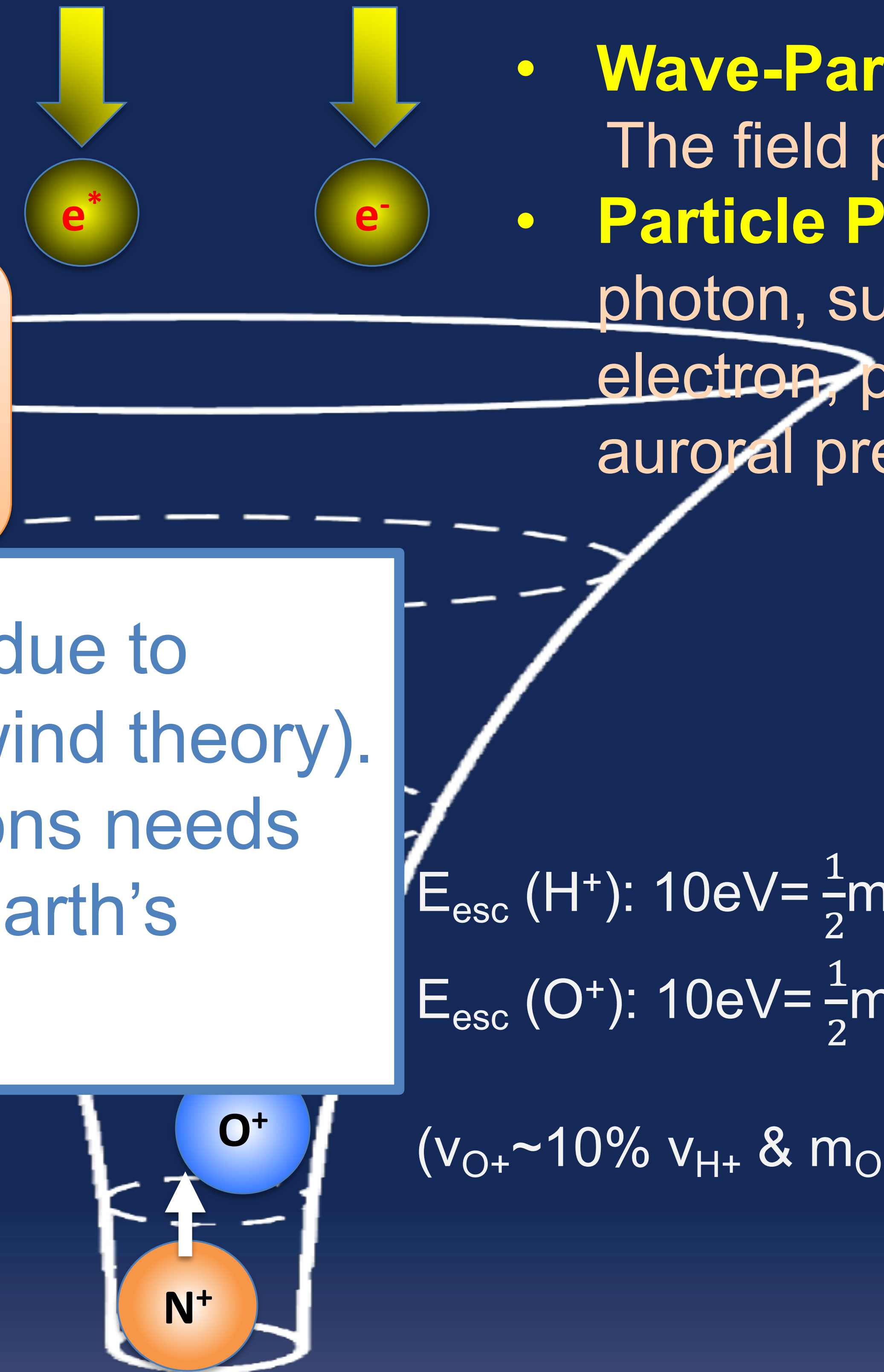
$E = \frac{1}{2}mv^2 - \frac{gMm}{r}$

$E_{esc}(H^+) \sim 10\text{eV}$
$E_{esc}(e^-) = 0.7\text{eV}$

Ambipolar electric field



Ambipolar electric field



- **Wave-Particle Interaction:** The field perturbations
- **Particle Precipitation:** photon, suprathermal electron, polar rain and auroral precipitation.

Additional Source ?

- The transport of H^+ is mostly due to ambipolar E (classical polar wind theory).
- The transport of cold heavy ions needs additional source to escape Earth's ionosphere.

