# Kinetic e$^-$ Polar Wind Outflow Model (KePWOM)

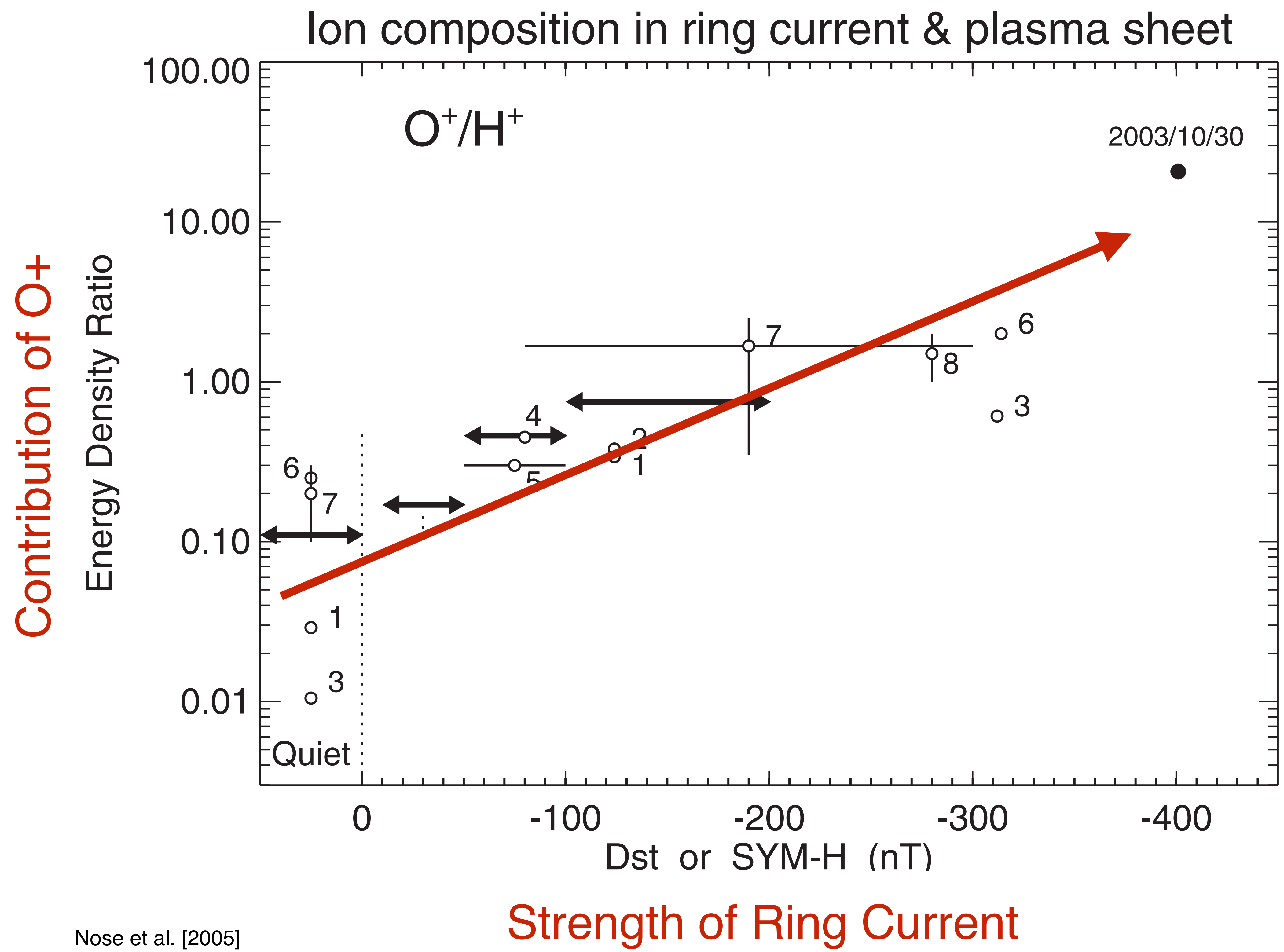
A. Glocer

G. Khazanov, K. Garcia-Sage, M. Liemohn, G. Toth, J. Bell, T. Gombosi

# Outline

- Ionospheric plasma has system wide consequences for the magnetosphere.
- Particle and electrodynamic energy inputs are critical to generating ionospheric outflows.
- We have developed a new model that simulates how these inputs drive outflows.
- The ionospheric outflow occurs at planets other than Earth.
- Next steps

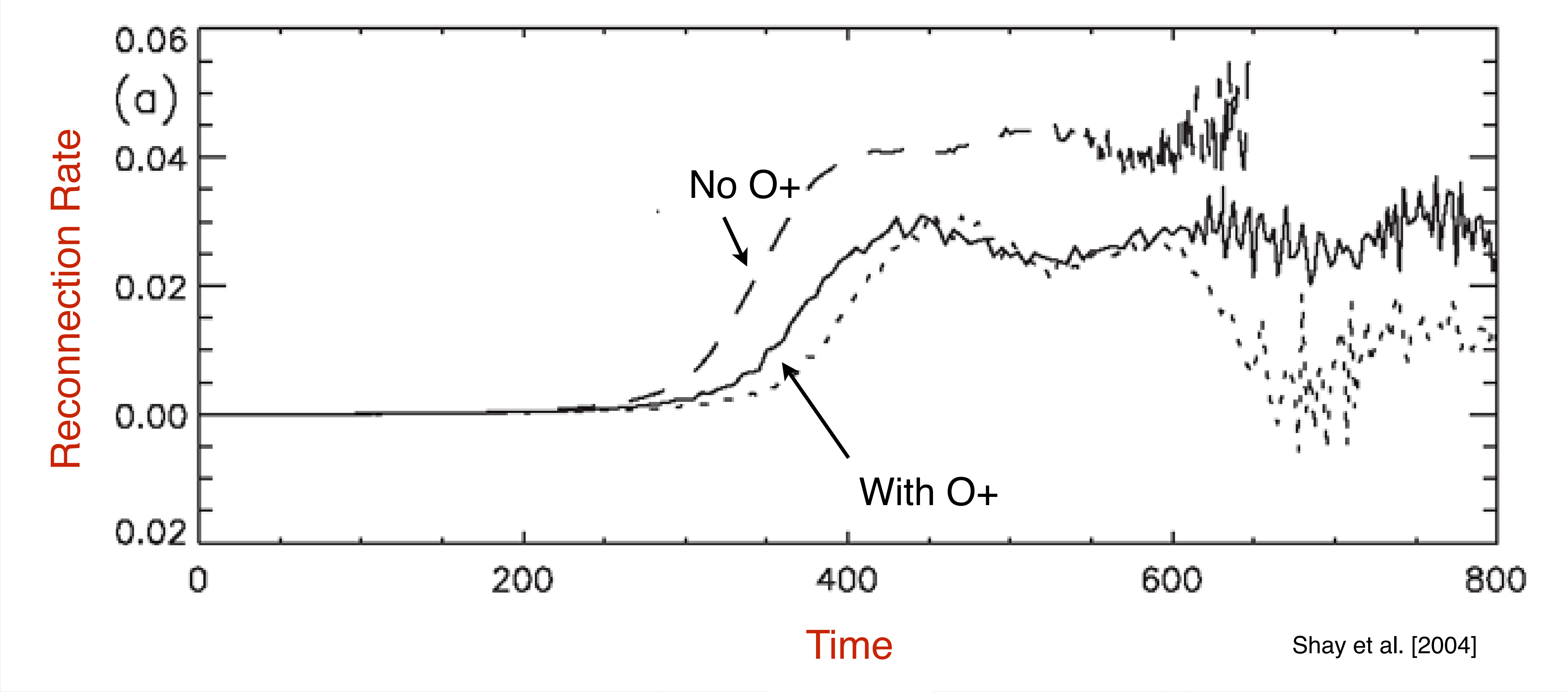
# Ionospheric Plasma has System Wide Effects




Nose et al. [2005]

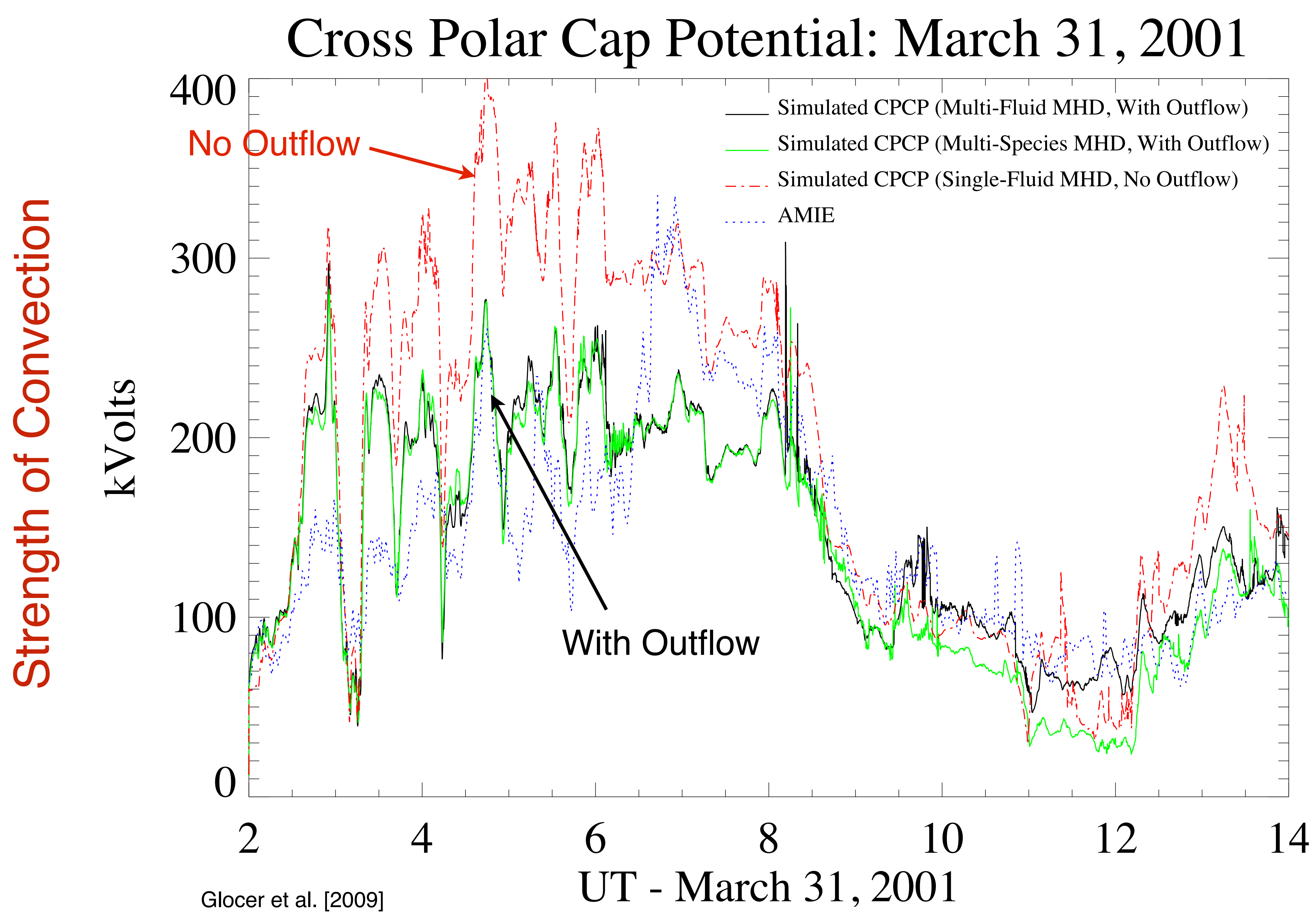
# Ionospheric Plasma has System Wide Effects

## $O^{+}$ and Reconnection

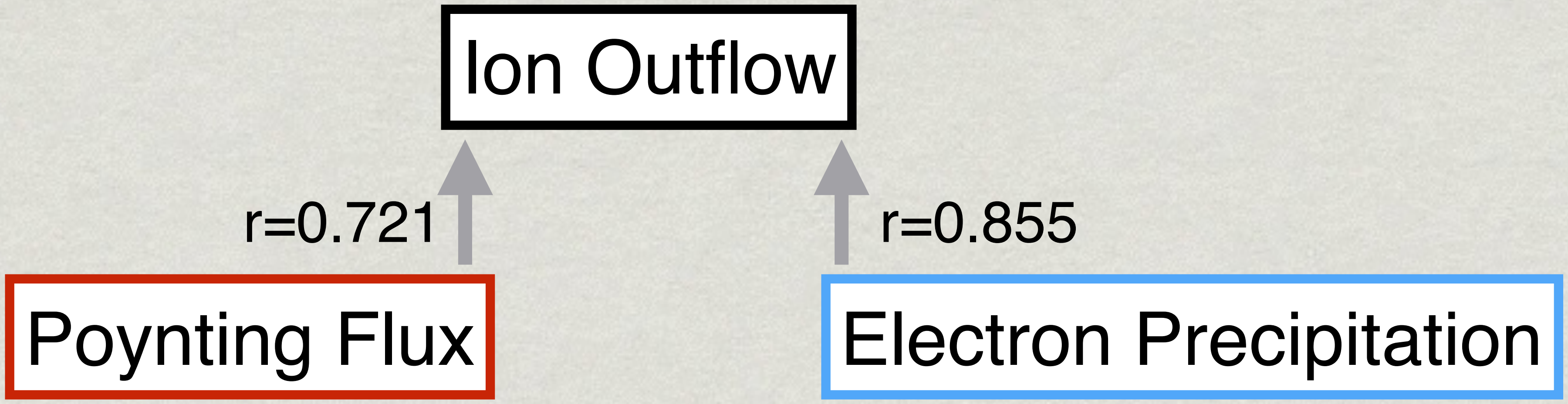


# Ionospheric Plasma has System Wide Effects

## O+ and Convection



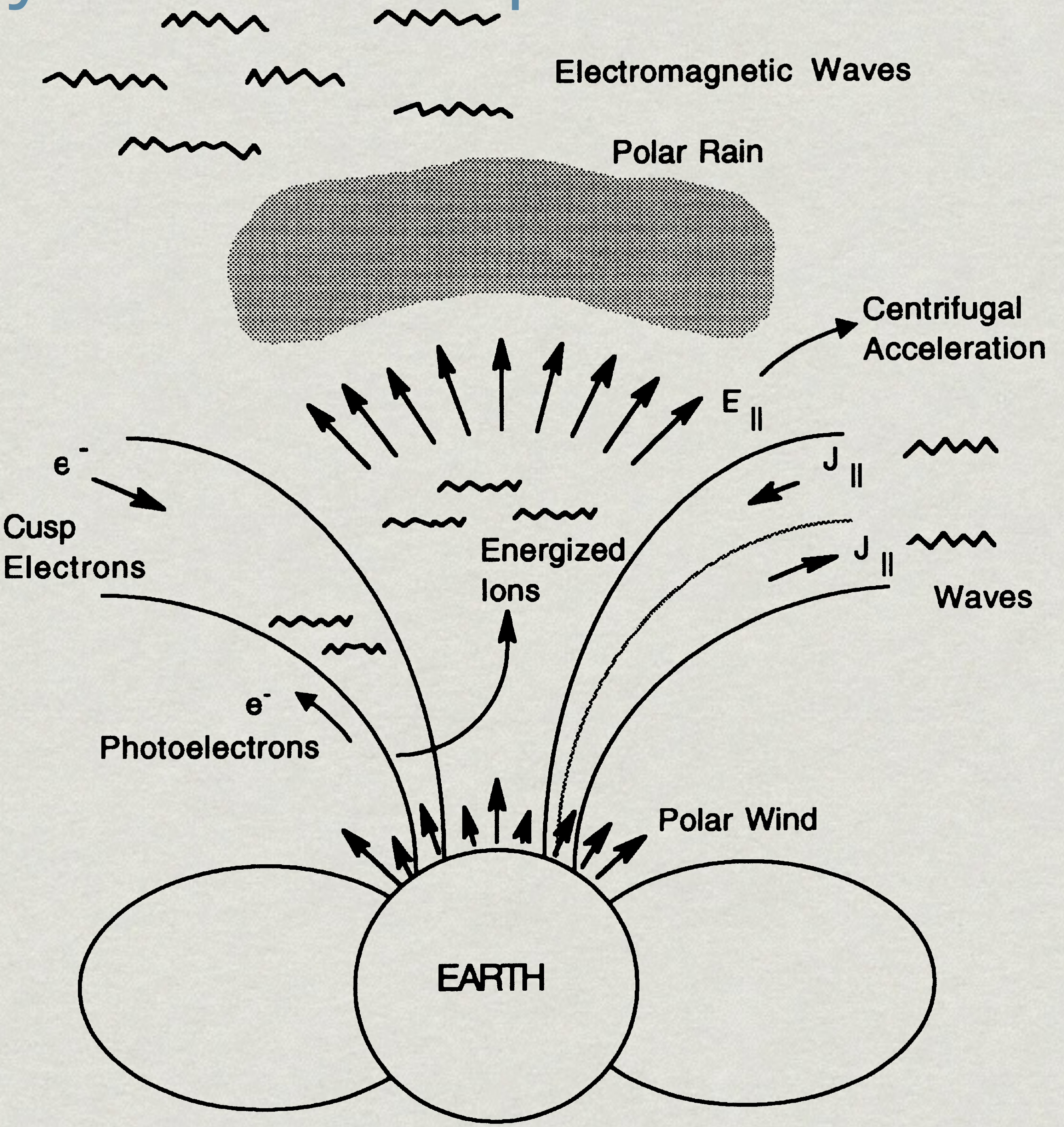
# Understanding the Ionospheric Source




*STRANGEWAY ET AL.* [2005]

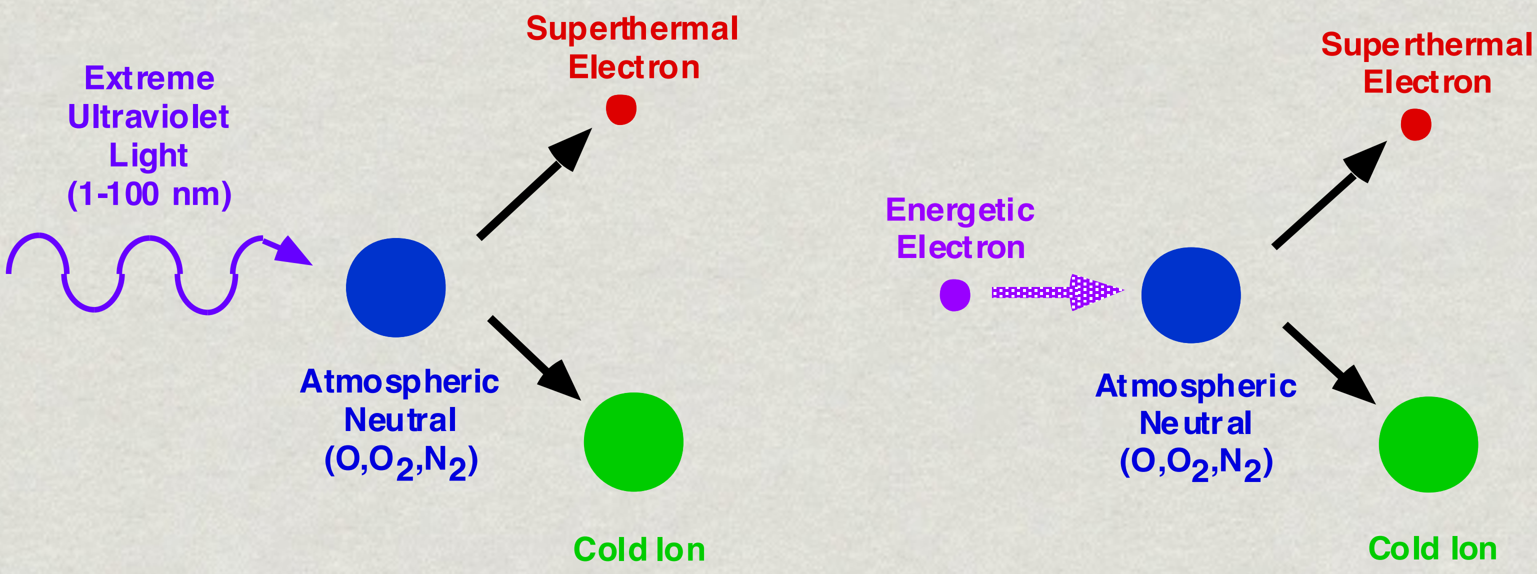
- Two types of inputs drive outflow: Electromagnetic and Particle
- The first principles channels through which these inputs operate are still not fully understood.