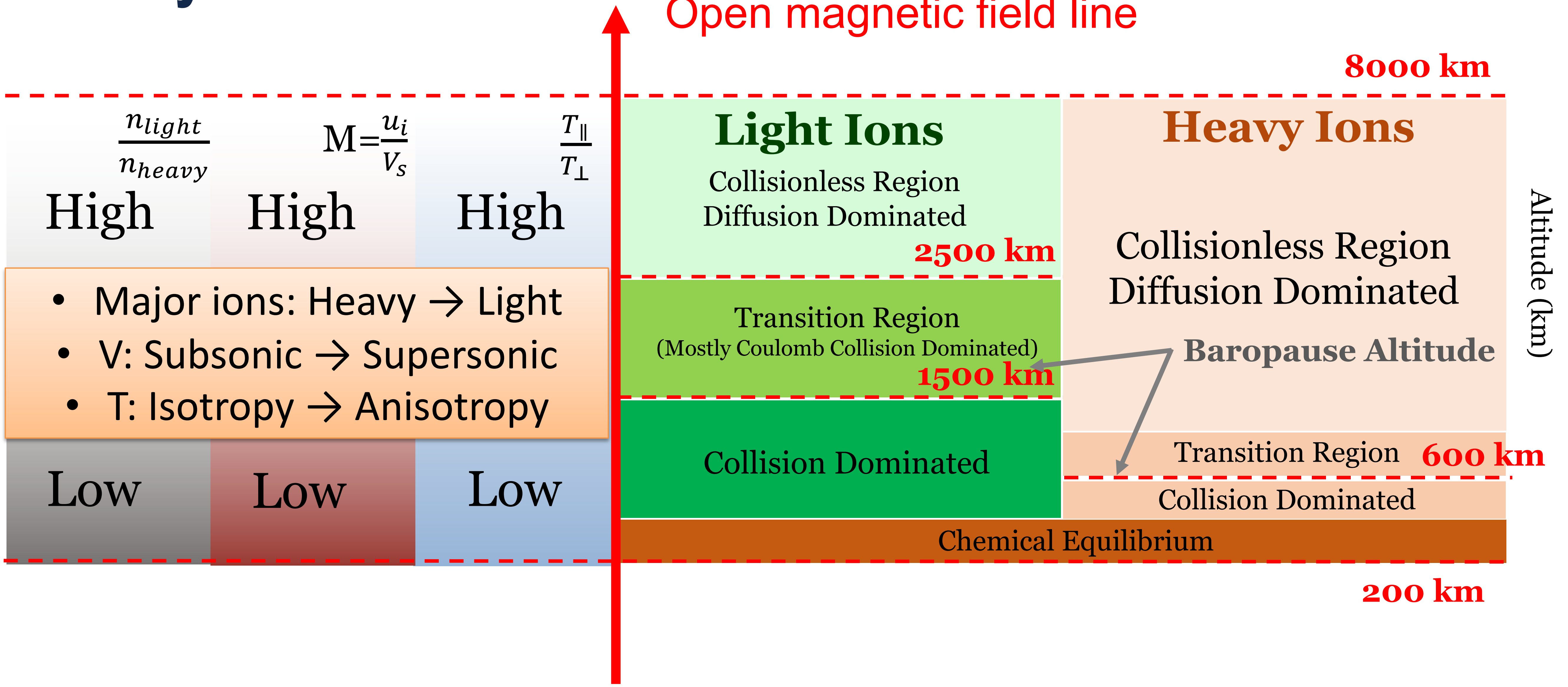
$$O + h\nu \rightarrow O^+ + e^-$$

$$E_{esc}\,(H^+):\ 10\text{eV} = \frac{1}{2} m_{H+} v_{H+}^2 - \frac{gMm_{H+}}{r}$$

$$E_{esc}\,(O^+):\ 10\text{eV} = \frac{1}{2} m_{O+} v_{O+}^2 - \frac{gMm_{O+}}{r} \quad +?$$

($v_{O+} \sim 10\%\ v_{H+}$ & $m_{O+} \sim 16 m_{H+}$)

Summary of Ion Outflow



Open magnetic field line

$\frac{n_{light}}{n_{heavy}}$ High

$M=\frac{u_i}{V_s}$ High

$\frac{T_\parallel}{T_\perp}$ High

- Major ions: Heavy → Light
- V: Subsonic → Supersonic
- T: Isotropy → Anisotropy

Low Low Low

Light Ions

Collisionless Region
Diffusion Dominated

Transition Region
(Mostly Coulomb Collision Dominated)

Collision Dominated

Heavy Ions

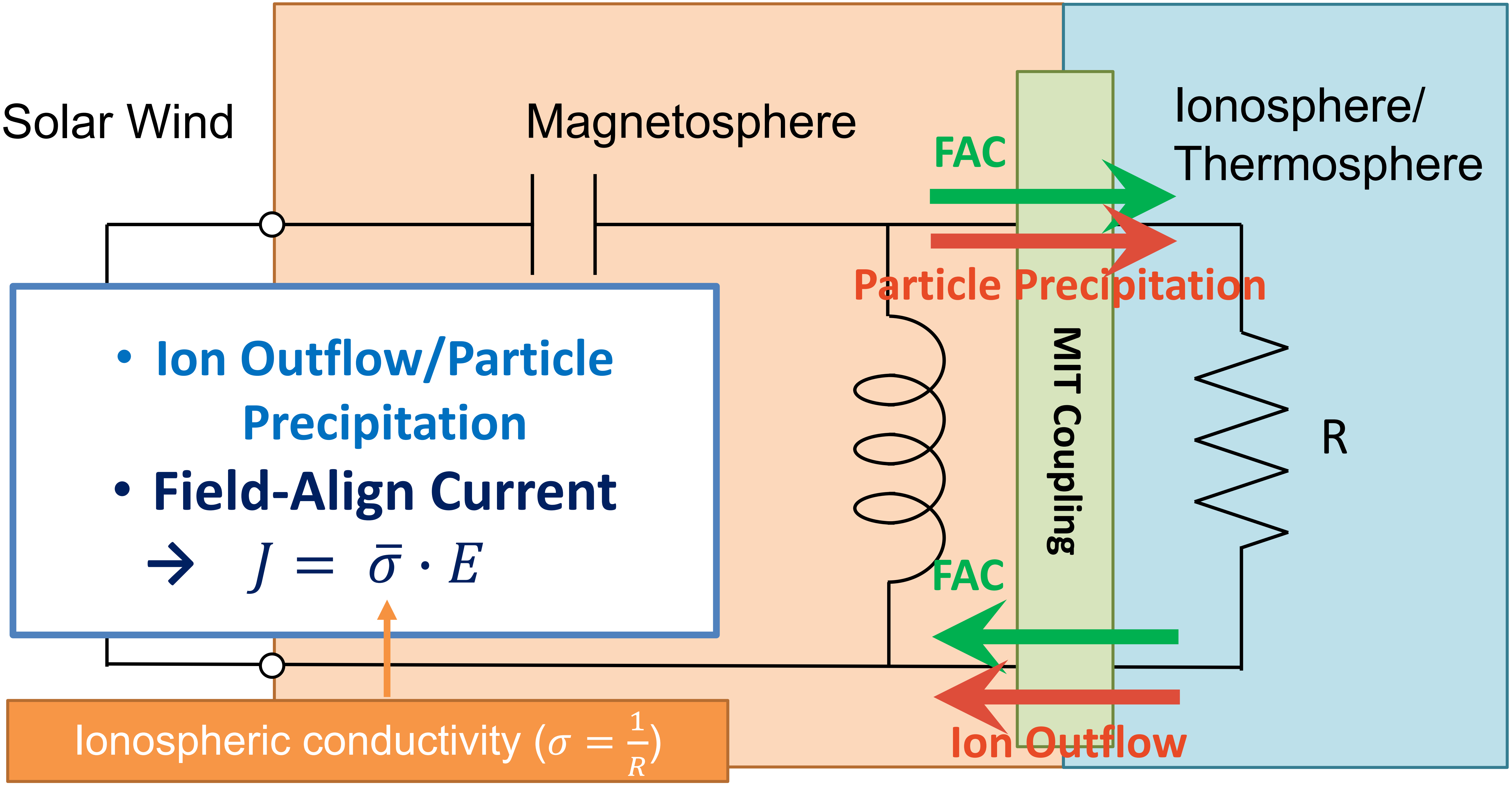
Collisionless Region
Diffusion Dominated

Baropause Altitude

Transition Region

Collision Dominated

Chemical Equilibrium



Solar Wind

Magnetosphere

Ionosphere/
Thermosphere

FAC

Particle Precipitation

MIT Coupling

R

FAC

Ion Outflow

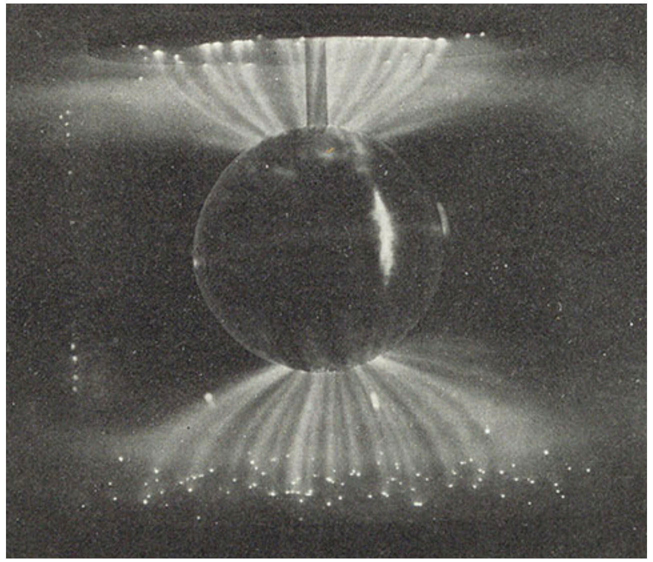
- **Ion Outflow/Particle Precipitation**
- **Field-Align Current**

→ $J = \bar{\sigma} \cdot E$

Ionospheric conductivity ($\sigma = \frac{1}{R}$)

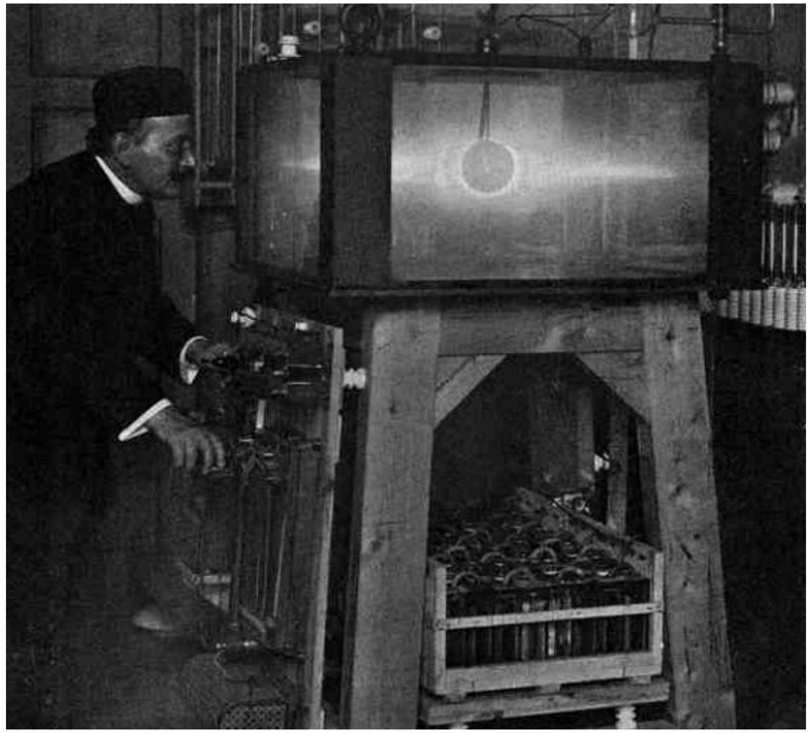
The discovery of field-aligned current

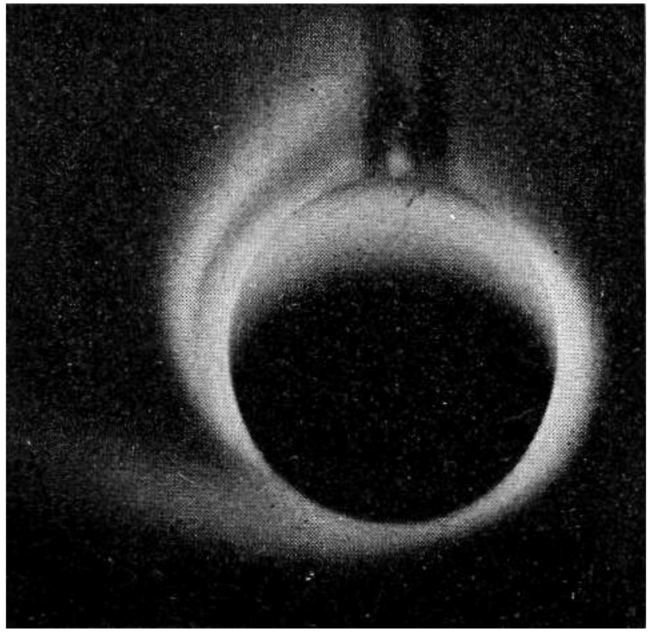
- Kristian Birkeland first suggested the auroral field-aligned current by operating Terrella experiments in 1895.
- He was shooting cathode rays onto a magnetized sphere. Currents were guided by magnetic field towards the sphere.