# Pathways of Ionospheric Outflow



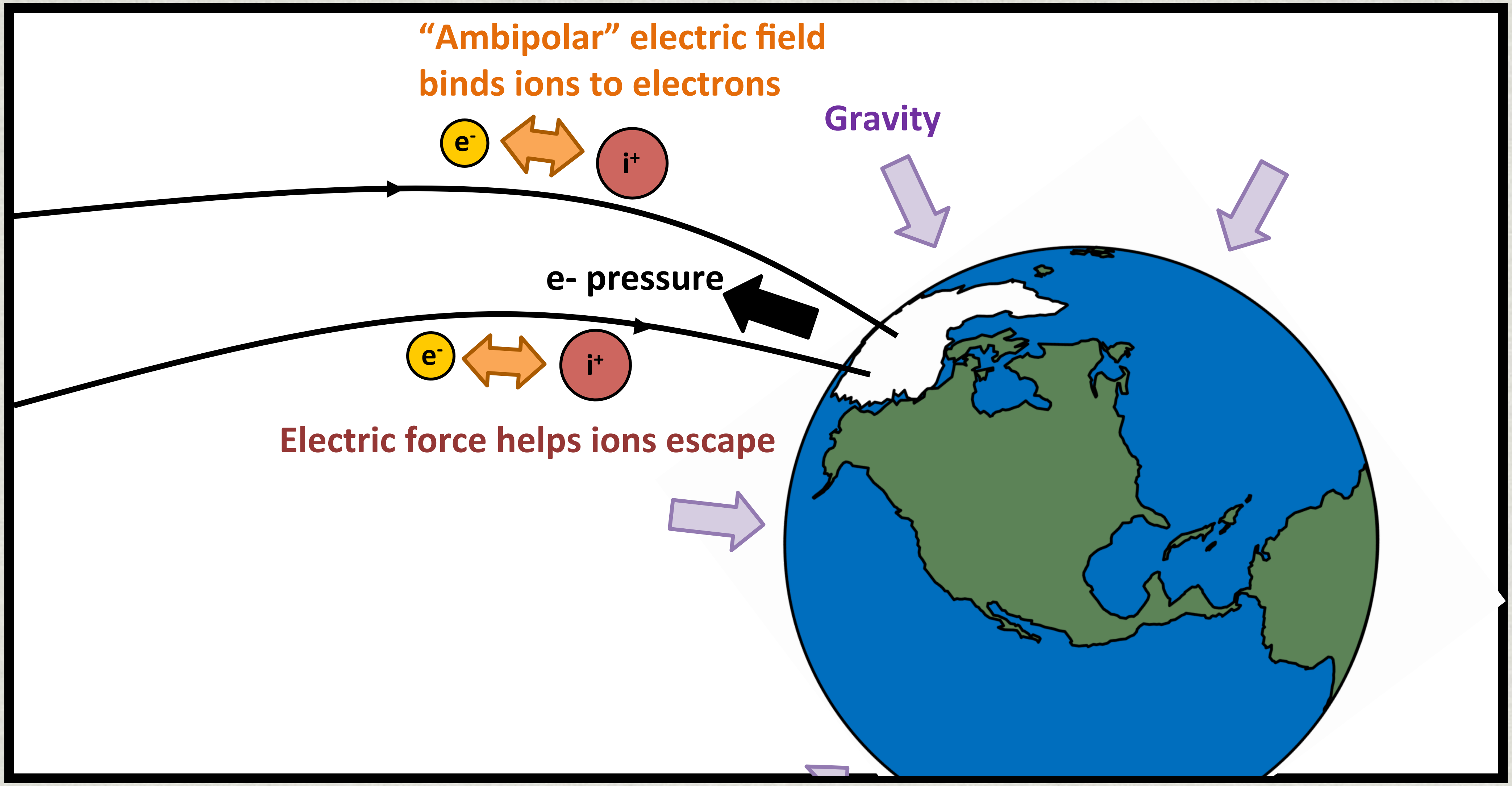

Schunk and Sojka, [1997]

# Superthermal Electrons (SEs)




- SEs = $e^-$ with Energy >> $T_e$
- Three types of SEs:
  - Photoelectrons - from photoionization of the neutral atmosphere.
  - Primary Electrons - auroral precipitation, diffuse precipitation, and polar rain.
  - Secondary Electrons - generated by impact

# Superthermal Electrons (SEs)




- Mechanisms by which SEs affect outflow
  - Formation of the self-consistent ambipolar electric field
  - Coulomb collisions between the superthermal and thermal electrons raising Te.

# A New Model

- To model the effect of SEs, three things are required

  1. A treatment of the SEs (typically kinetic)
  2. A treatment of the thermal plasma (typically fluid)
  3. Self-consistent interaction between the two populations through the $E_{||}$ and and collisional interactions.

- We have developed just such a model.

# Field-Aligned Transport Equations

Continuity

$$\frac{\partial}{\partial t}(A\rho_i) + \frac{\partial}{\partial r}(A\rho_i u_i) = AS_i$$

Momentum

$$\frac{\partial}{\partial t}(A\rho_i u_i) + \frac{\partial}{\partial r}\left(A\rho_i u_i^2\right) + A\frac{\partial p_i}{\partial r} =$$
$$A\rho_i\left(\frac{e}{m_i}E_{\|} - g\right) + A\frac{\delta M_i}{\delta t} + Au_iS_i$$

Energy

$$\frac{\partial}{\partial t}\left(\frac{1}{2}A\rho_i u_i^2 + \frac{1}{\gamma_i - 1}Ap_i\right) + \frac{\partial}{\partial r}\left(\frac{1}{2}A\rho_i u_i^3 + \frac{\gamma_i}{\gamma_i - 1}Au_ip_i\right)$$
$$= A\rho_i u_i\left(\frac{e}{m_i}E_{\|} - g\right) + \frac{\partial}{\partial r}\left(A\kappa_i\frac{\partial T_i}{\partial r}\right) + A\frac{\delta E_i}{\delta t}$$
$$+ Au_i\frac{\delta M_i}{\delta t} + \frac{1}{2}Au_i^2S_i$$

Ambipolar E-Field

$$E_{\|} = -\frac{1}{en_e}\left[\frac{\partial}{\partial r}\left(p_e + \rho_e u_e^2\right) + \frac{A'}{A}\rho_e u_e^2\right] +$$
$$\frac{1}{en_e}\frac{\partial}{\partial r}\left(\sum_i \frac{m_e}{m_i}\left[(u_e - u_i)\,S_i - \frac{\delta M_i}{\delta t}\right] + \frac{\delta M_e}{\partial t}\right)$$

Gombosi et al. (1989)

# Equations: Electrons + Superthermal electrons

Continuity

$$n_e + n_\alpha = \sum_i n_i$$

Momentum

$$n_e u_e + n_\alpha u_\alpha = \sum_i n_i u_i - \frac{j}{e}$$

$$j = j_0 \frac{A_0}{A}$$

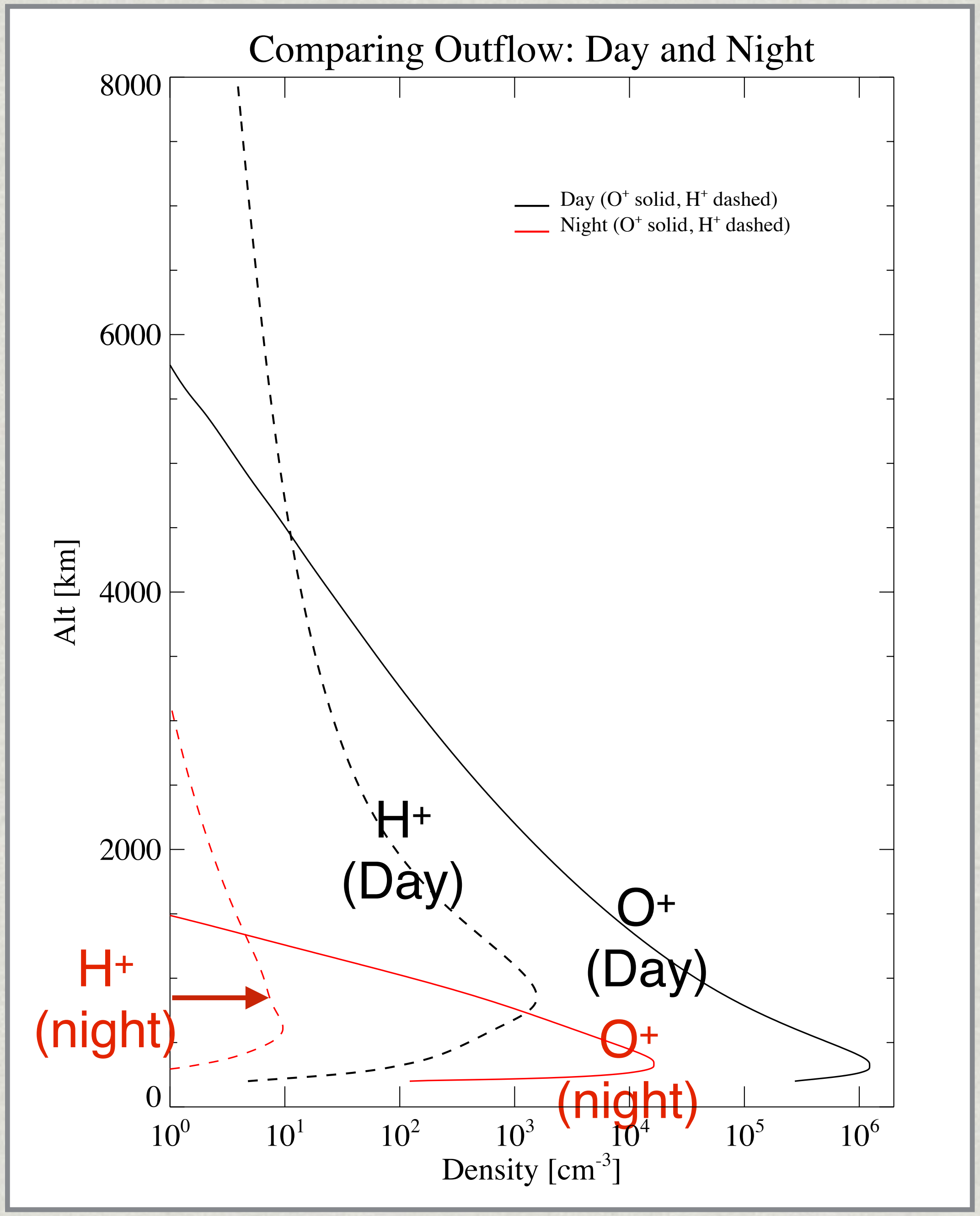
Temperature

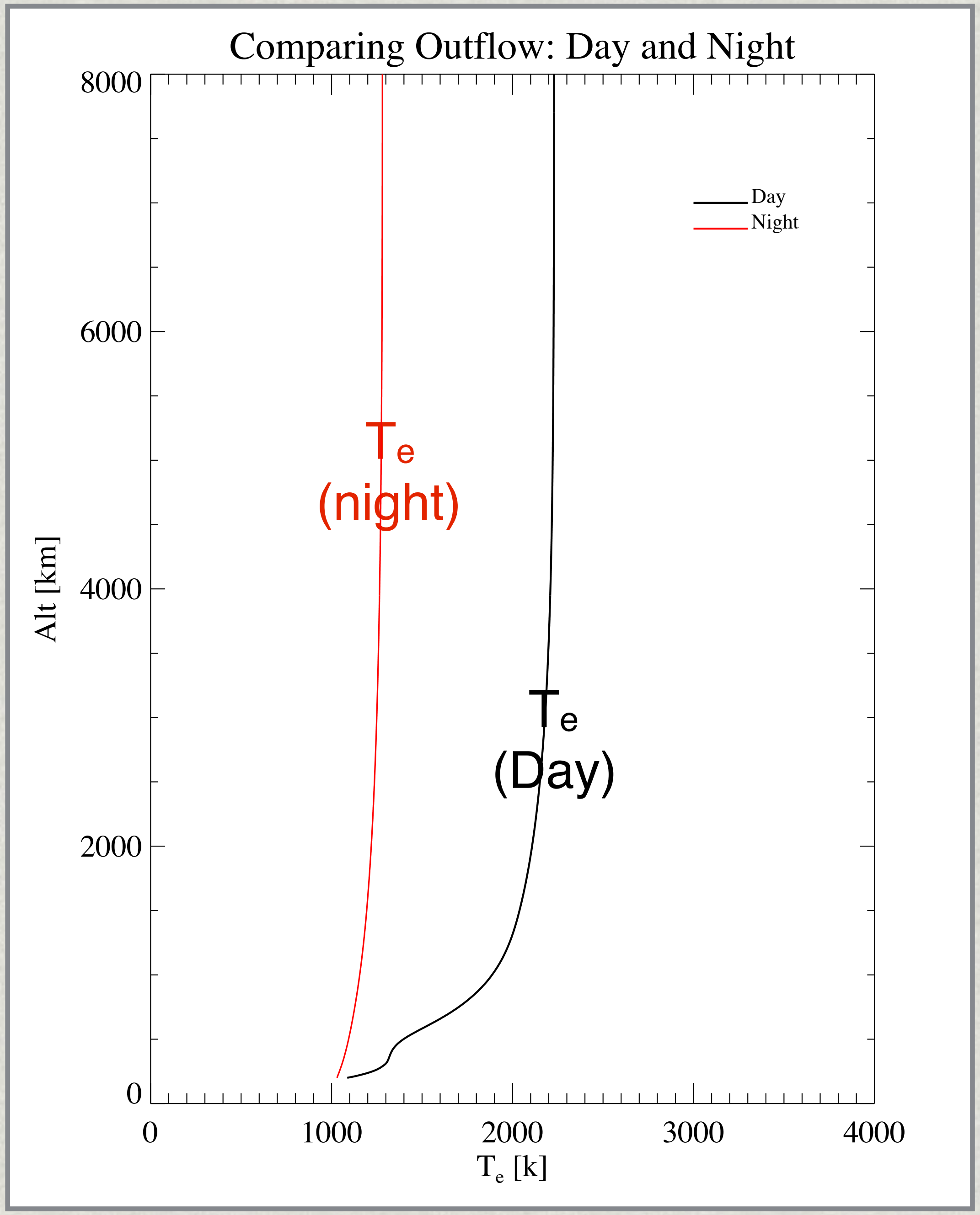
$$\rho_e \frac{\partial T_e}{\partial t} = (\gamma_e - 1) \frac{m_e}{kA} \frac{\partial}{\partial r} \left( A \kappa_e \frac{\partial T_e}{\partial r} \right) - \rho_e u_e \frac{\partial T_e}{\partial r} -$$
$$T_e \left[ S_e + \frac{\gamma_e - 1}{A} \rho_e \frac{\partial}{\partial r} (A u_e) \right] + (\gamma_e - 1) \frac{m_e}{k} \frac{\delta E}{\delta t}$$

Superthermal e-

$$\frac{1}{v}\frac{\partial \Phi}{\partial t} + \mu \frac{\partial \Phi}{\partial s} - \frac{1-\mu^2}{2} \left( \frac{1}{B}\frac{\partial B}{\partial s} - \frac{F}{E} \right) \frac{\partial \Phi}{\partial \mu} + EF\mu \frac{\partial \Phi}{\partial E} = Q + \langle S \rangle$$