Terrella:
small model of Earth

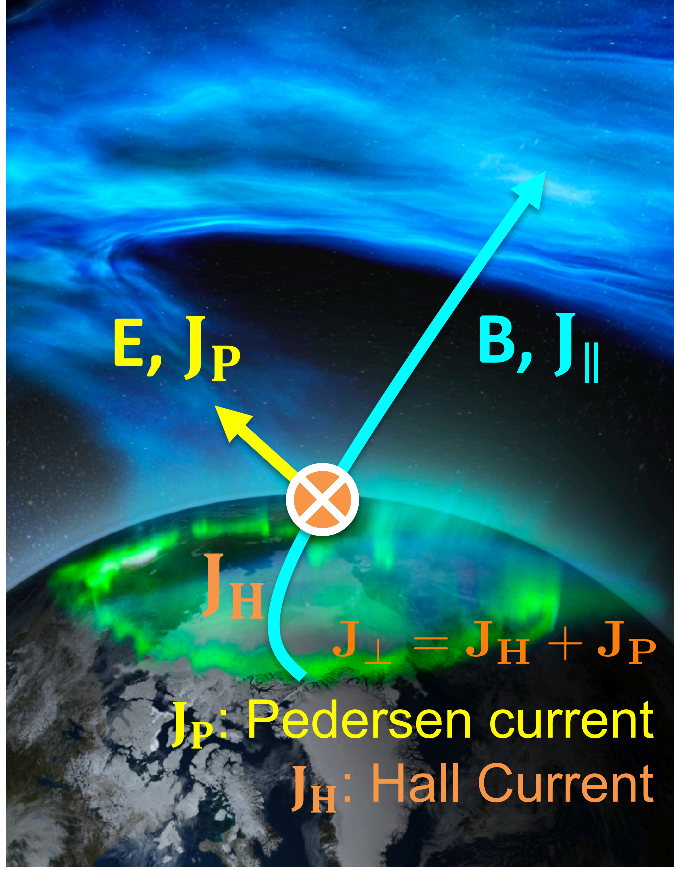
Auroral FACs are also termed “Birkeland currents” as a reference to his early pioneering work.





Birkeland’s Terella Experiments, 1895

Theory of field-aligned currents ($J_\parallel$)



- MHD equation is only included $J_\perp$ ($\boldsymbol{u_s}\times \boldsymbol{B} \neq \mathbf{0}$), not $J_\parallel$

$$\rho_s \frac{d\mathbf{u_s}}{ds} + \frac{dp}{ds} - \rho_s \mathbf{G} - n_s e(\mathbf{E} + \mathbf{u_s} \times \mathbf{B}) = \Sigma \rho_s \nu_s t(\mathbf{u_t} - \mathbf{u_s})$$

- Start with Maxwell's equations and assume electrostatic ionosphere

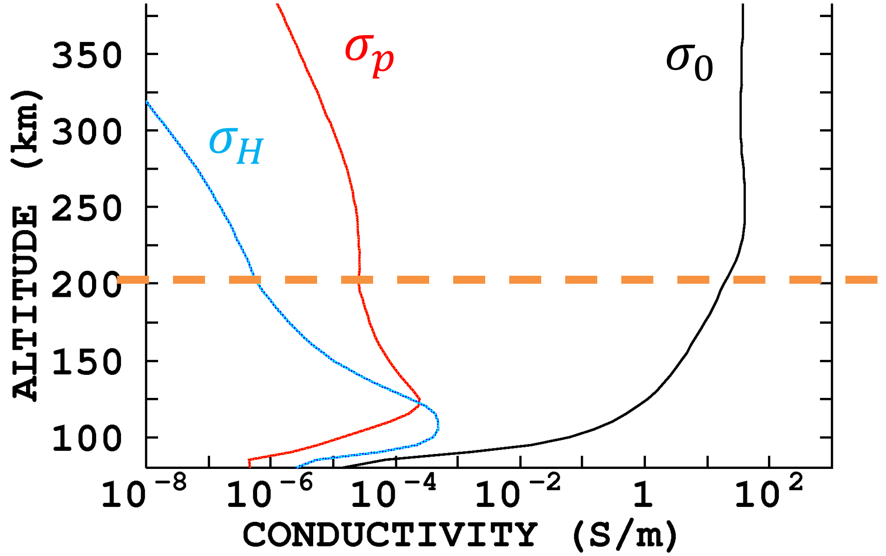
$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} \longrightarrow \nabla \cdot \mathbf{J} = 0 \quad (\mathbf{J} = \mathbf{J}_\perp + \mathbf{J}_\parallel = \mathbf{J_H} + \mathbf{J_P} + \mathbf{J}_\parallel)$$