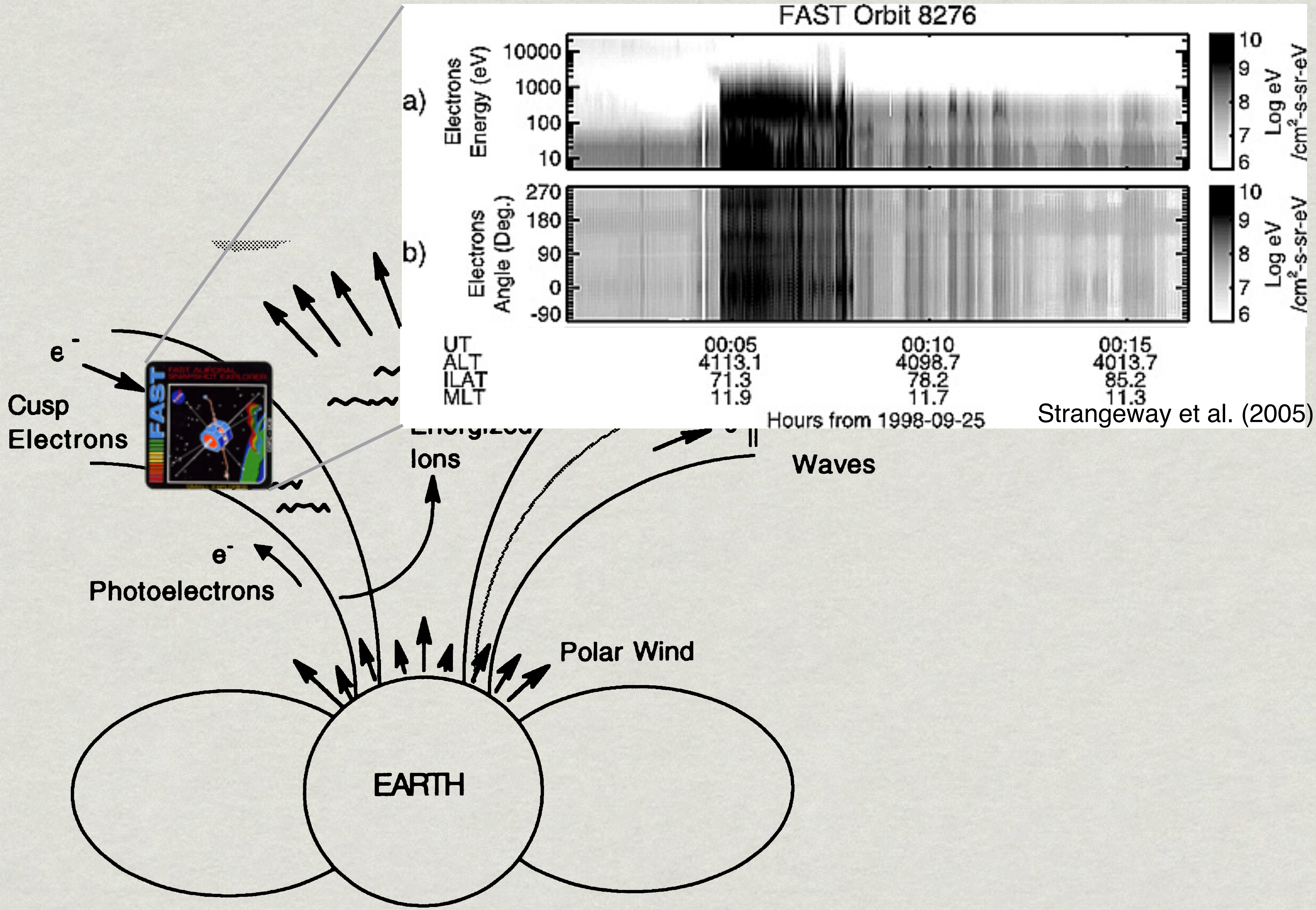
# Modeling Effect of Photoelectrons



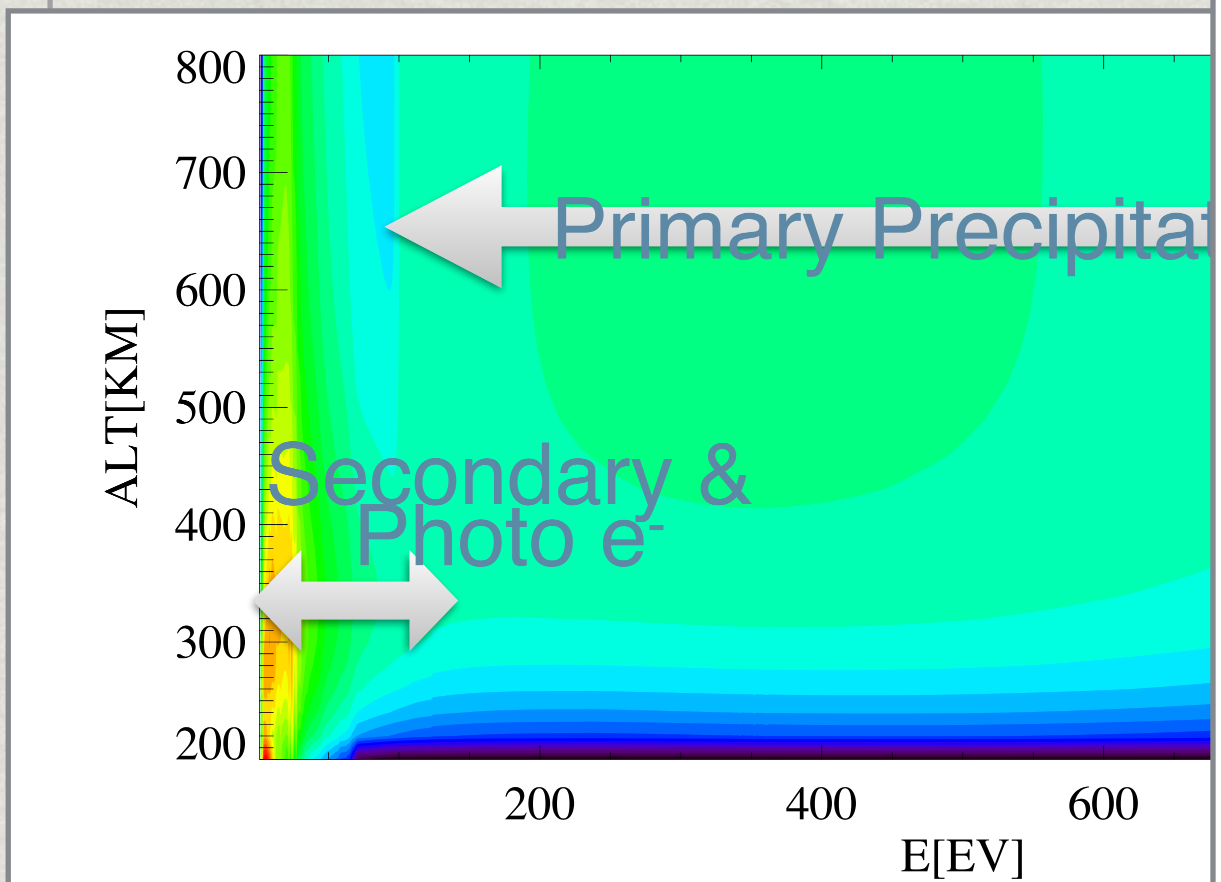



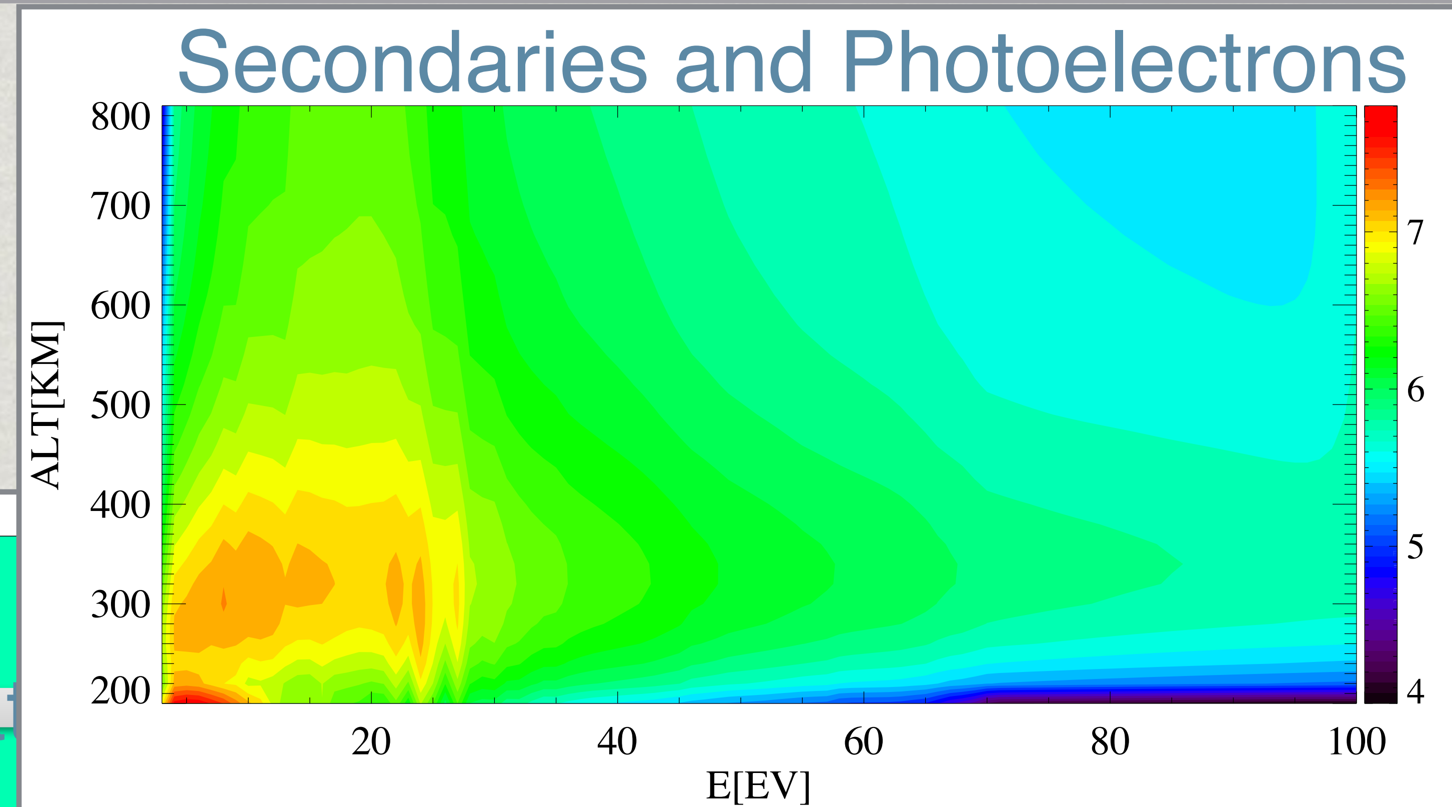

- Steady state solution of stationary field line.
- Solution with photoelectrons increases O+/H+ crossover alt.

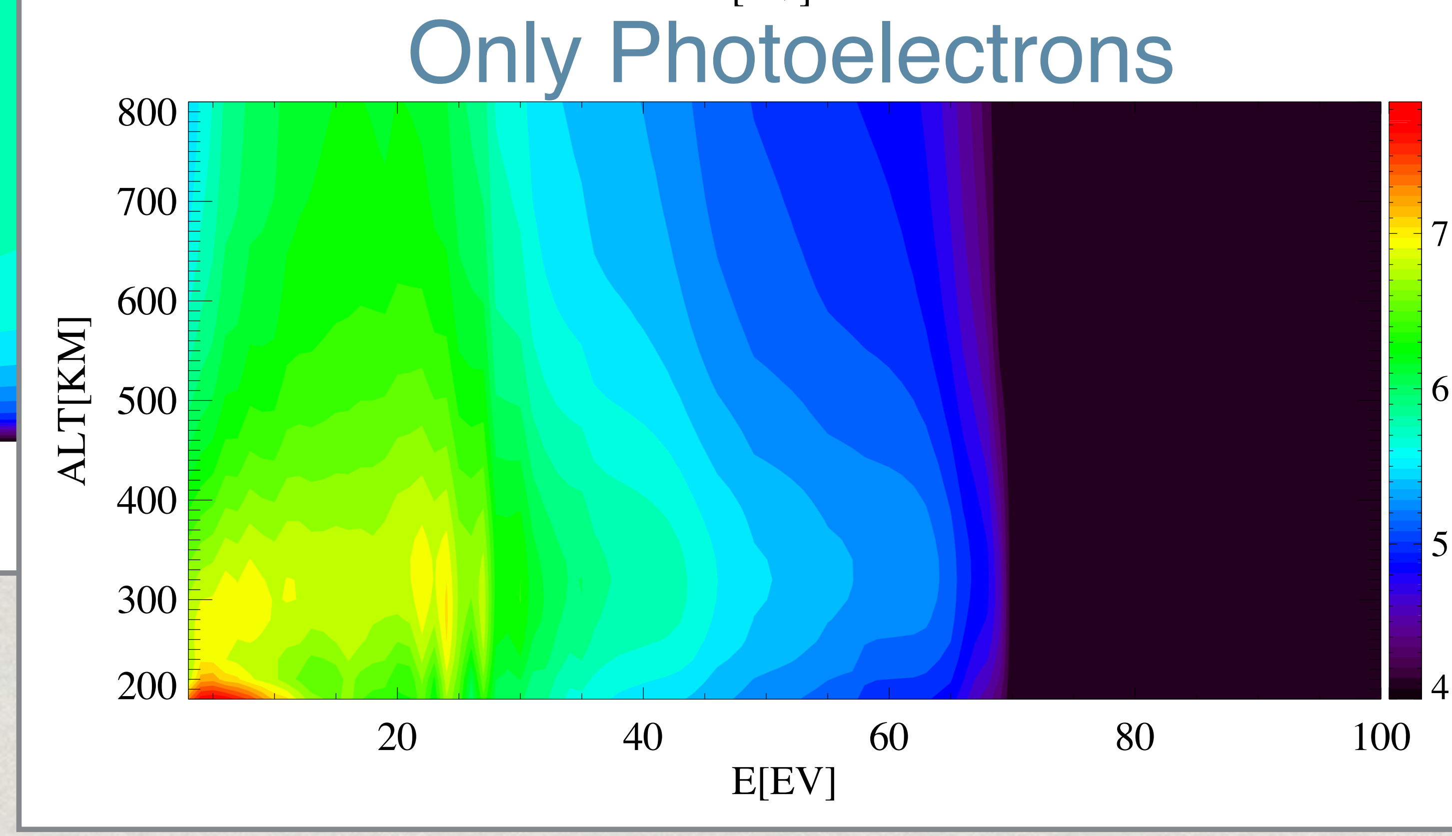
# Modeling Effects of a Soft e⁻ Precipitation Event



# Comparing SE Spectra

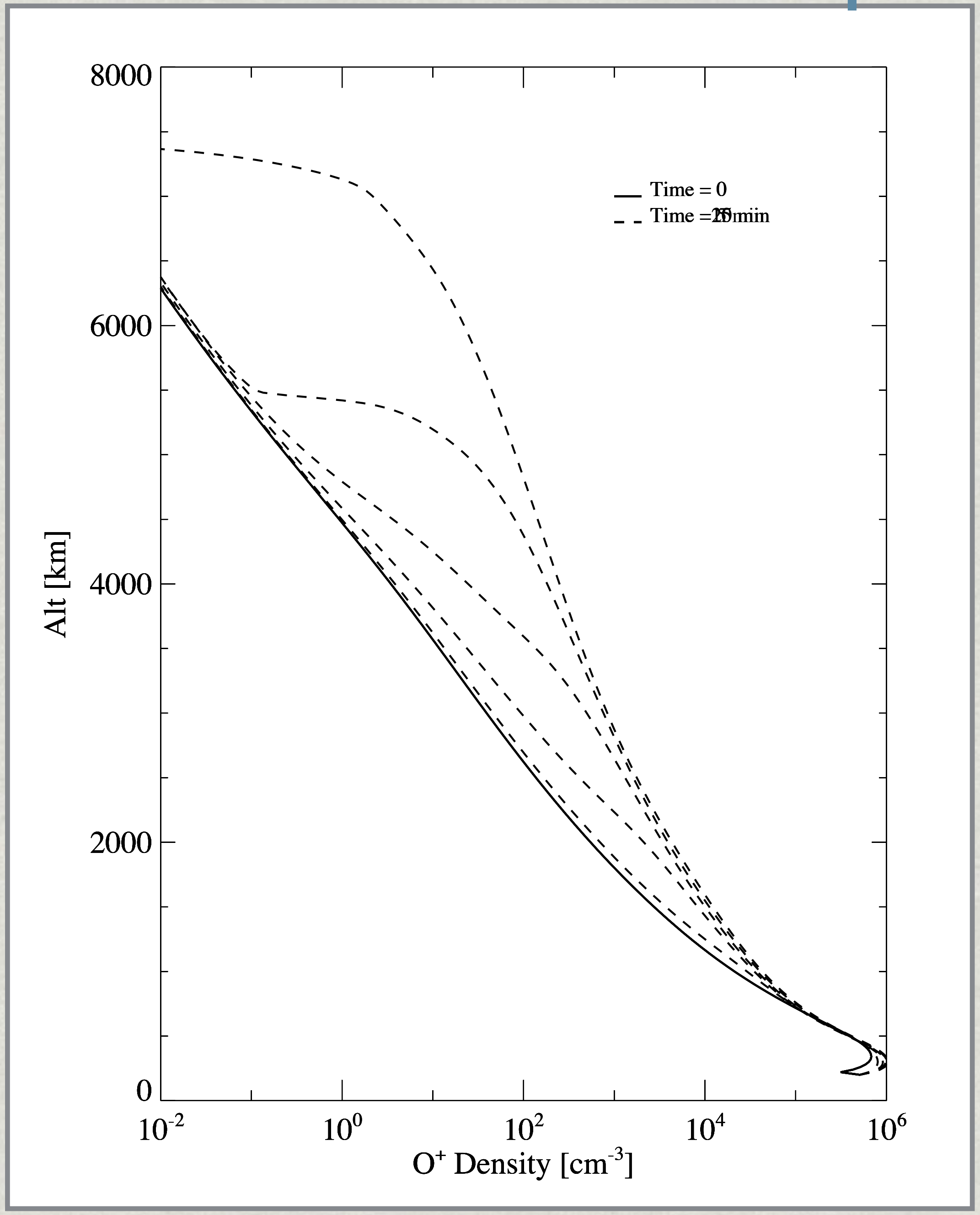


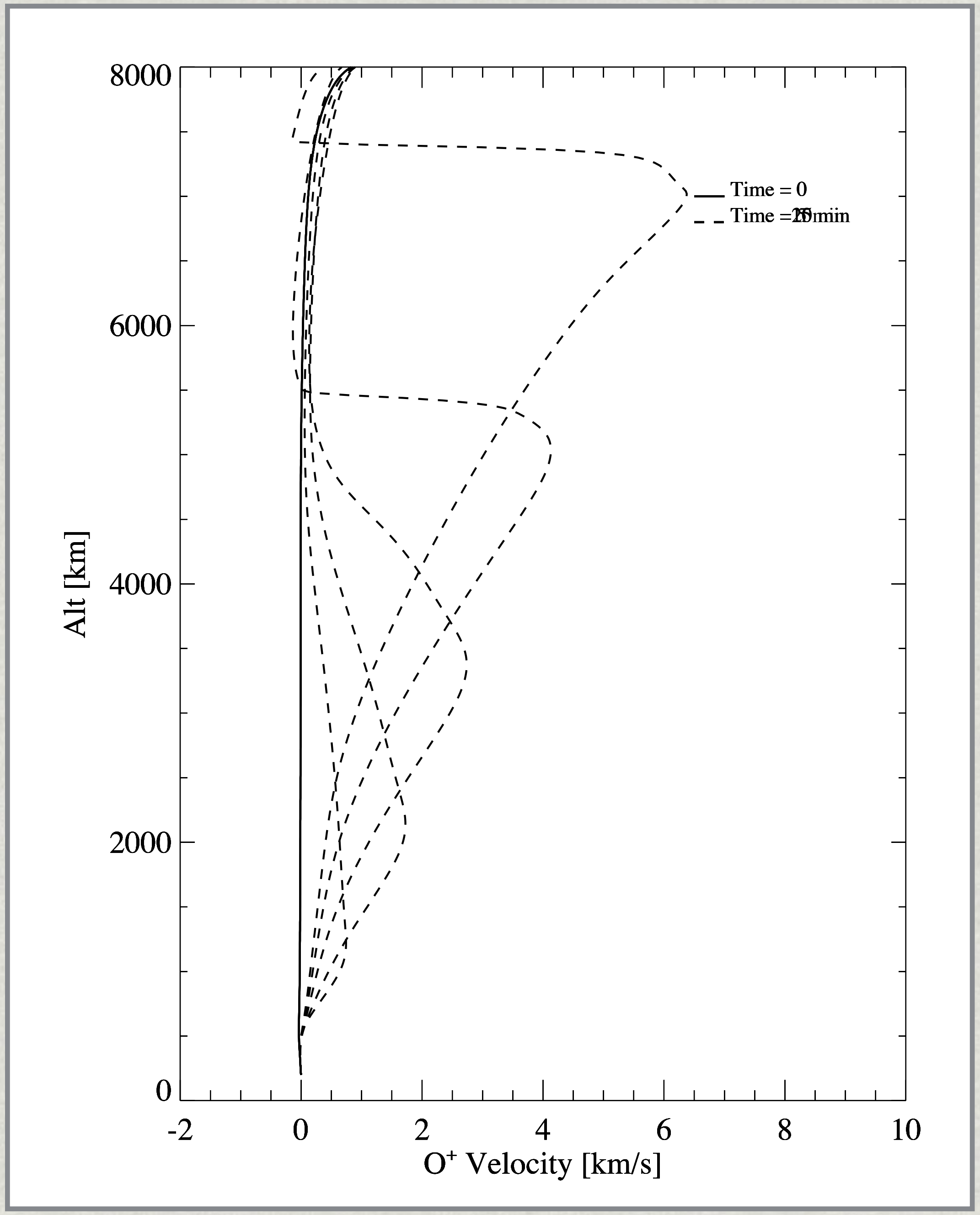




- Soft e- precipitation generates secondaries in topside F region.
- Secondaries contribute much more to the number flux than the primaries.
- Photoelectrons from real conditions of illumination.

# Modeling Effects of a Soft e⁻ Precipitation Event

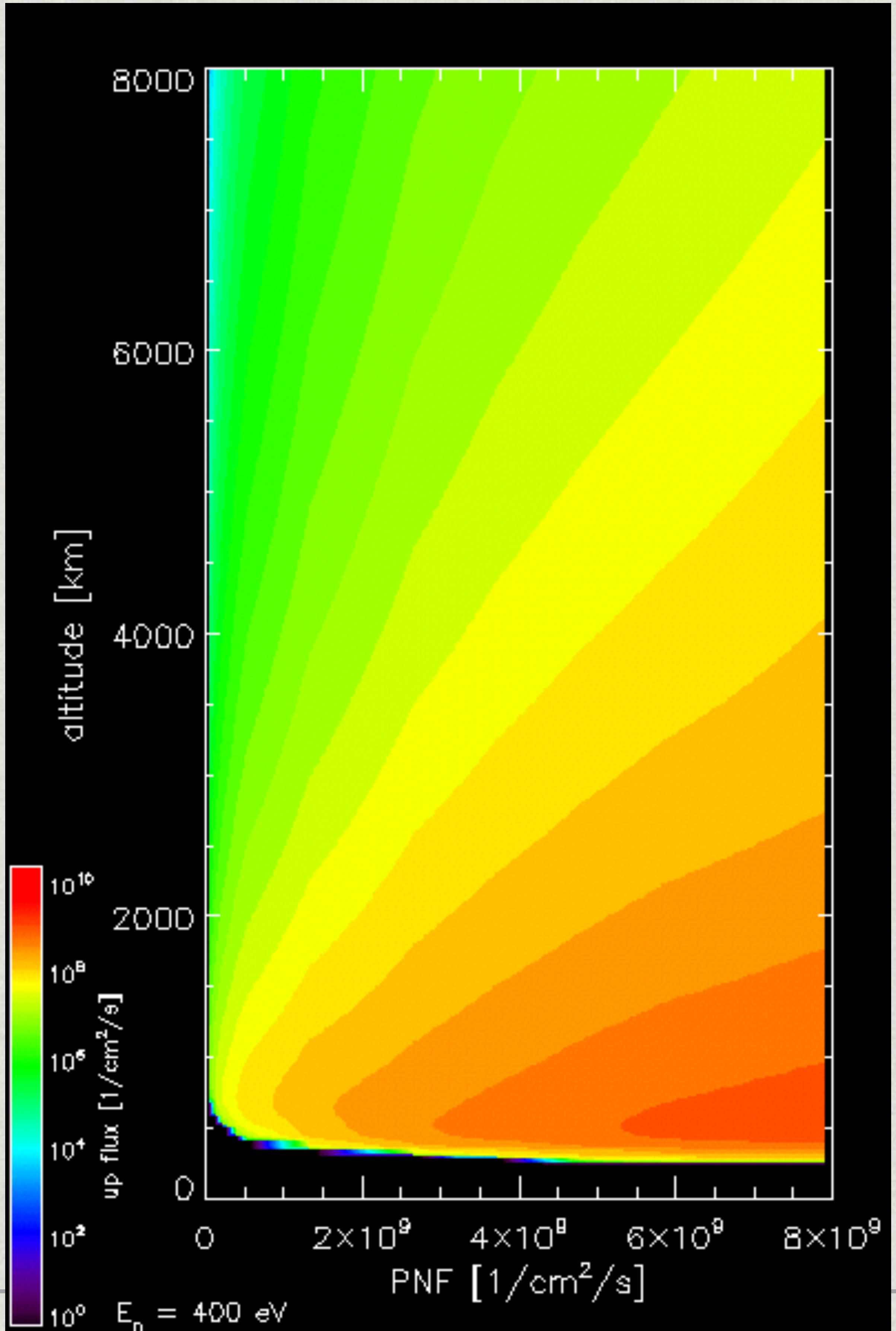



- Strongest response is seen in the O+ where densities at high altitudes increase by orders of magnitude.