- Ionospheric plasma is anisotropic and applied generalized Ohm's law

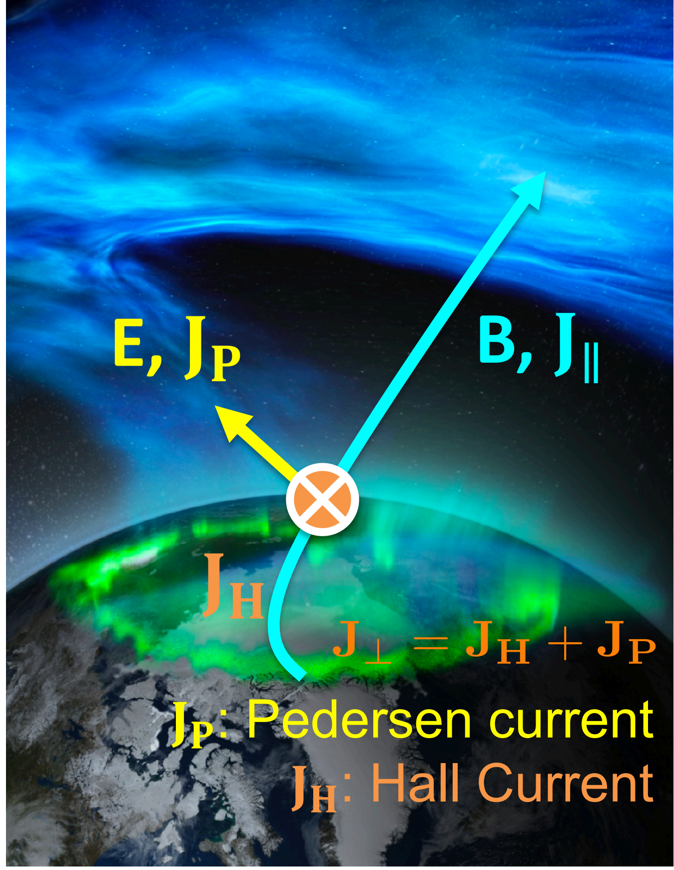
$$\boldsymbol{J} = \bar{\sigma} \cdot \boldsymbol{E} = \begin{bmatrix} \sigma_p & -\sigma_H & 0 \\ \sigma_H & \sigma_p & 0 \\ 0 & 0 & \sigma_0 \end{bmatrix} \cdot \mathbf{E} \quad \begin{array}{l} \left.\begin{array}{l} \\ \\ \end{array}\right\} J_\perp \\ \rightarrow J_\parallel \end{array}$$

- From low to high altitudes, $J_\perp$ **decreases while $J_\parallel$ increases**

$$\nabla \cdot \mathbf{J} = \nabla \cdot (\mathbf{J}_\perp + \mathbf{J}_\parallel) = 0 \longrightarrow -\nabla \cdot \mathbf{J}_\perp = \nabla \cdot \mathbf{J}_\parallel$$



Theory of field-aligned currents ($J_{\parallel}$)

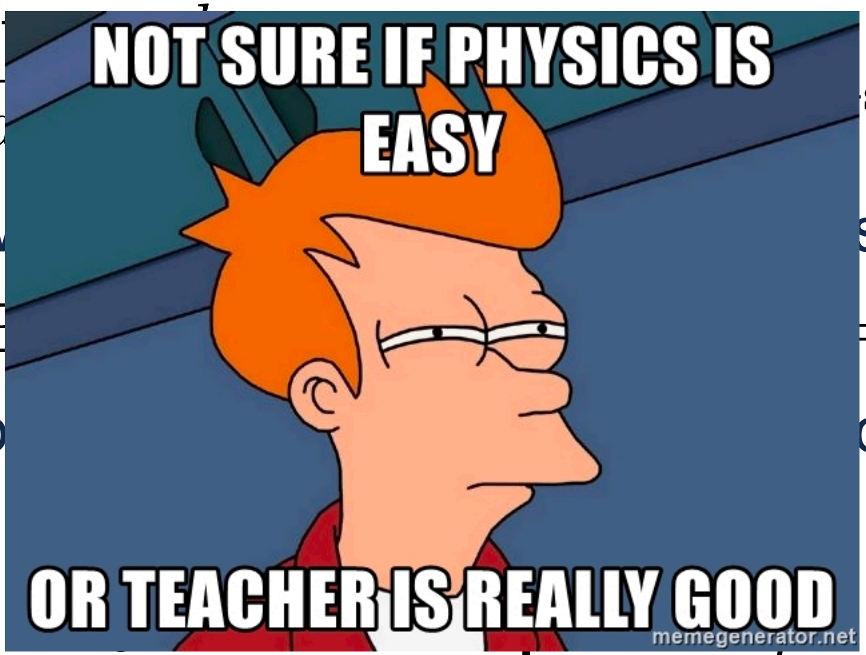


$\mathbf{J_P}$: Pedersen current

$\mathbf{J_H}$: Hall Current

- MHD equation is only included $J_{\perp}$ ($\boldsymbol{u_s} \times \boldsymbol{B} \neq \mathbf{0}$), not $J_{\parallel}$

$$\rho_s \frac{d}{d} \quad \mathbf{s} \times \mathbf{B}) = \Sigma \rho_s \nu_s t(\mathbf{u_t} - \mathbf{u_s})$$

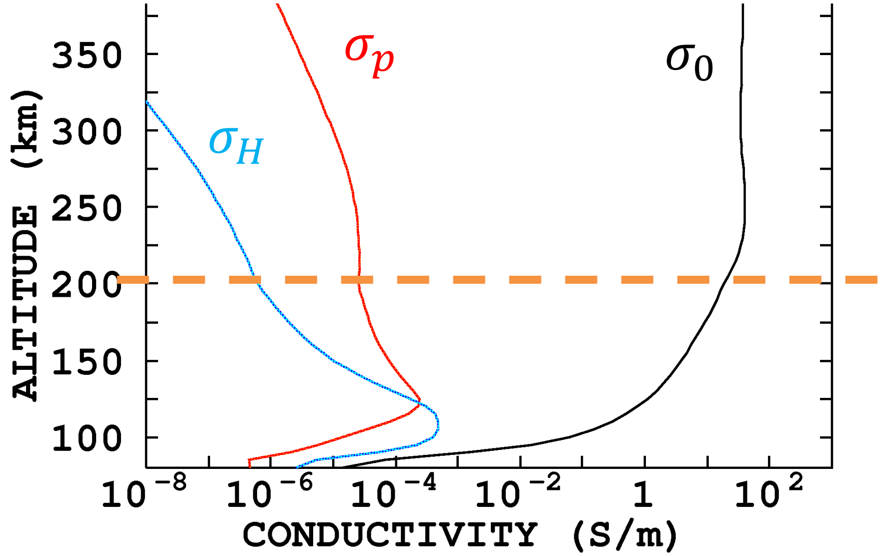


- Start w ssume electrostatic ionosphere

$$\nabla \times \mathbf{E} \quad = \mathbf{J_{\perp}} + \mathbf{J_{\parallel}} = \mathbf{J_H} + \mathbf{J_P} + \mathbf{J_{\parallel}})$$