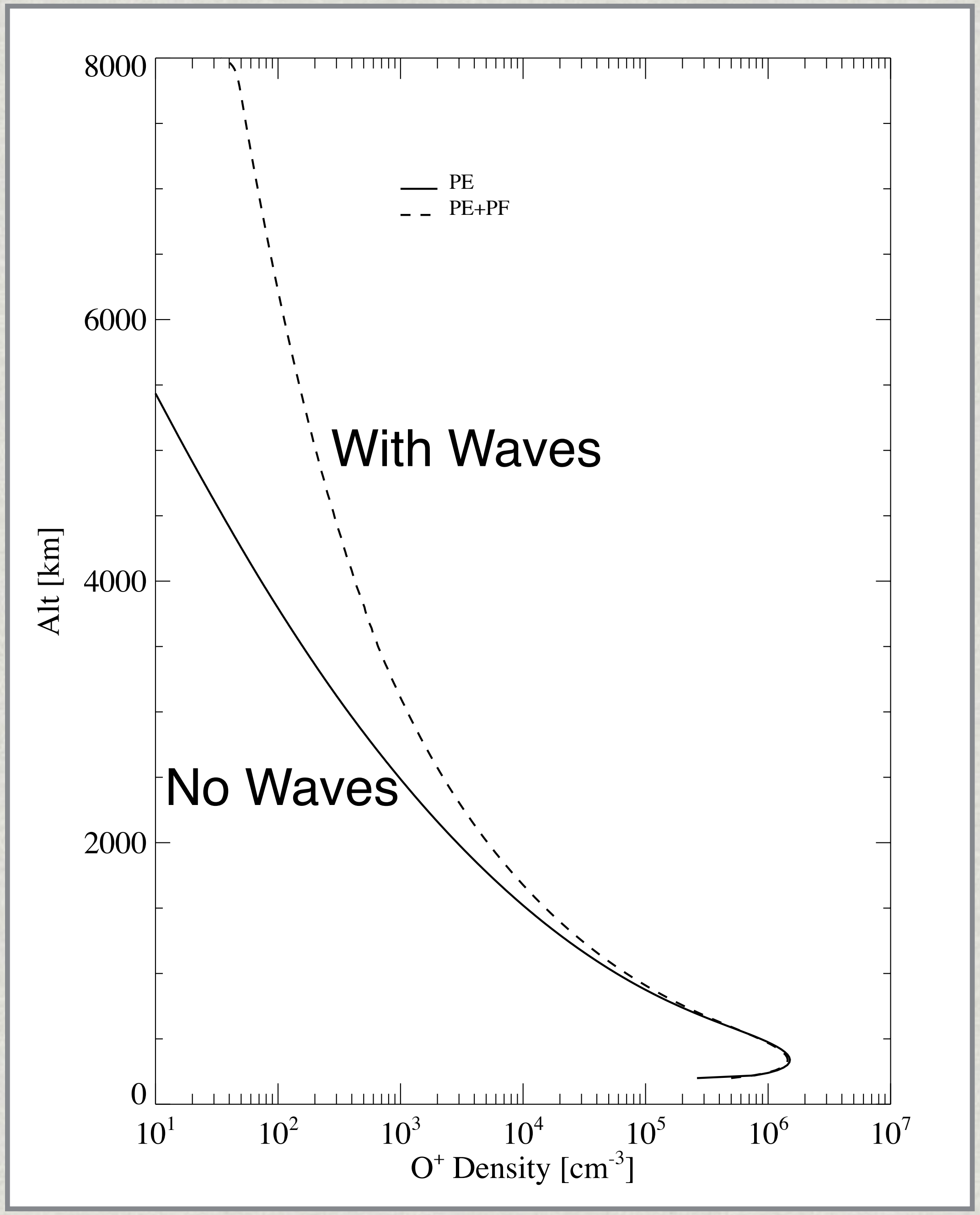
# Scaling of O+ flux with precipitation

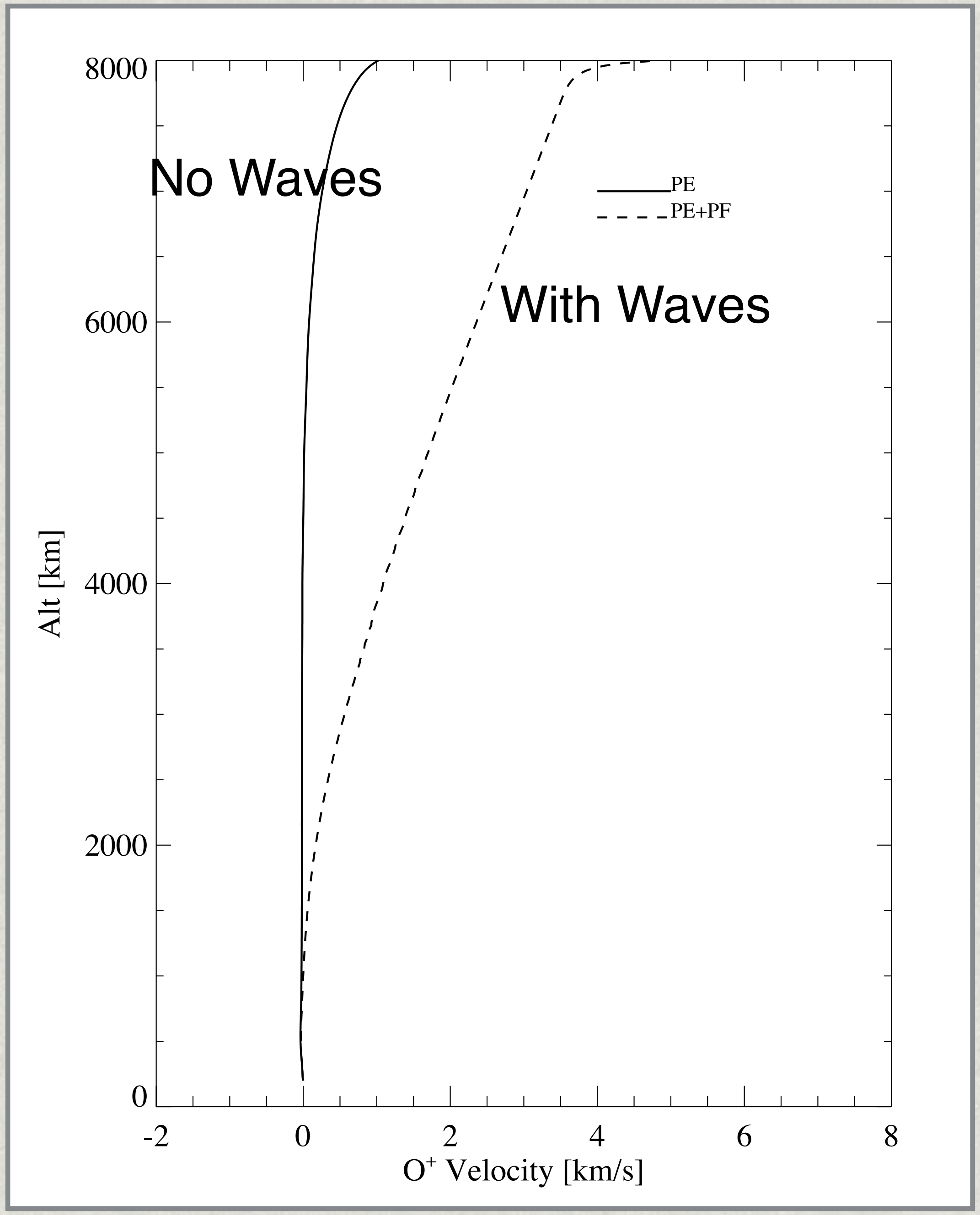
- Holding $E_0$=400eV we increase the intensity of the precipitation in each run.
- The peak O+ flux at each altitude increases with the precipitating number flux.




*Glocer et al.*, [2015]

# Including the Effect of Waves



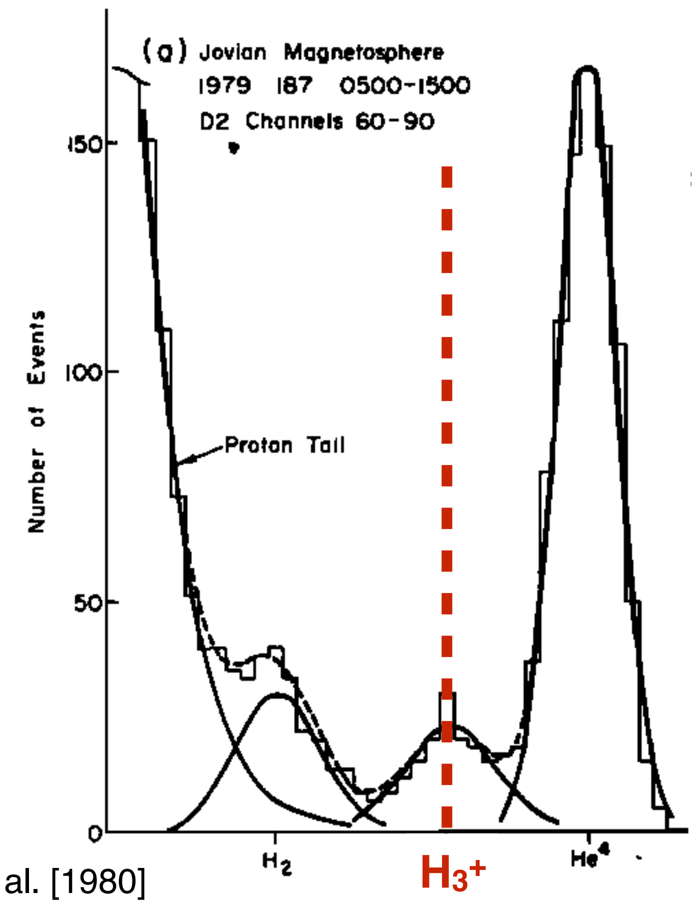




- Assume wave with E=50 mV/m

$$F_p = -\frac{1}{8}\frac{E^2_{wave}}{B^2_o}\frac{\rho_o}{\rho^{1.5}}\frac{\partial \rho}{\partial r}$$

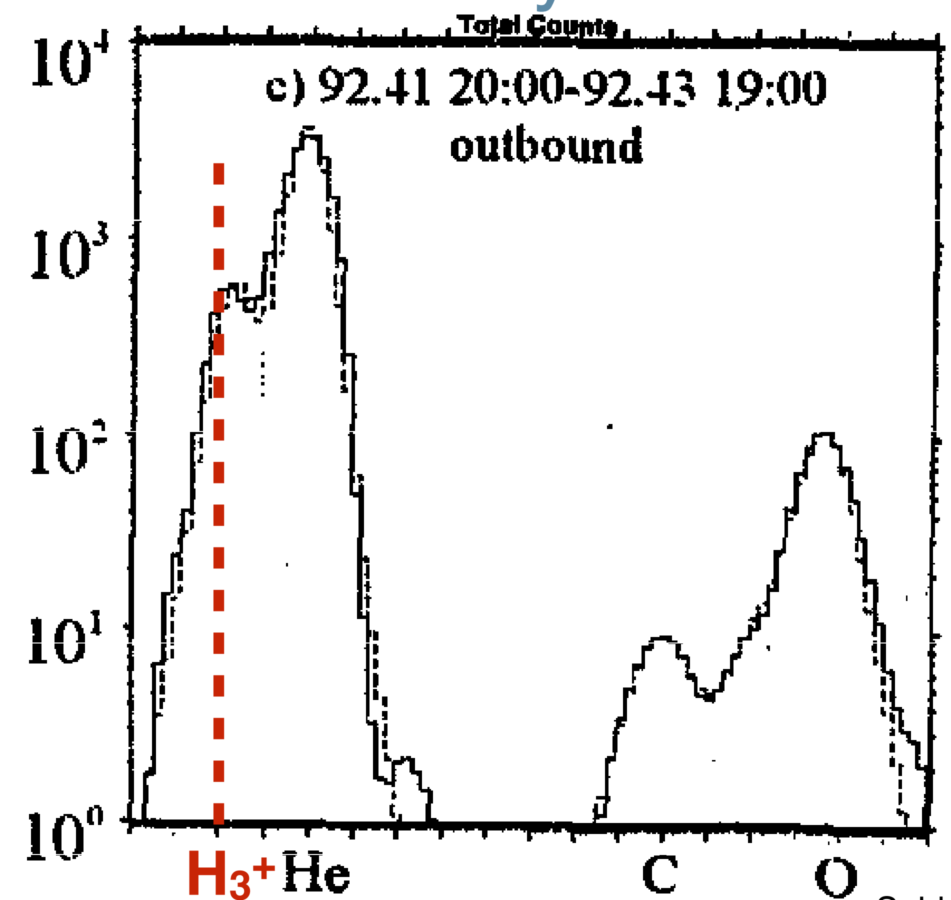
# Jupiter's Ionosphere a a Magnetospheric Plasma Source

## Voyager 2

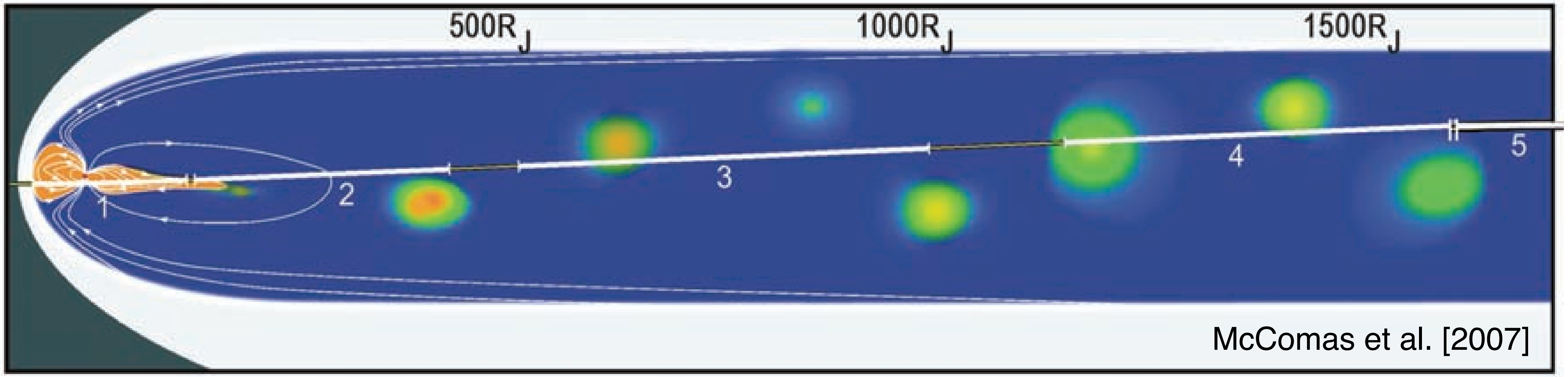



Hamilton et al. [1980]

## Ulysses




Seidel et al. [1997]



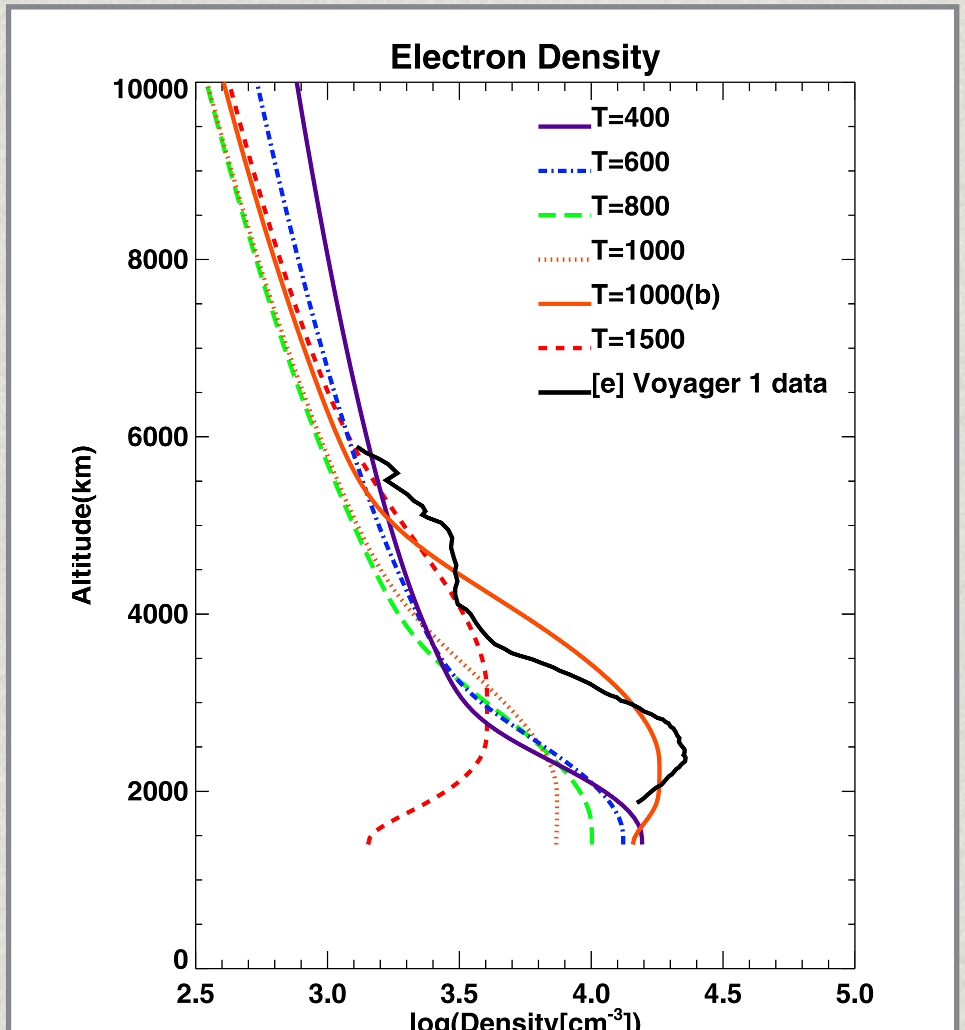

McComas et al. [2007]

# Next Steps

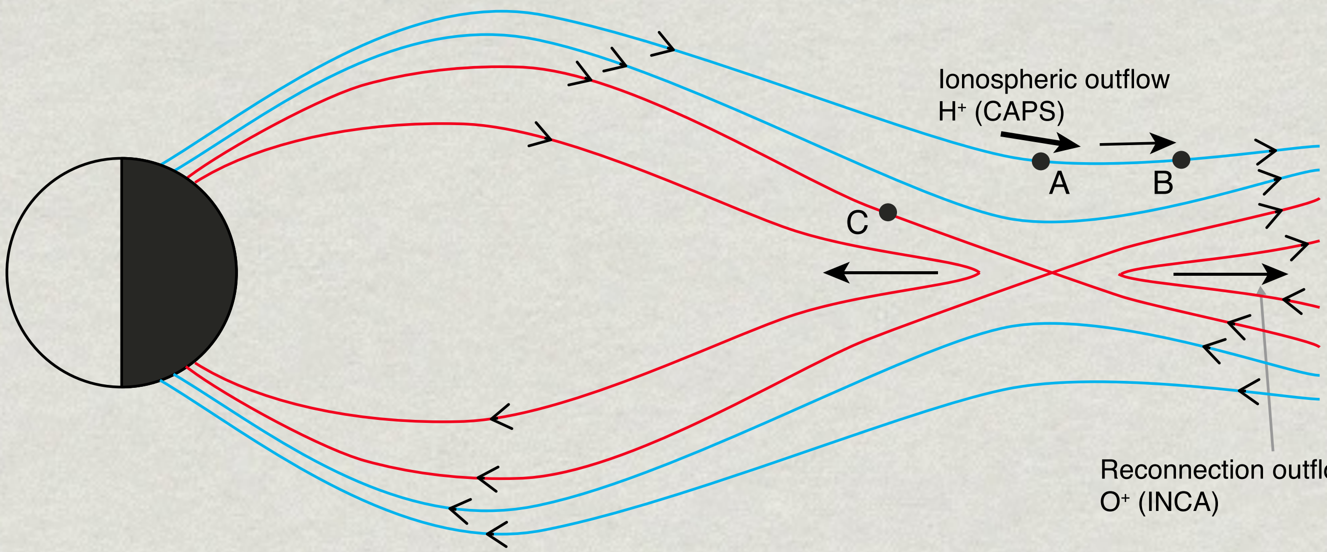
- Recent development will be published (papers in preparation).
- Planetary applications such as Jupiter, Saturn, exoplanets are being pursued.
- KePWOM will soon be updated in SWMF.
- KePWOM made available through CCMC this year.

# Thank You

# Ionospheric Outflow at Saturn



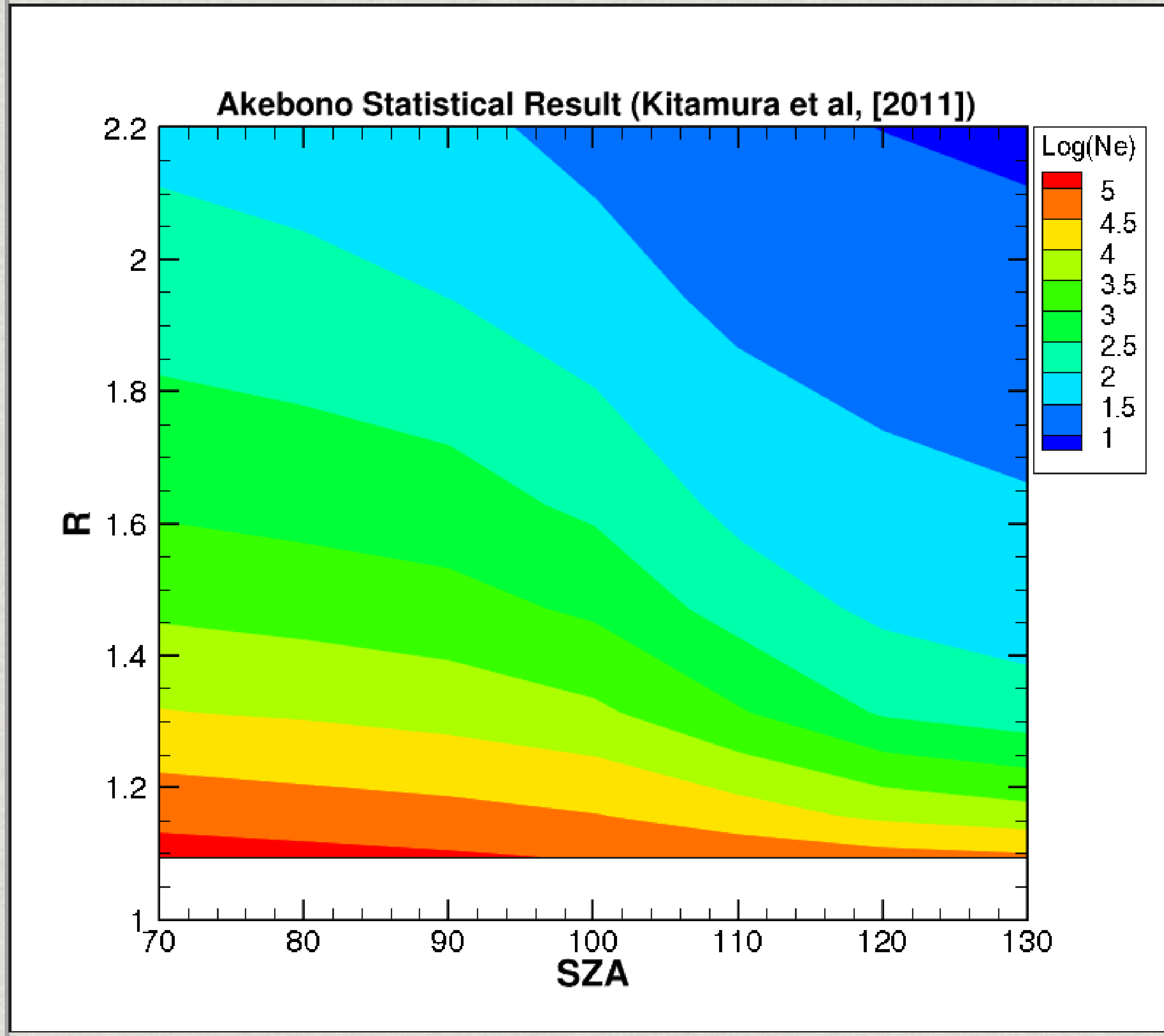

Glocer et al. [2006]

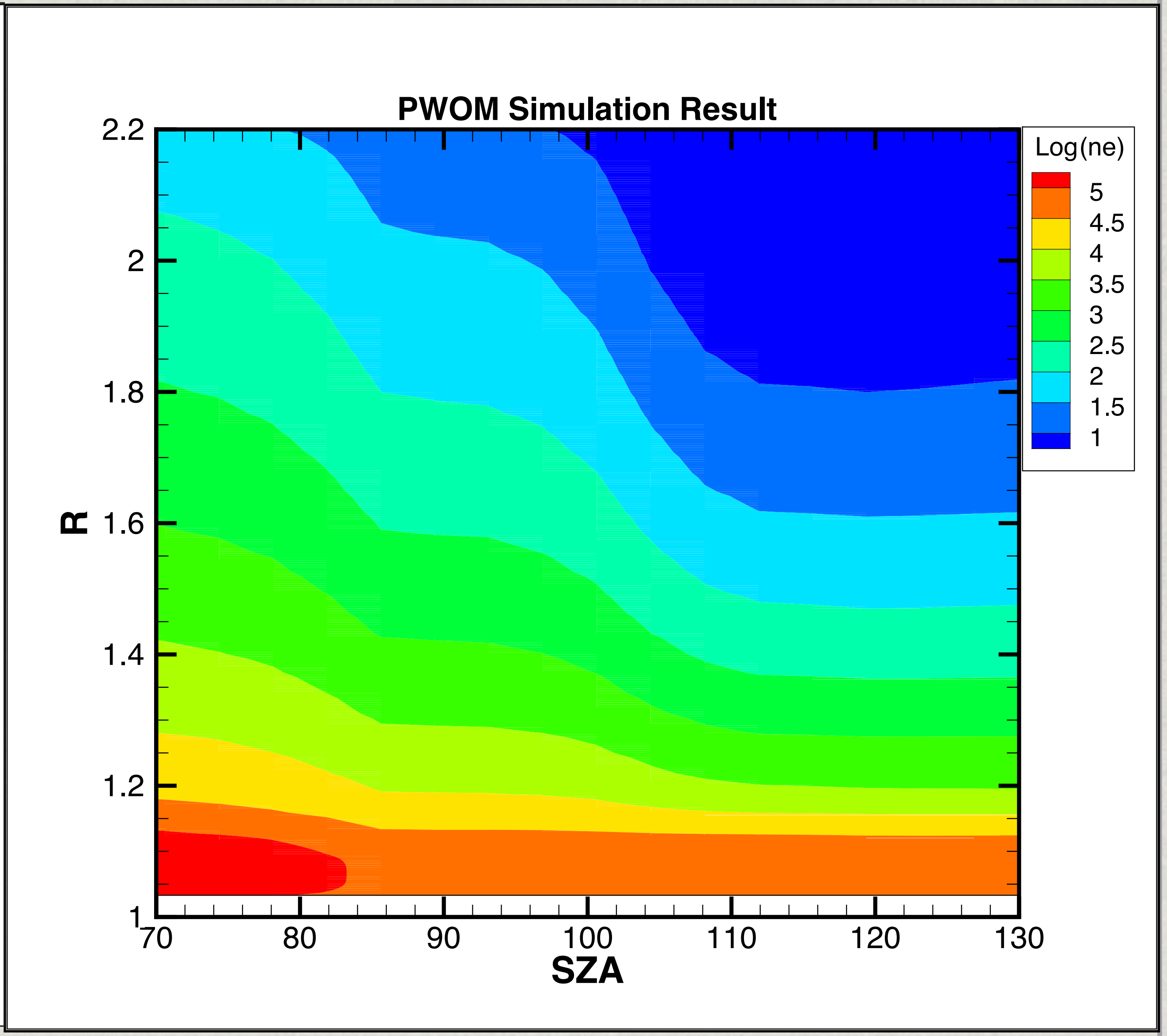



Felici et al. [2016]

- *Glocer et al.* [2006]: Fluxes ~$10^8$cm$^{-2}$s$^{-1}$ at 10,000km
- *Felici et al.* [2016]: Fluxes ~$10^9$-$10^{10}$ cm$^{-2}$s$^{-1}$ at 10,000km
- Discrepancy points to importance of auroral processes not included in prior theoretical calculation.

# SZA Dependence of $N_e$

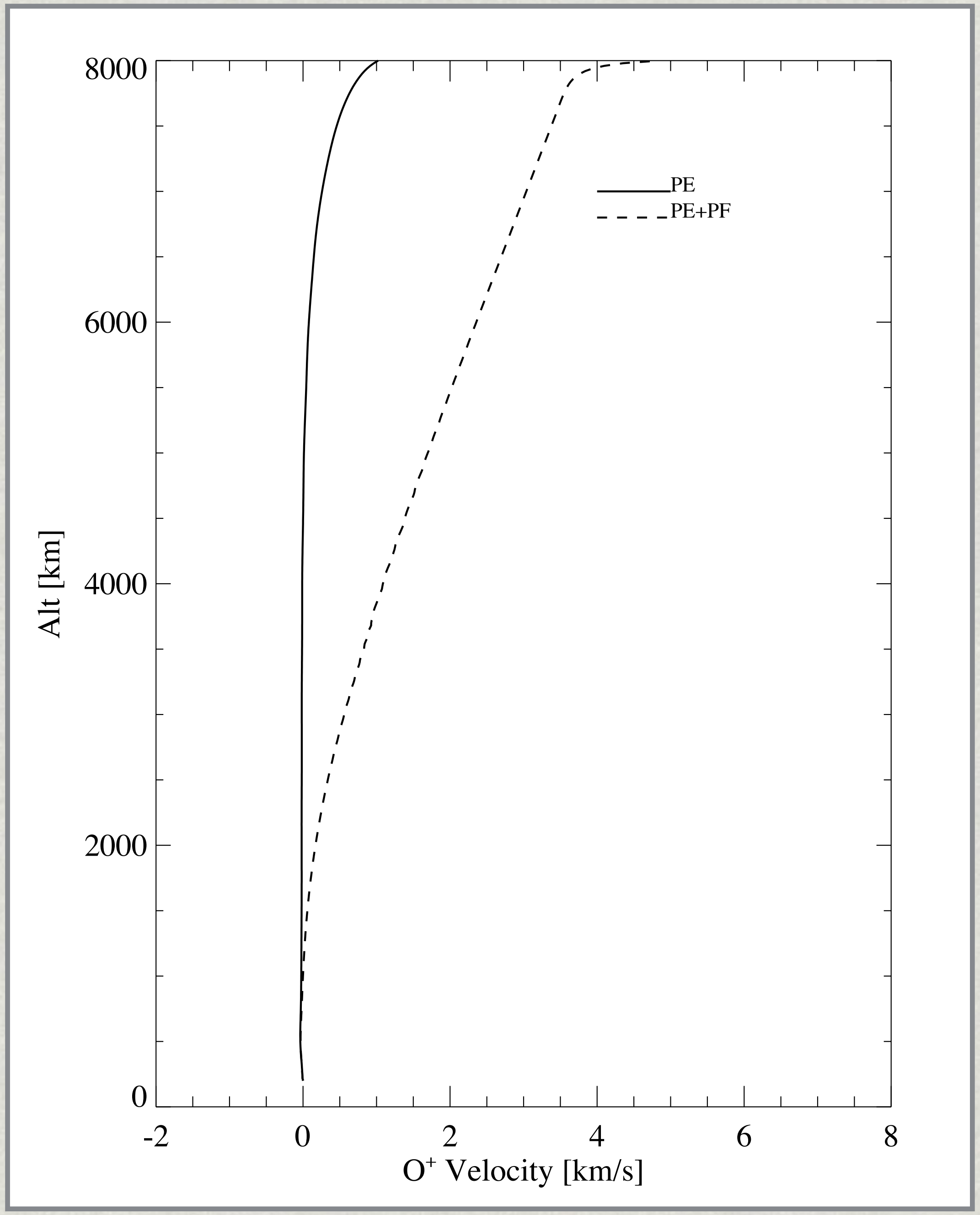



- Comparison of Empirical fit to Akebono data and PWOM Calculation
- Photoelectrons can explain the SZA structure in the quite time outflow

*Glocer et al.*, [2012]

# Modeling Effect of Ponderomotive Force

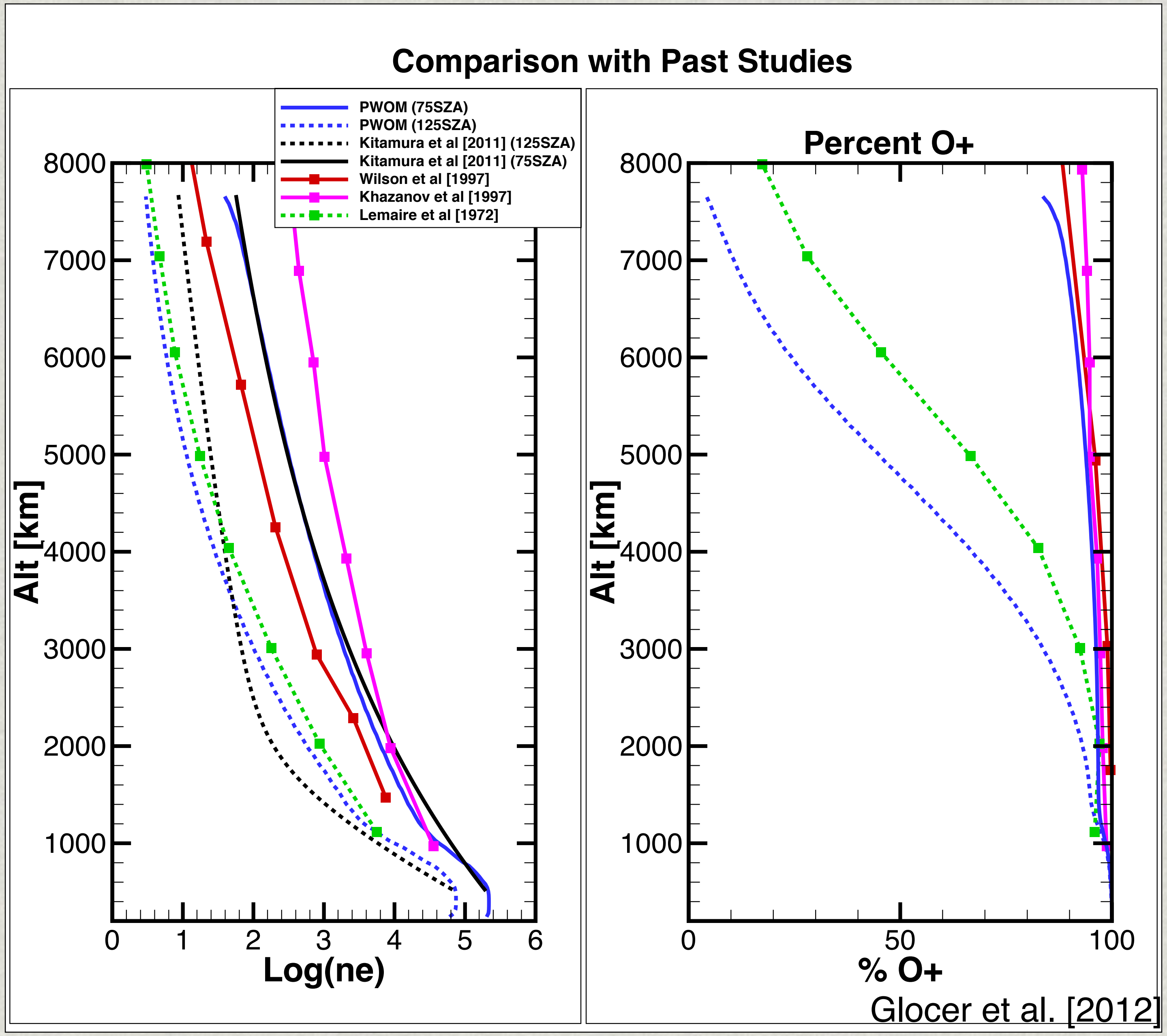


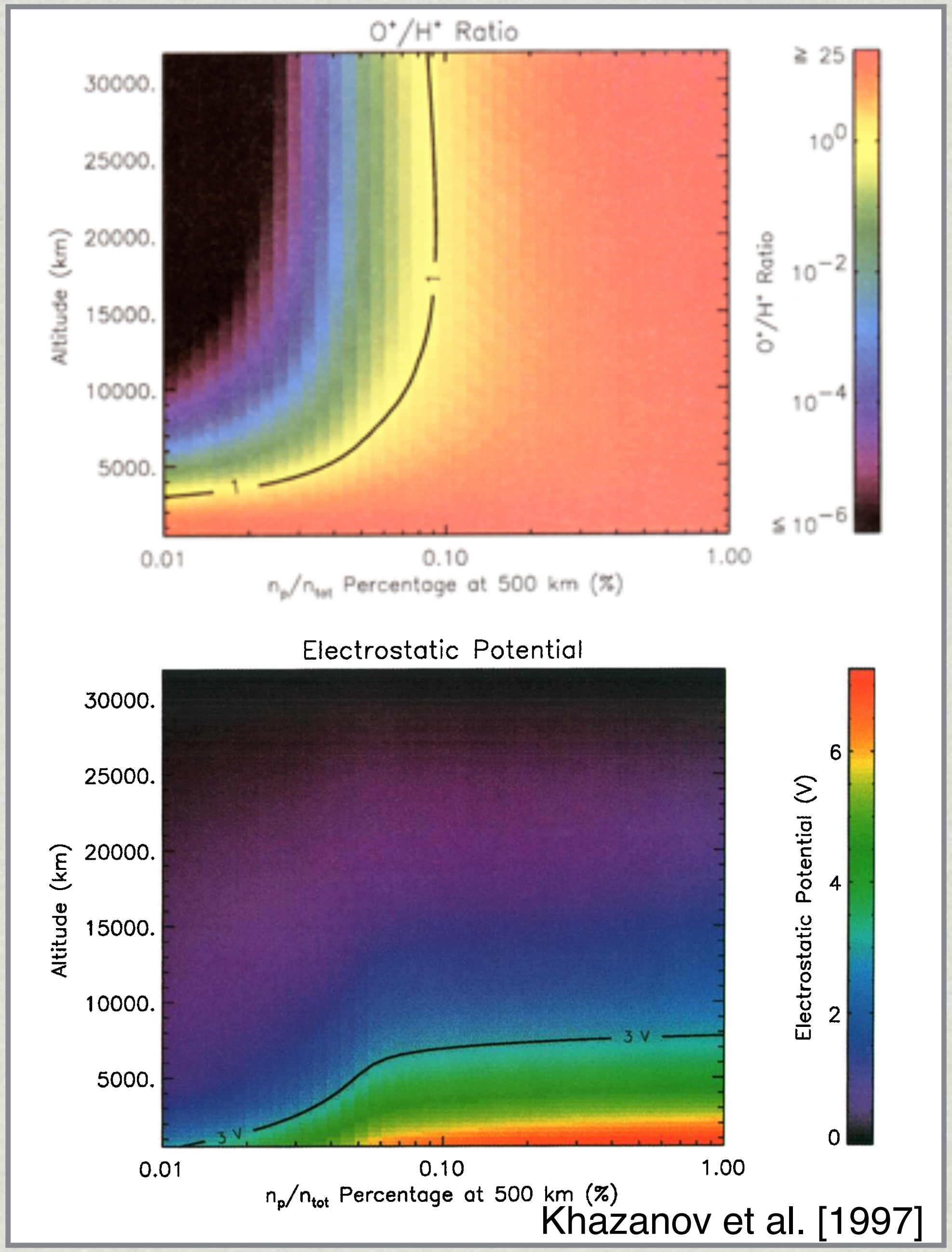

- Assume wave with E=50 mV/m

$$F_p = -\frac{1}{8}\frac{E_{wave}^2}{B_o^2}\frac{\rho_o}{\rho^{1.5}}\frac{\partial \rho}{\partial r}$$

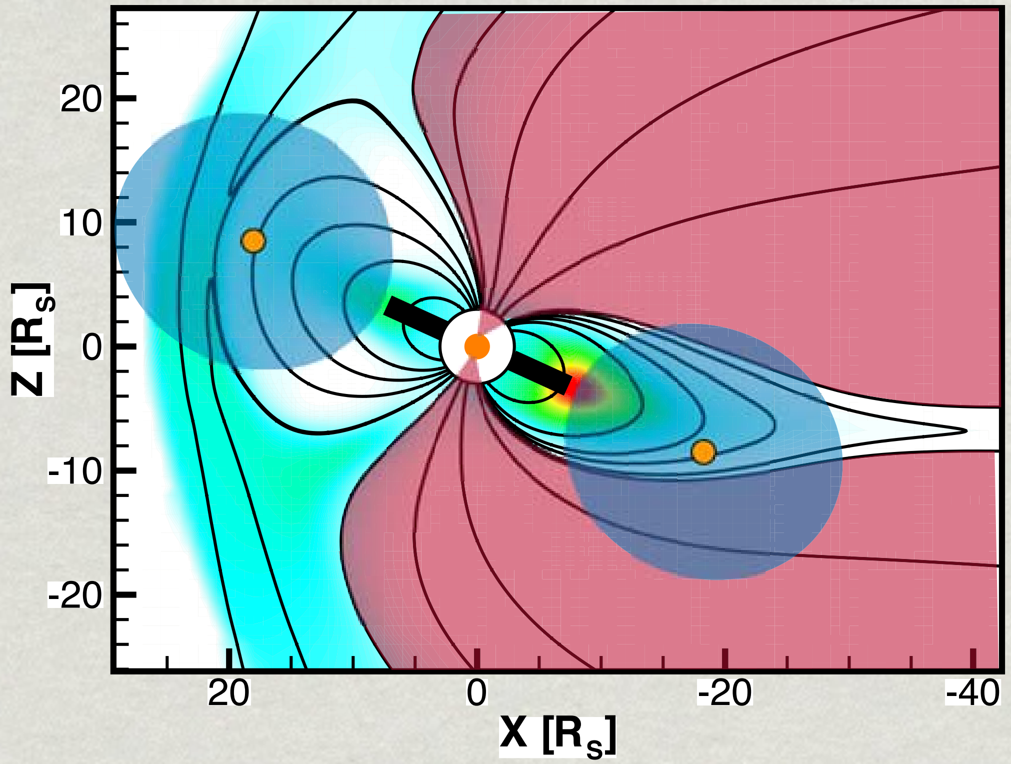
*Glocer et al.*, [2015]

# Effect of SEs on Composition

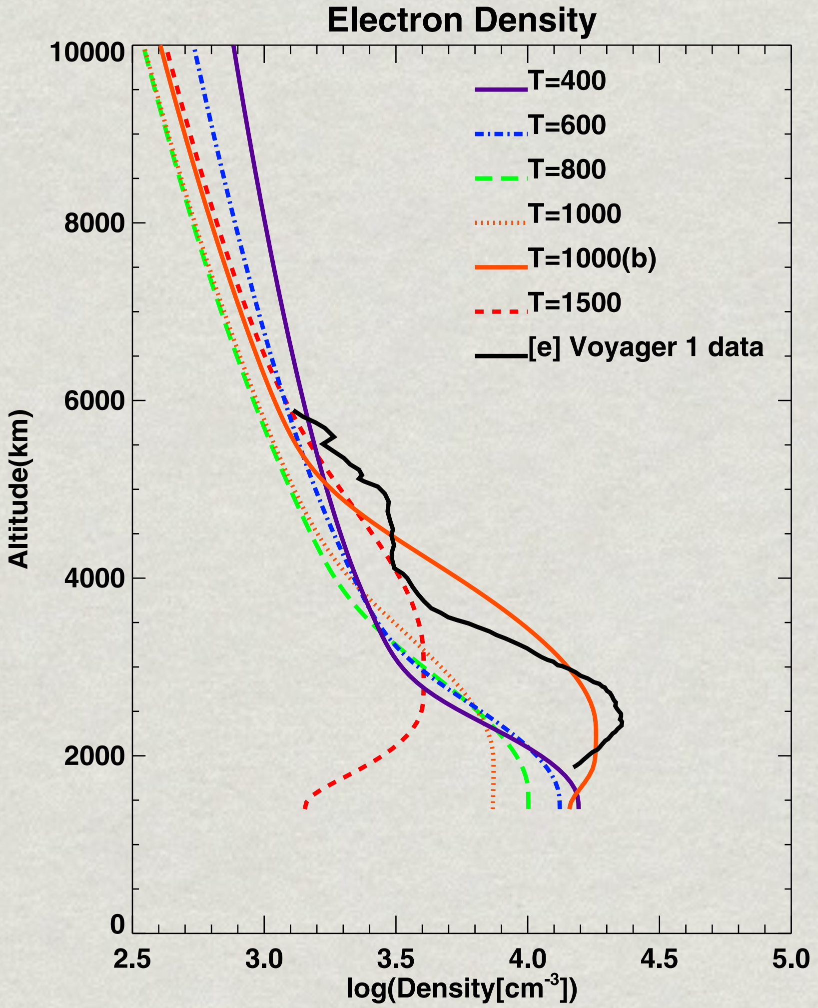



- Studies including photoelectrons are primarily $O^+$ to high altitude as photoelectron concentration increases.
- Secondary electrons act just as photoelectrons do.