- Ionosp d applied generalized Ohm's law

$$\begin{bmatrix} & & 0 \\ & & 0 \\ 0 & 0 & \sigma_0 \end{bmatrix} \cdot \mathbf{E} \quad \begin{matrix} \left.\right\} J_{\perp} \\ \rightarrow J_{\parallel} \end{matrix}$$



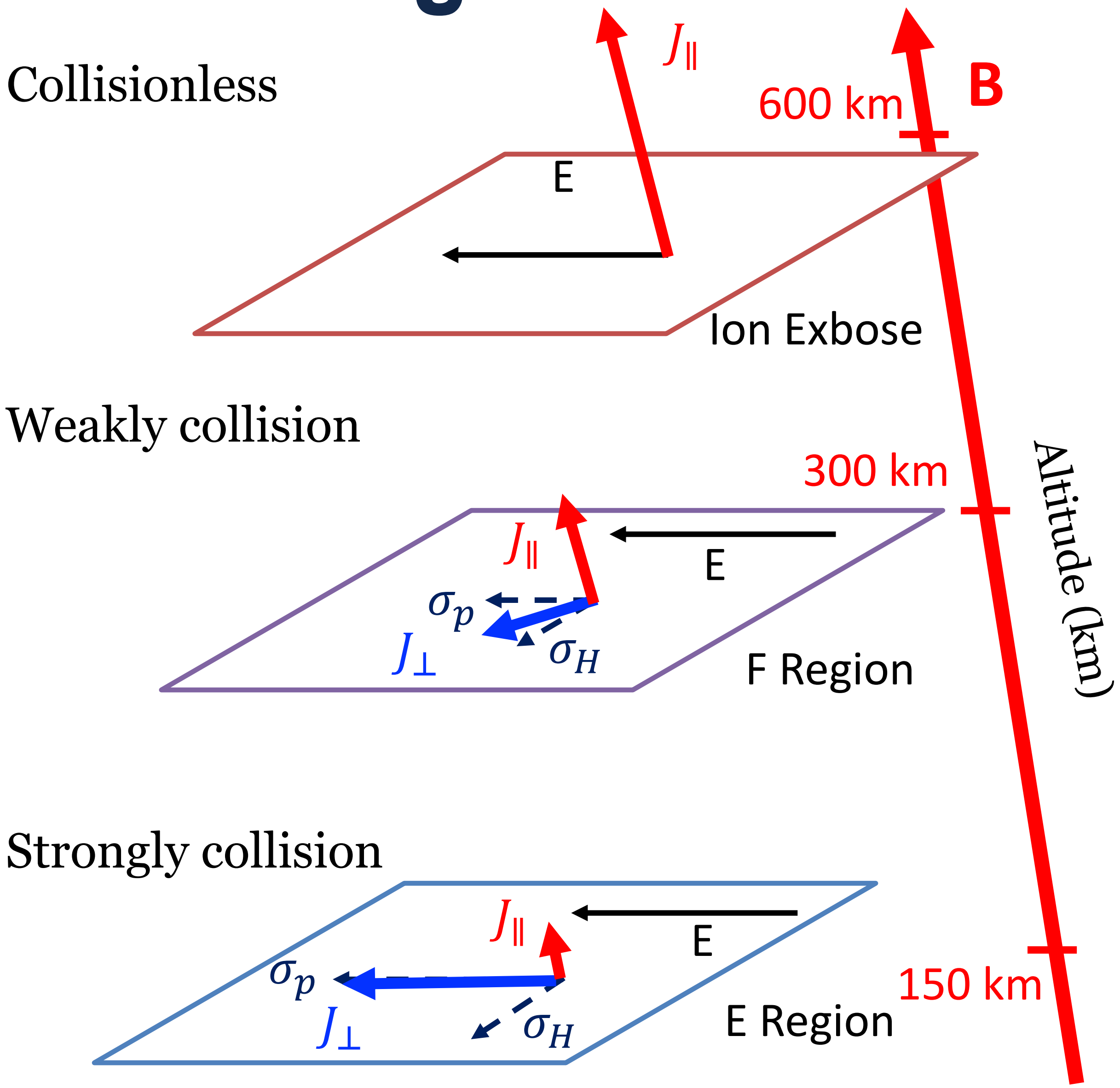
- From low to high altitudes, $J_{\perp}$ **decreases while** $J_{\parallel}$ **increases**

$$\nabla \cdot \mathbf{J} = \nabla \cdot (\mathbf{J_{\perp}} + \mathbf{J_{\parallel}}) = 0 \quad \longrightarrow \quad -\nabla \cdot \mathbf{J_{\perp}} = \nabla \cdot \mathbf{J_{\parallel}}$$

Field-aligned current division

$$\nabla \cdot \mathbf{J} = \nabla \cdot (\mathbf{J}_\perp + \mathbf{J}_\parallel) = 0$$