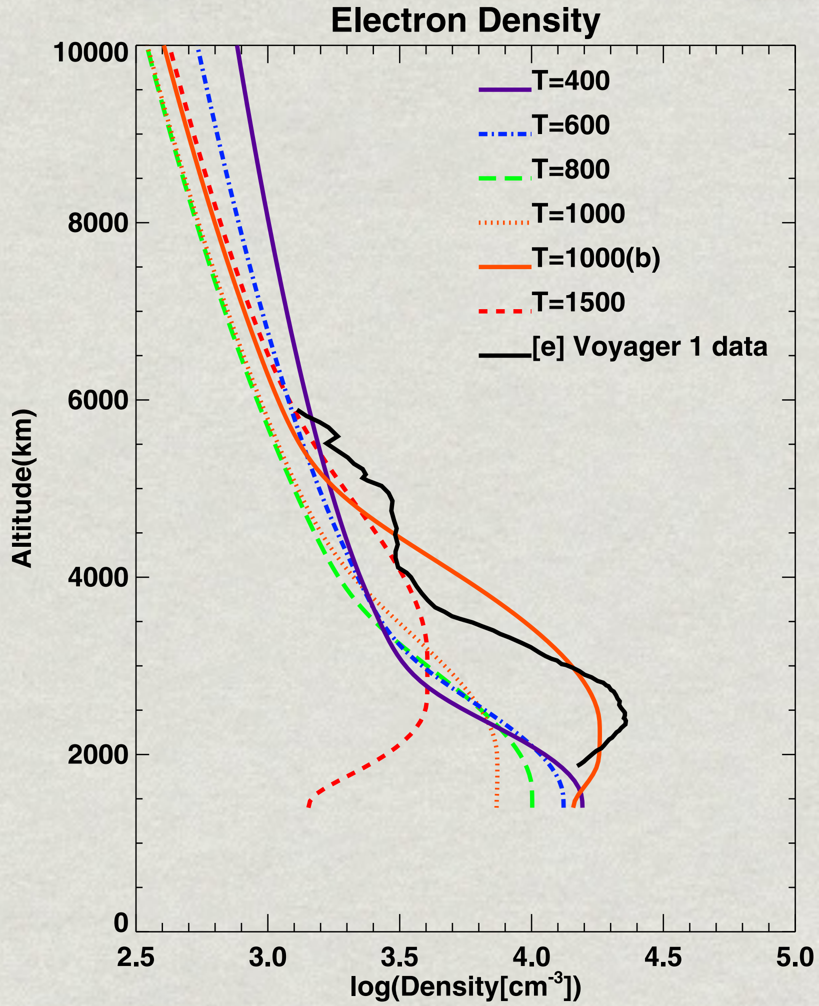


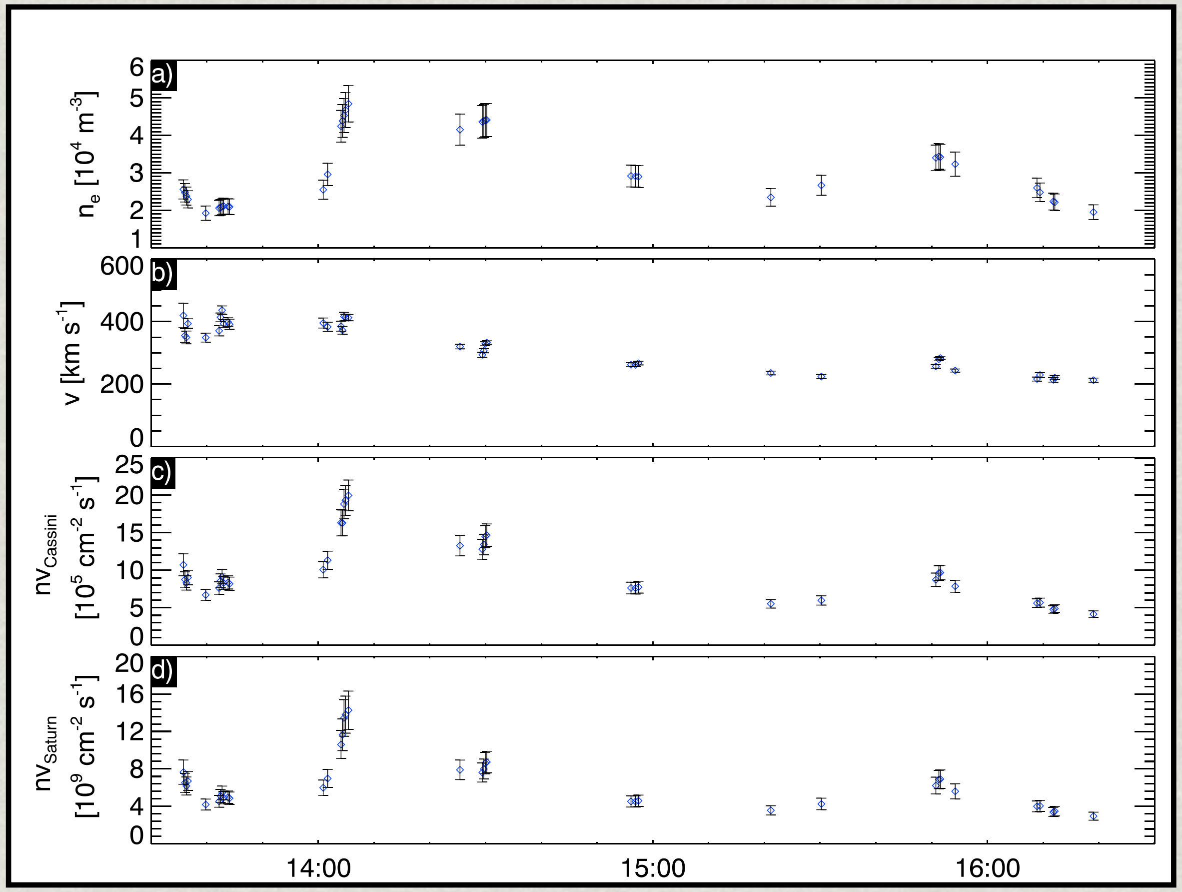
20
10
0
-10
-20
Z [R_S]
20
0
-20
-40
X [R_S]

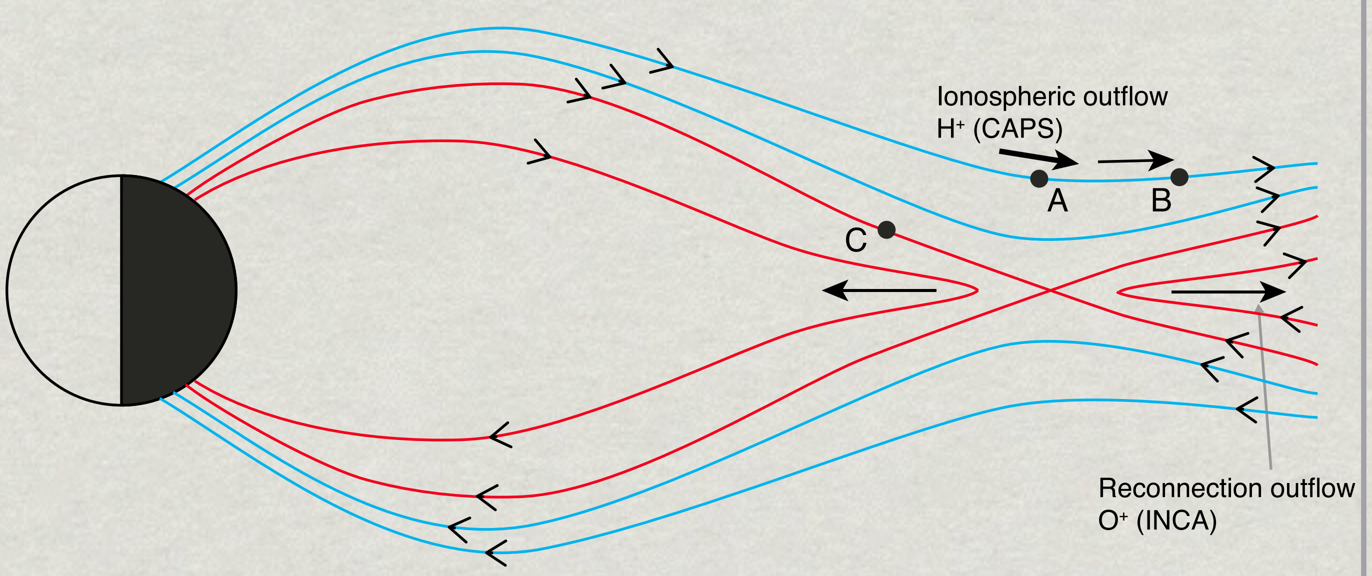



Electron Density
T=400
T=600
T=800
T=1000
T=1000(b)
T=1500
[e] Voyager 1 data
Altitude(km)
10000
8000
6000
4000
2000
0
2.5
3.0
3.5
4.0
4.5
5.0
log(Density[cm^-3])

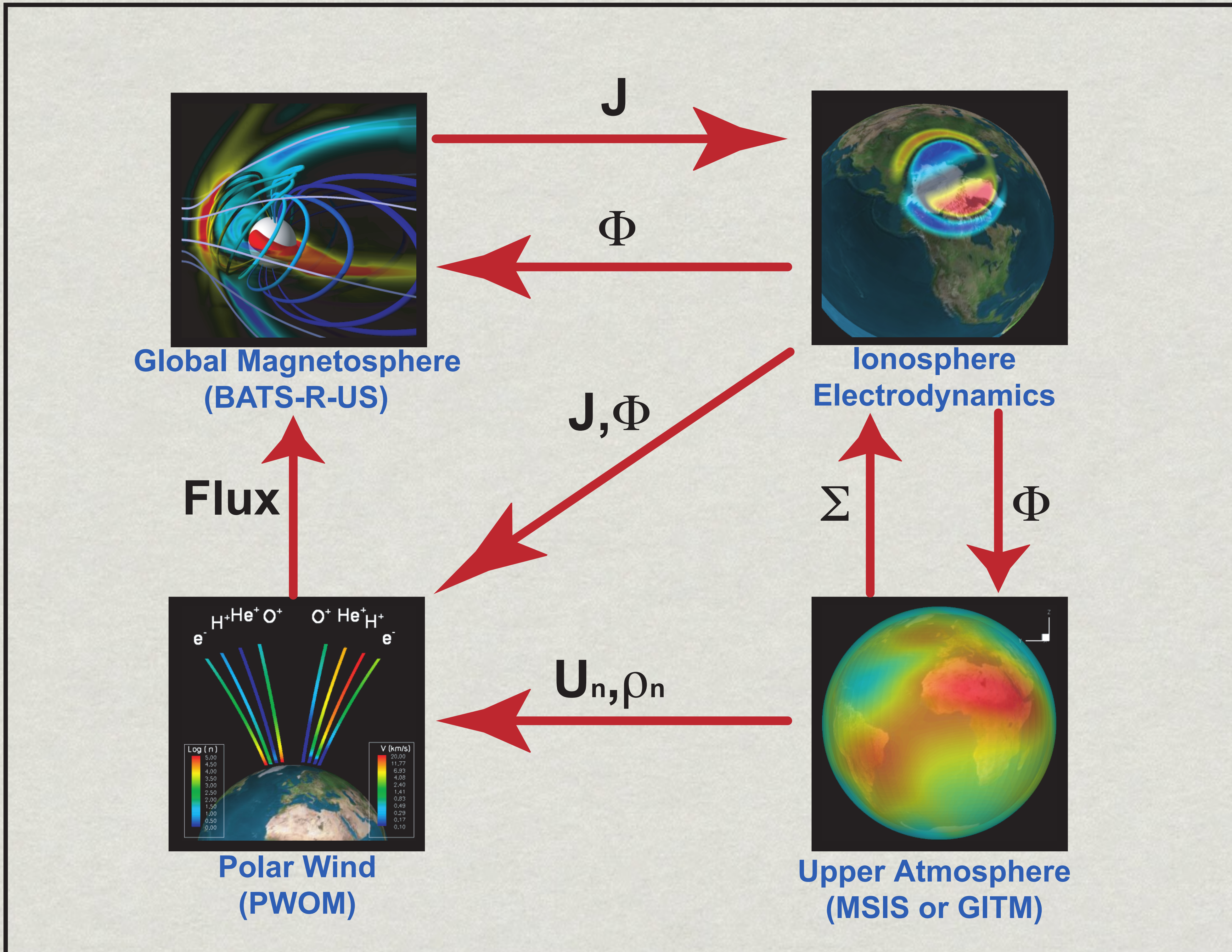
# Ionospheric Outflow at Saturn



# Coupling PWOM to Global MHD



# The Topside Electron Heat flux

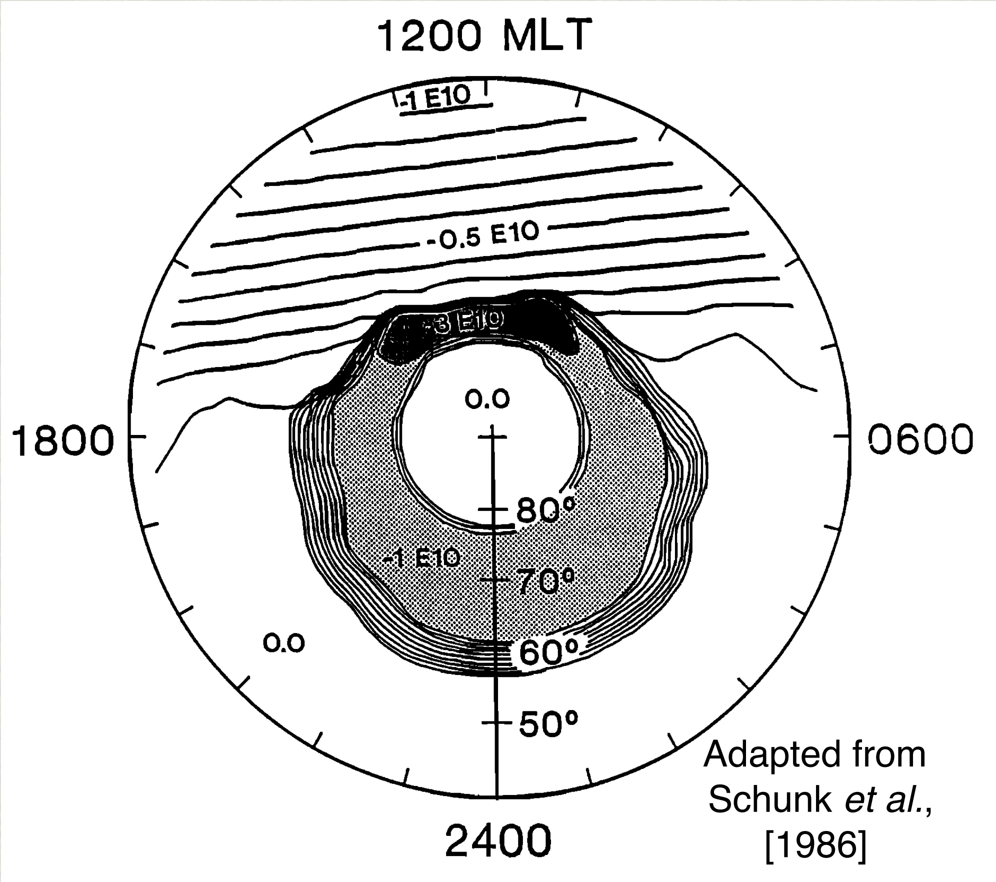
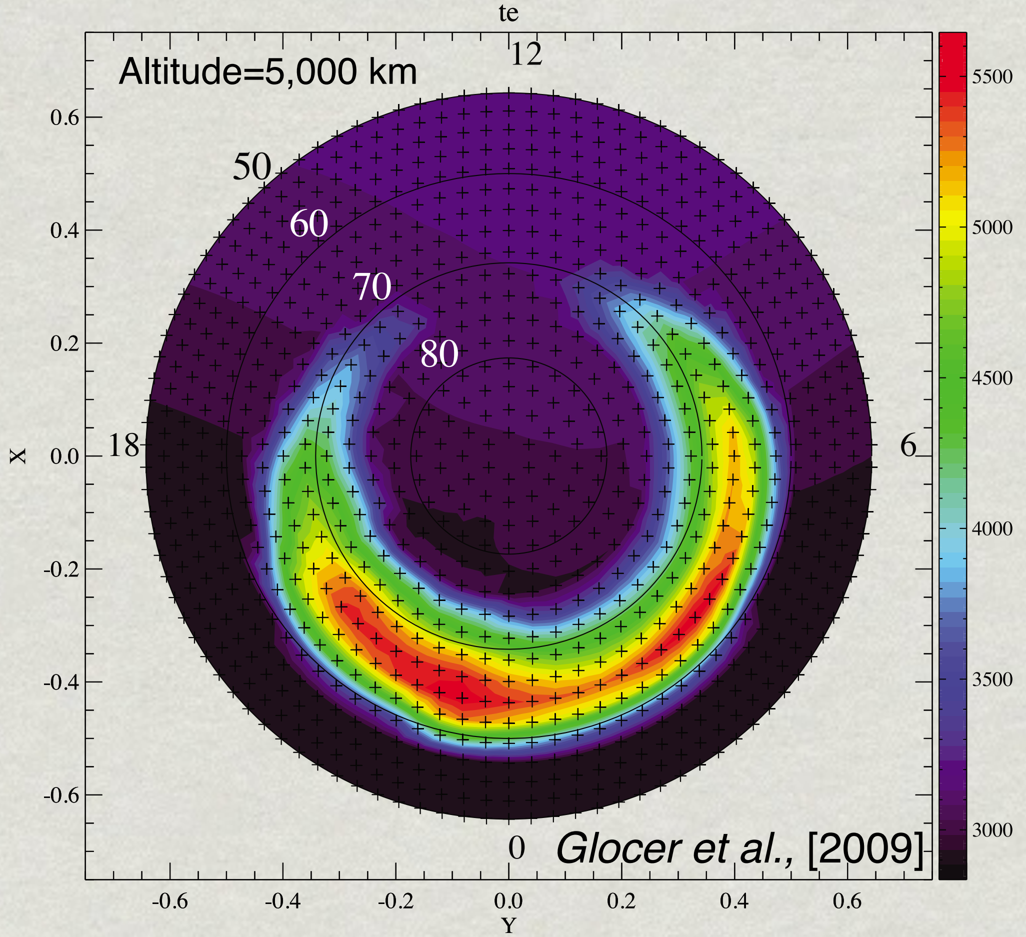
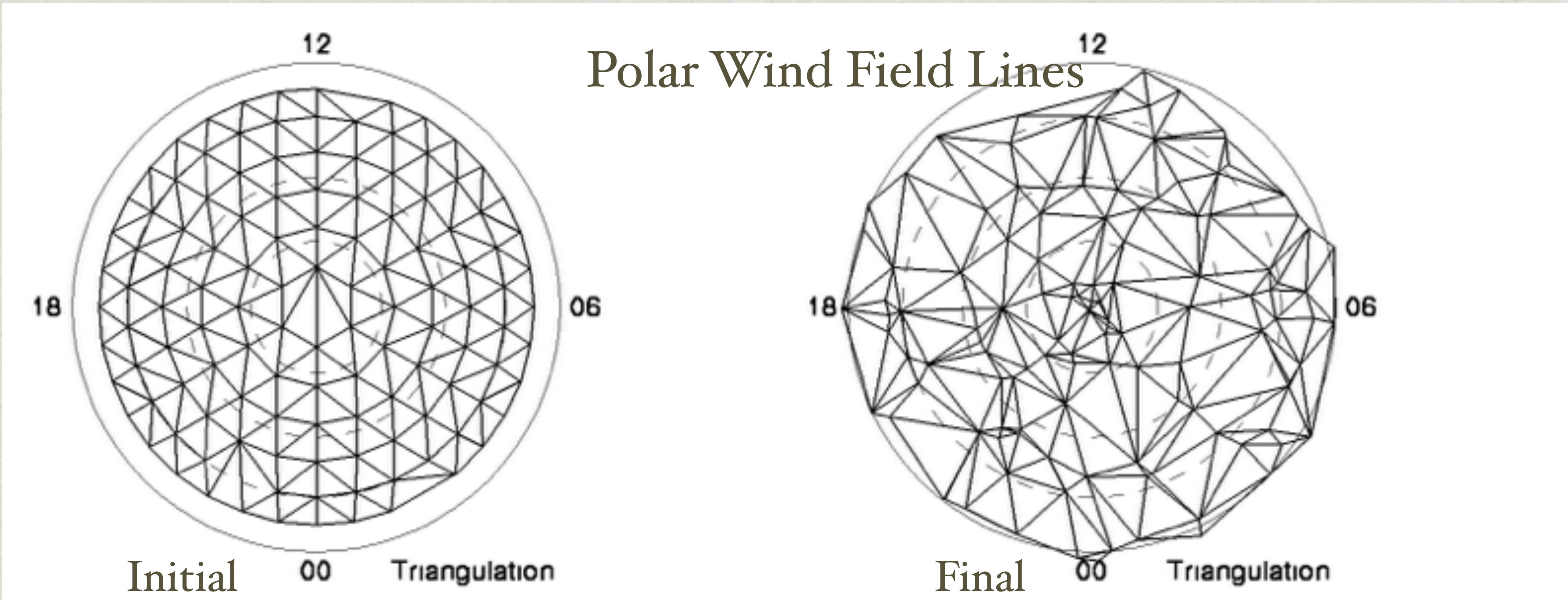


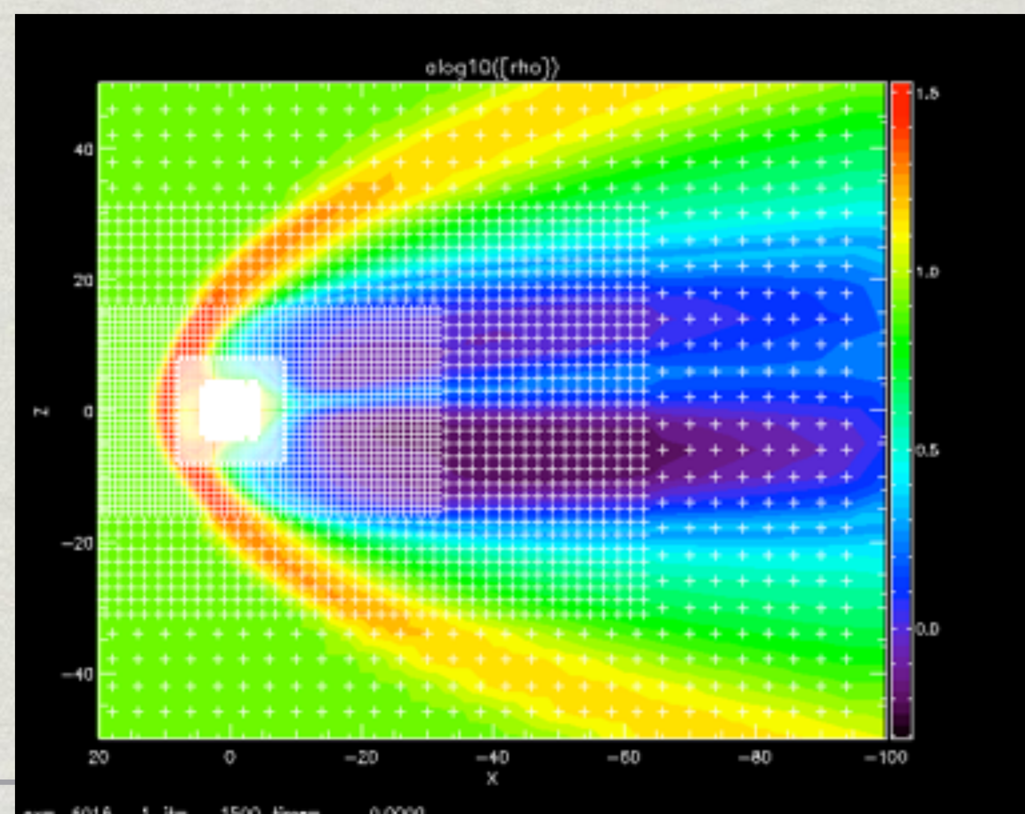

Fig. 12. Upper boundary heat flux (eV cm$^{-2}$ s$^{-1}$) at 1700 UT as a function of magnetic latitude and MLT.



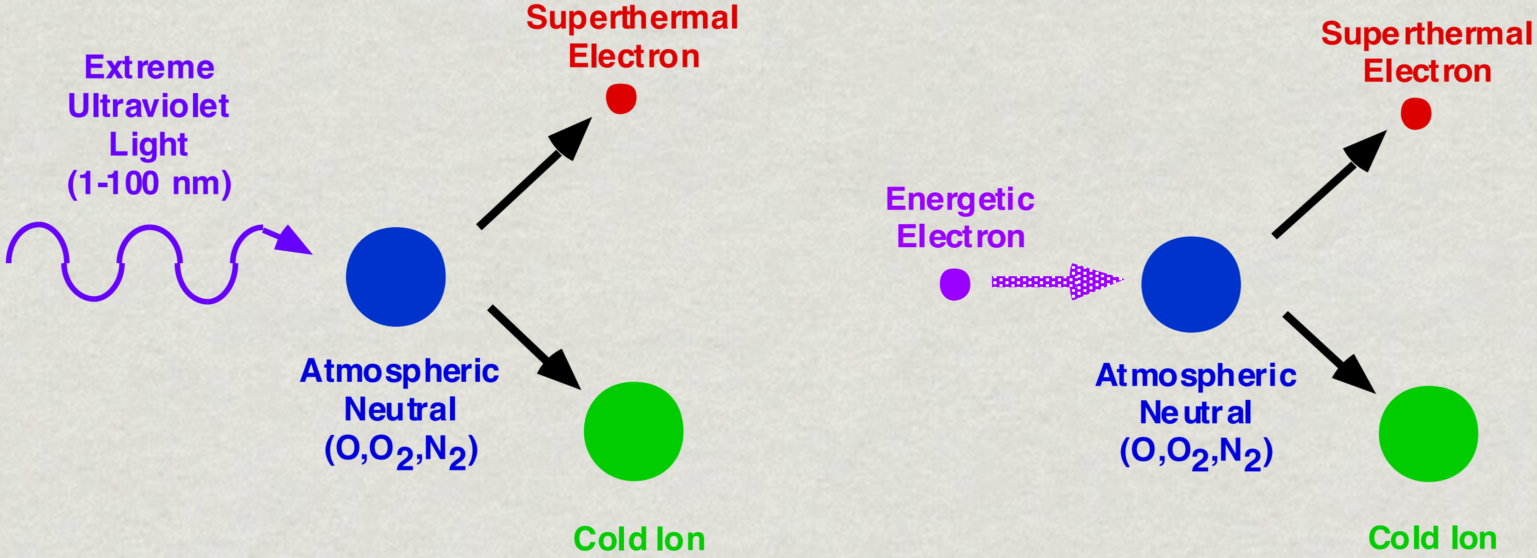

- A crude way to include the effects of SEs is to specify the topside electron heat flux.
- *Schunk et al.*, [1986] proposed a "heat flux map" that could give electron temperatures roughly consistant with data (see left).
- We adapt a modified version of this in PWOM and the electron temperatures that result are shown on the right.
- However this is a very ill-constrained parameter! Proper treatment of SEs is needed to handle this problem properly.

# Interfacing PW and GM



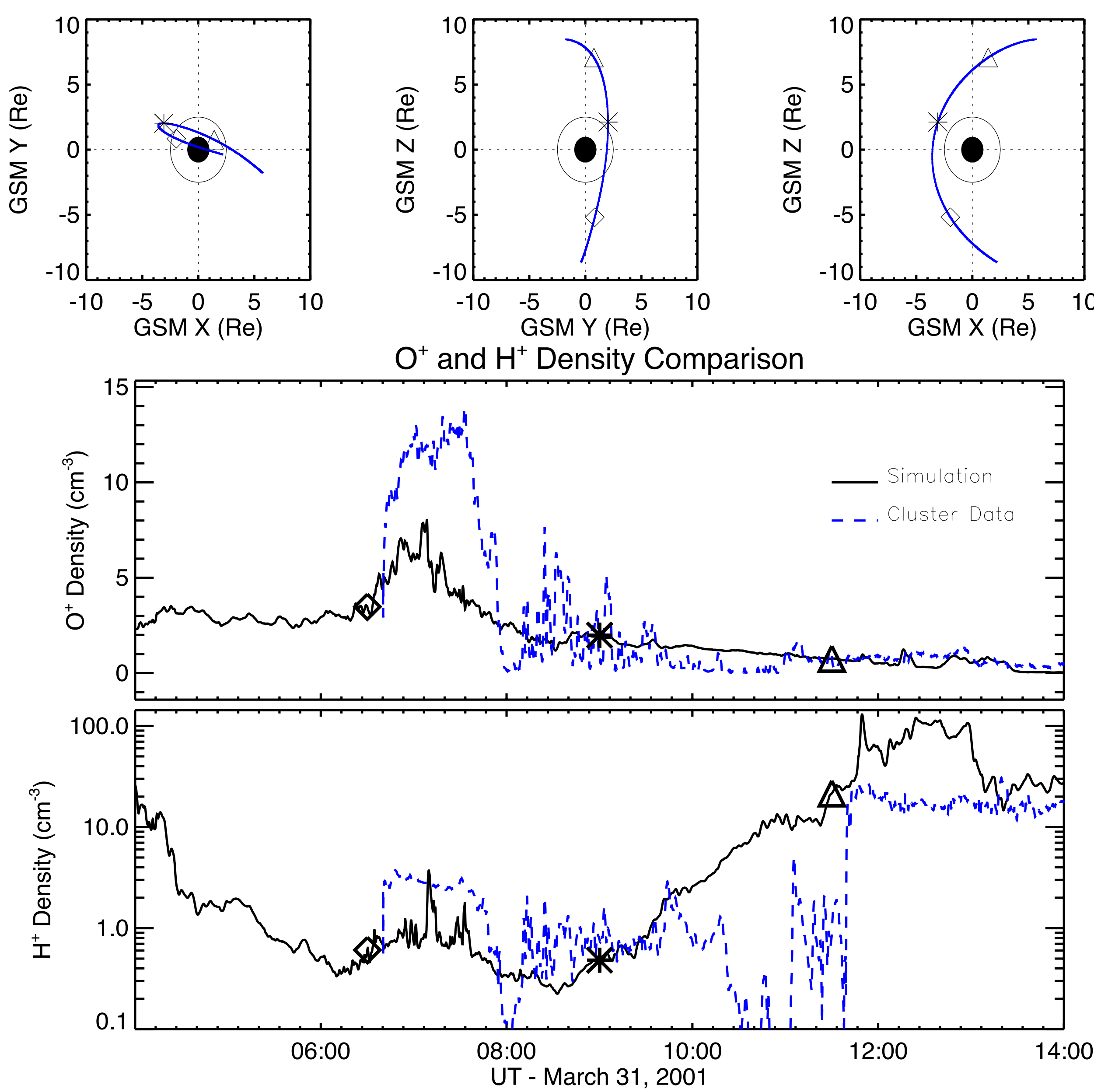



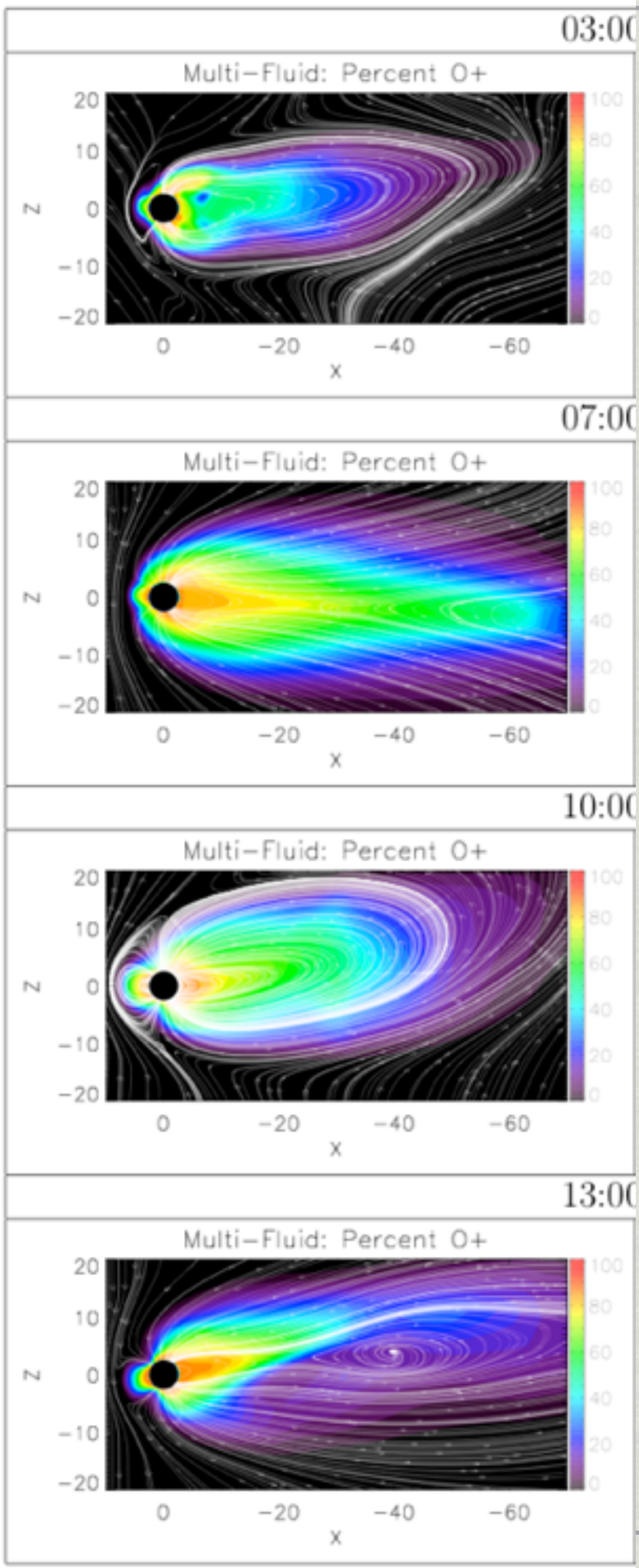
# Superthermal Electrons (SEs)




- Origins of SEs
  - Photoelectrons - from photoionization of the neutral atmosphere.
  - Primary Electrons - auroral precipitation, diffuse precipitation, and polar rain.
  - Secondary Electrons - generated by impact
- Mechanisms by which SEs affect outflow
  - Formation of the self-consistent ambipolar electric field
  - Coulomb collisions between the superthermal and thermal electrons raising Te.

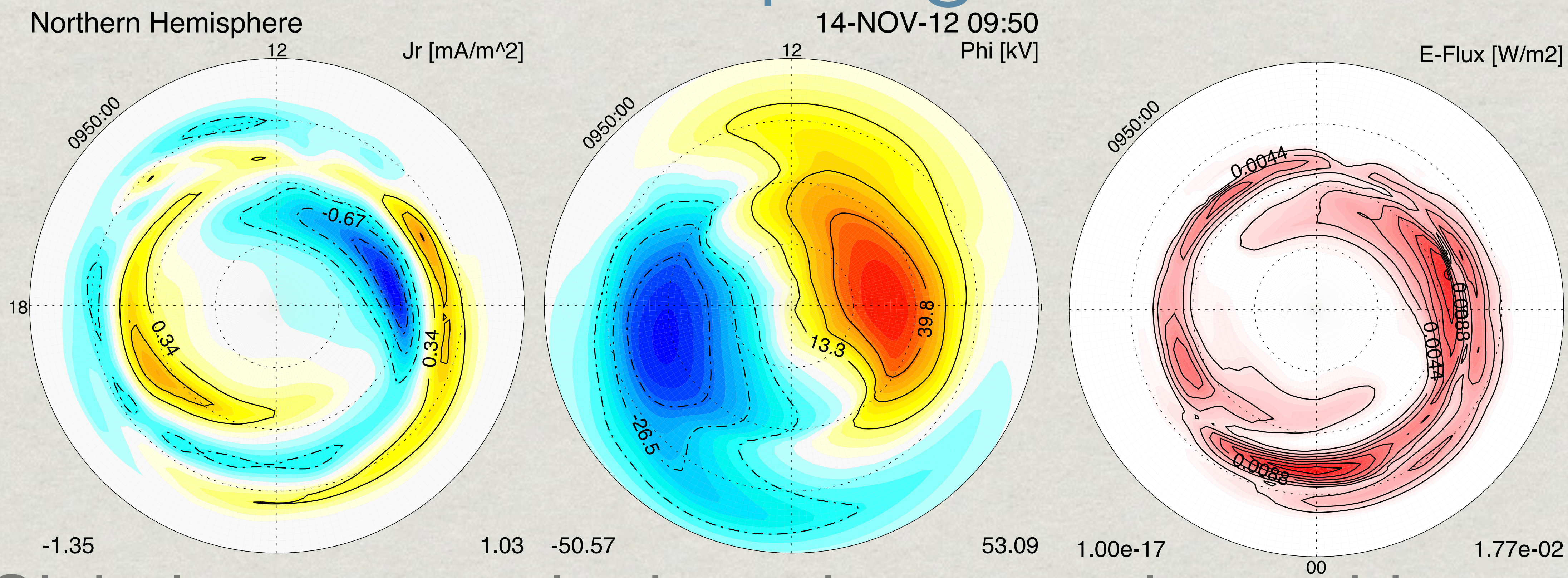
# Ionospheric O+ can dominate during storms



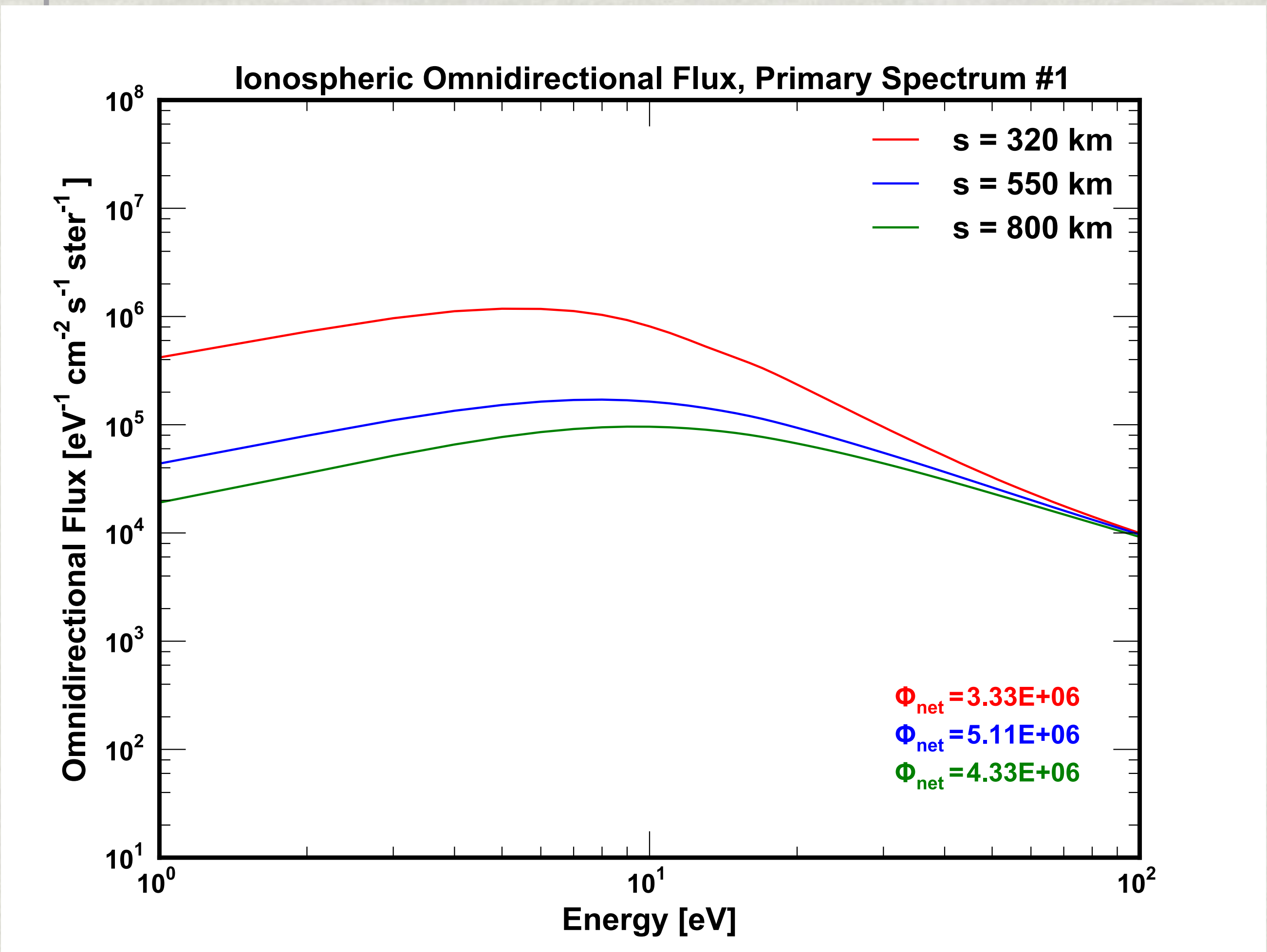

Glocer et al [2009]