$$-\nabla \cdot \mathbf{J}_\perp = \nabla \cdot \mathbf{J}_\parallel$$

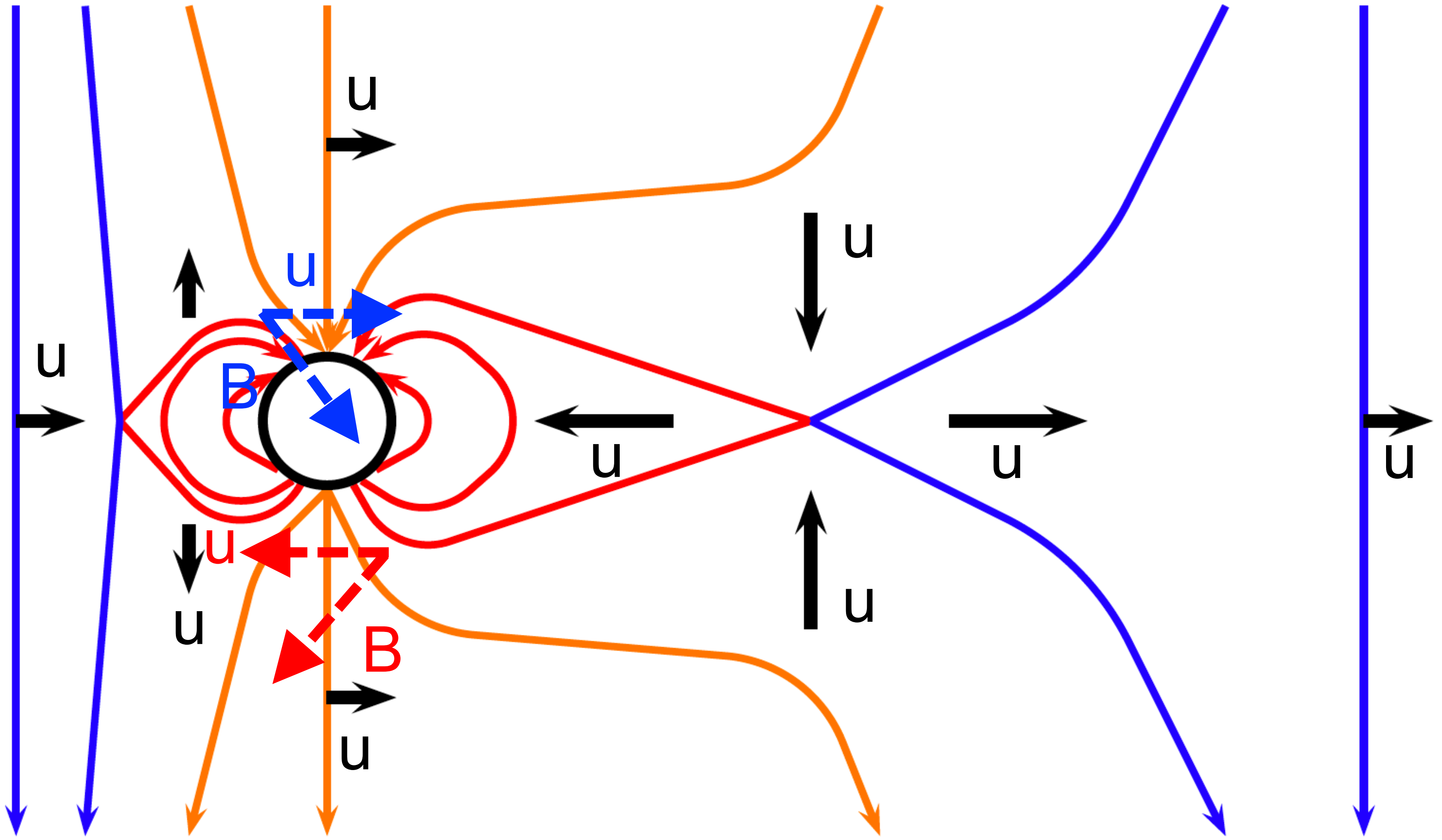


Where do FACs close?

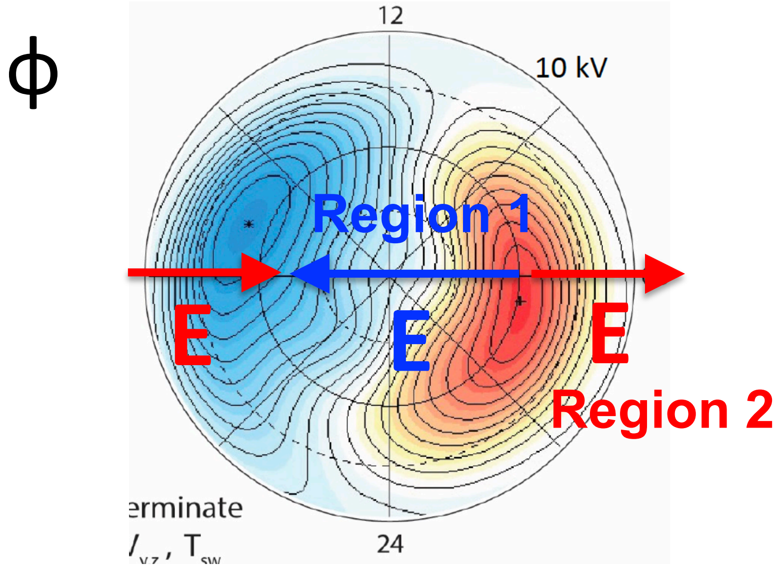
$$\nabla \times \mathbf{E} = 0$$

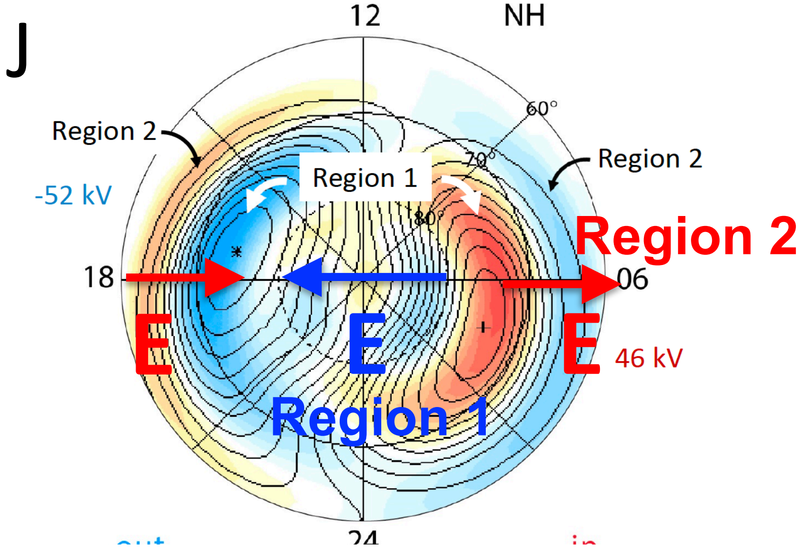
$$\mathbf{E} = -\nabla \phi$$

R1 and R2 FAC: Convection during south IMF

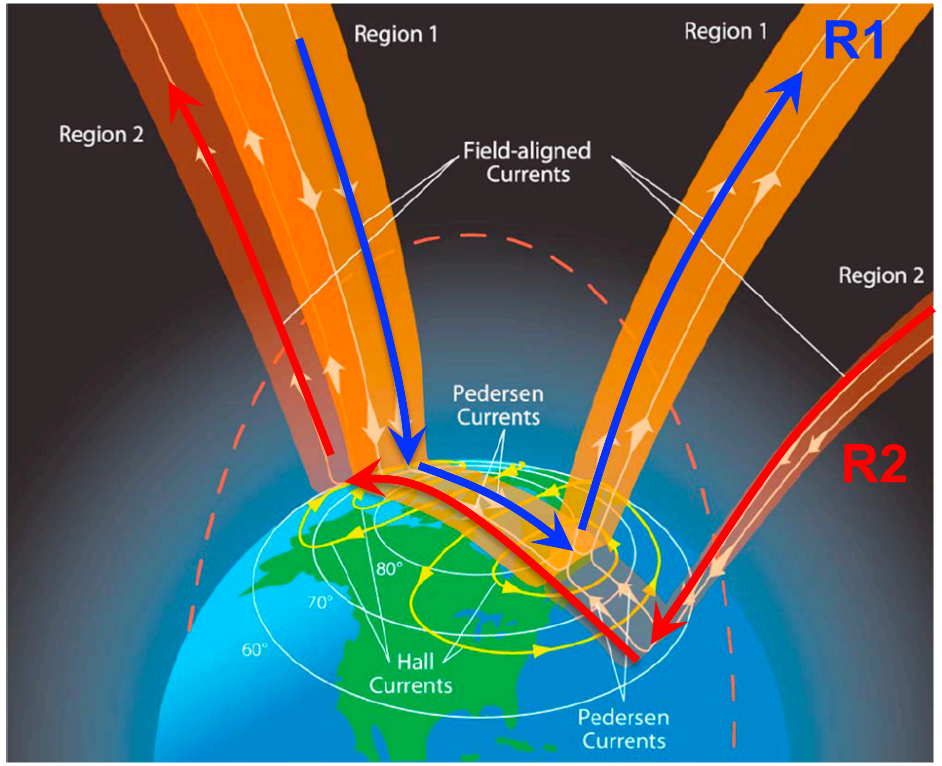


$$\mathbf{E} = -\mathbf{u_{sw}} \times \mathbf{B}$$



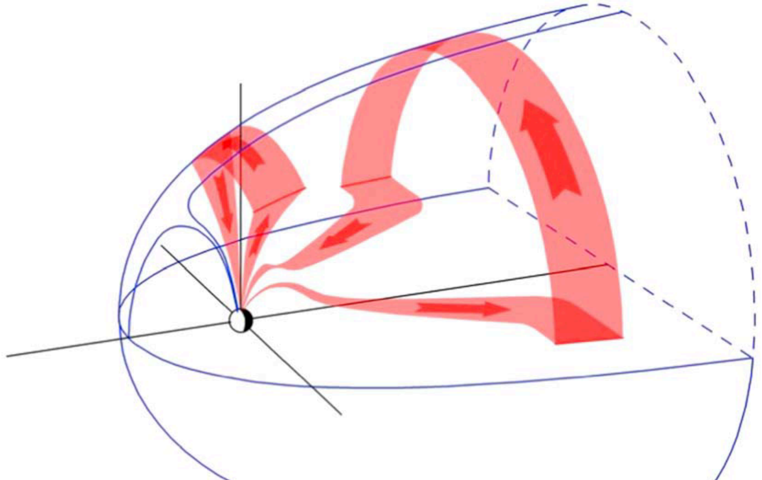


R1 and R2 FAC: Close at different regions



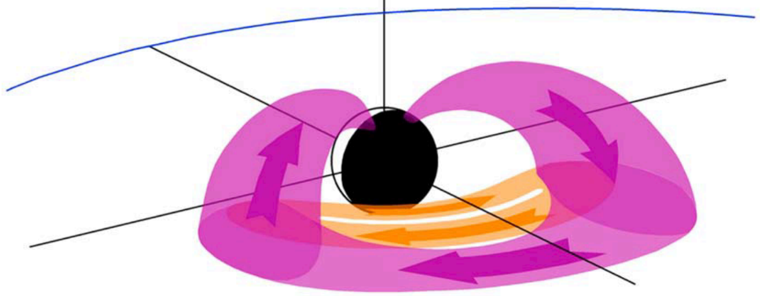
R1: Poleward FAC

R2: Equatorward FAC



- Open field line: Dayside magnetopause
- Close field line: Nightside magnetopause

- Close field line: Partial ring current



$$\nabla \cdot \mathbf{J} =$$

- R1 current closes with magnetopause current.
- R2 current closes with partial ring current.

(Credit: Ganushkina et al., 2018)

Focus Group

- IEMIT: Tuesday
  - Understand Momentum/Energy input from the magnetosphere to the upper atmosphere
  - Understand IT feedbacks to the magnetosphere
- **M3I2: Wednesday**
  - **[1:45 - 1:55 PM (EST) How does the polar wind solution change in response to the presence of N^+ ions? (Mei-Yun Lin)**
  - **The effects of ion outflow population on magnetospheric dynamics**
  - **The energization processes of the ion upflow/outflow**
- IHMIC: Thursday
  - Interhemispheric differences in ionospheric conductivity and storm signatures
  - The neutral wind dynamo contribute to the interhemispheric asymmetry in M-I coupling
- CP: Thursday
  - Measurements to understand the role of the cold plasma in magnetospheric physics
  - Include the impact of the cold-plasma in magnetospheric modeling