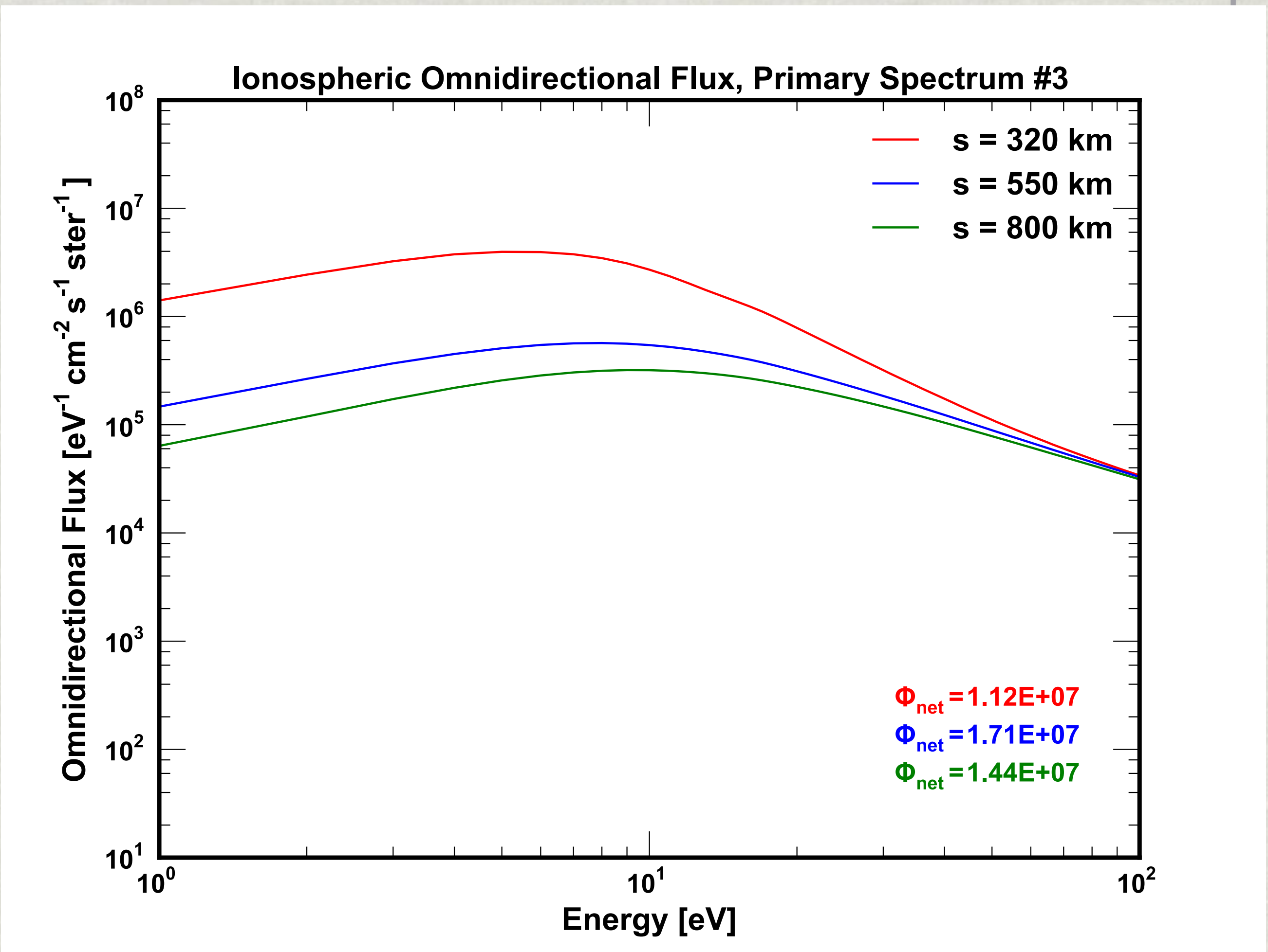
# Issues of MI-Coupling




- Global magnetospheric codes currently provide us several quantities to work with
  - FACs are directly applicable in the current conservation equations.
  - The cross polar cap potential allows us to describe the perpendicular drift.
  - Precipitation can also be used in more comprehensive way.
  - Using the energy flux and average energy we can define a precipitating spectrum and calculate secondary production and E field as well as ion production.

# Calculating Secondary Production




- Using different primary spectra but the same energy flux and characteristic energy we computed secondary production.
  - The secondary electron spectra have similar shapes but the integrated flux is different by a factor of ~3
  - If we have the shape of the primary spectrum from data we can do the calculation precisely.
  - Global models, however, are not able to provide the shape of the primary spectrum

# The Next Step

## Creating a Merged Fluid-Kinetic Model

- **Issue:** All SE populations should be treated together in the context of the ionospheric outflow.
- **Approach:** Use the PWOM code to represent the ions and thermal electrons and a kinetic FP code for the SEs
- **Features of the merged code:**
  - Treats all SE populations together
  - Handles arbitrary precipitation source
  - Includes photoelectron and secondary electron production
  - Includes energy cascade and pitch-angle scattering
  - Formation of the self-consistent E-field to accelerate ions and restrain SEs
  - Energy deposition to thermal electrons from collisions
  - When including SEs solution the topside electron heat flux can be set arbitrarily small.
- Model development is complete and first results are shown shortly.

# FP Kinetic Model

$$\frac{\beta}{\sqrt{E}}\frac{\partial\Phi}{\partial t}+\mu\frac{\partial\Phi}{\partial s}-\frac{1-\mu^2}{2}\left(\frac{1}{B}\frac{\partial B}{\partial s}-\frac{F}{E}\right)\frac{\partial\Phi}{\partial\mu}+EF\mu\frac{\partial\Phi}{\partial E}=An_e\Bigg\{\frac{\partial}{\partial E}\Bigg[\left(1+\frac{m}{M_i}+2\frac{m}{M_n}\frac{\sigma_{en}^{tr}E^2n_n}{An_e}\right)\frac{\Phi}{E}$$

$$+\left(T_e+T_i\frac{m}{M_i}+2\frac{m}{M_n}T_n\frac{\sigma_{en}^{tr}E^2n_n}{An_e}\right)\frac{\partial}{\partial E}\left(\frac{\Phi}{E}\right)\Bigg]+$$

$$+\frac{1}{2E^2}\frac{\partial}{\partial\mu}\left[\left(1-\mu^2\right)\frac{\partial\Phi}{\partial\mu}\right]\Bigg]\Bigg\}+n_n\Bigg\{\int_0^{2\pi}\int_{-1}^{1}I_{en}\left(E,\mu_\chi\right)\Phi\left(\mu'\right)\sin\chi\, d\chi\, d\varepsilon+$$

$$+\sum_{j,k>j}\left[\Delta_n^j\sigma_{en}^{jk}\left(E+E_{jk}\right)\Phi\left(E+E_{jk}\right)+\Delta_n^k\sigma_{en}^{kj}\left(E-E_{jk}\right)\Phi\left(E-E_{jk}\right)\right]+$$

$$+\int_{E+E_n^+}^{2E+E_n^+}I_n^+\left(E',E'-E-E_n^+\right)\Phi\left(E'\right)dE'+\frac{1}{2\pi}\int_{2E+E_n^+}^{\infty}I_n^+\left(E',E\right)\left[\int_0^{2\pi}\Phi\left(E',\sqrt{1-\mu^2}\cos\varepsilon\right)\right]dE'-$$

$$-\left[\sigma_{en}+\sum_{j,k>j}\left(\Delta_n^j\sigma_{en}^{jk}+\Delta_n^k\sigma_{en}^{kj}+\sigma_n^++\frac{n_i}{n_n}\sigma_i^r\right)\right]\Phi\Bigg\}+q\,.$$

FP Collisional Operator

e- Neutral Boltzmann Collisional Operator

Excitation and Deexcitation

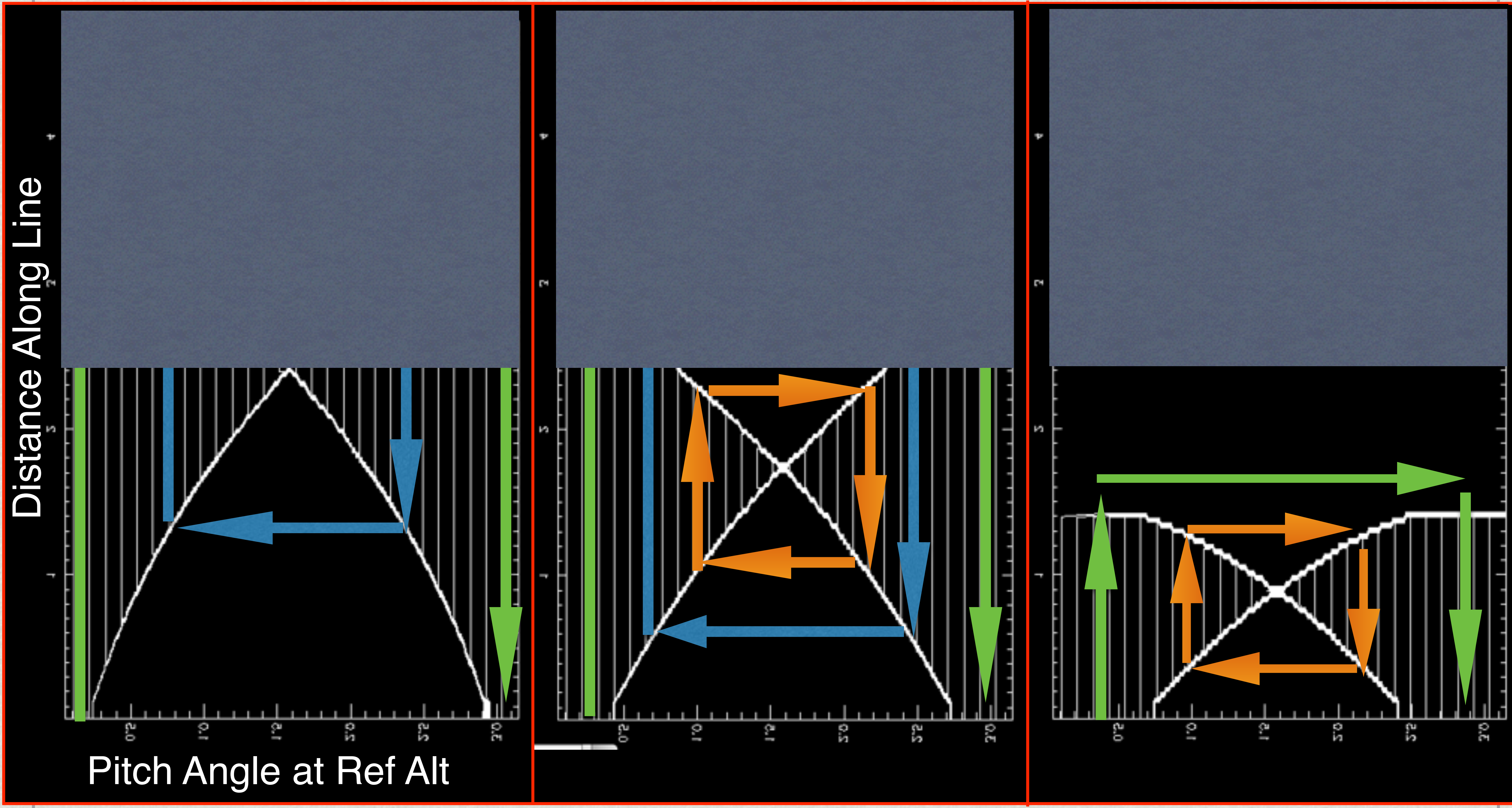
Loss and Gain from Cascade

Khazanov et al. (1997), Liemohn et al. (1997)

- **Issue:** Solving in E and μ coordinates makes particle trajectories curved relative to grid potentially leading to overestimate of trapping and heating
- **Solution:** Coordinate transformation to $E,\mu \rightarrow \varepsilon,\mu_0$

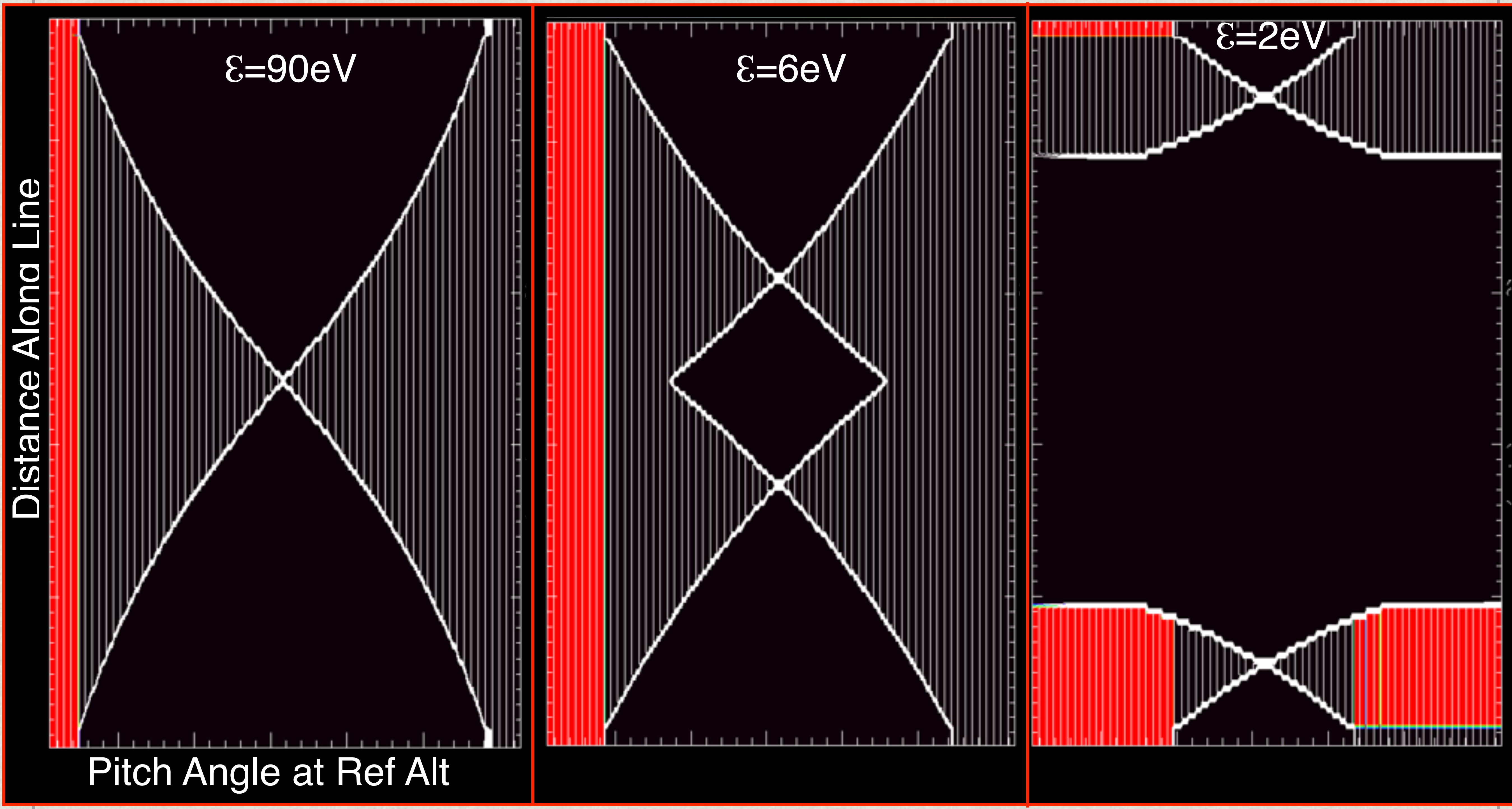
$$\frac{\beta}{\sqrt{E}}\frac{\partial\phi'}{\partial t}+E\mu\frac{\partial}{\partial s}\left(\frac{\phi'}{E}\right)=Q'+\langle S'\rangle$$

# Region of Existence for SEs



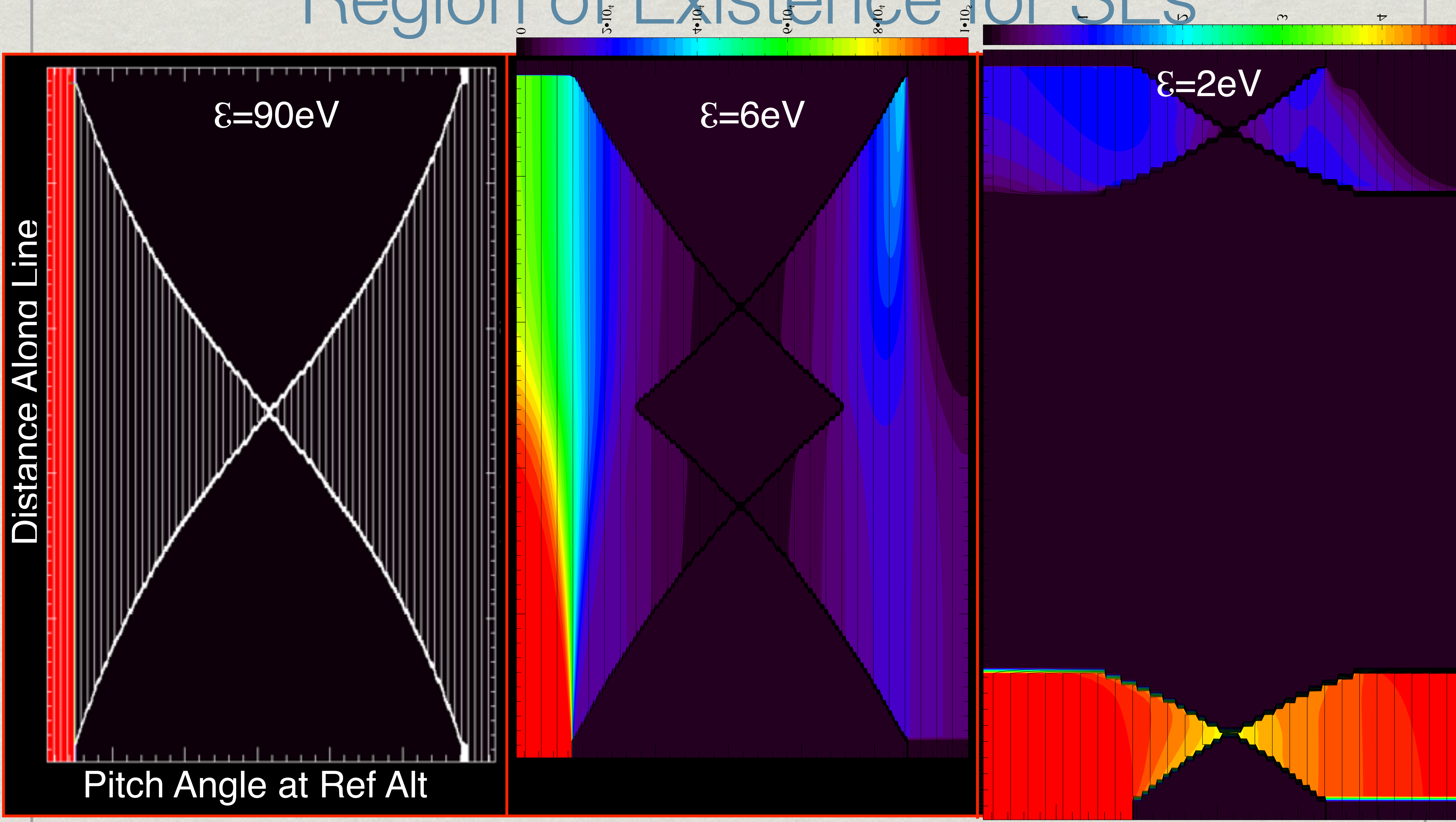

- Region of existence for SEs in the presence of a field aligned potential.
- The grid is aligned with particle trajectories when working in $\mathcal{E},\mu_0$ variables.

# Region of Existence for SEs

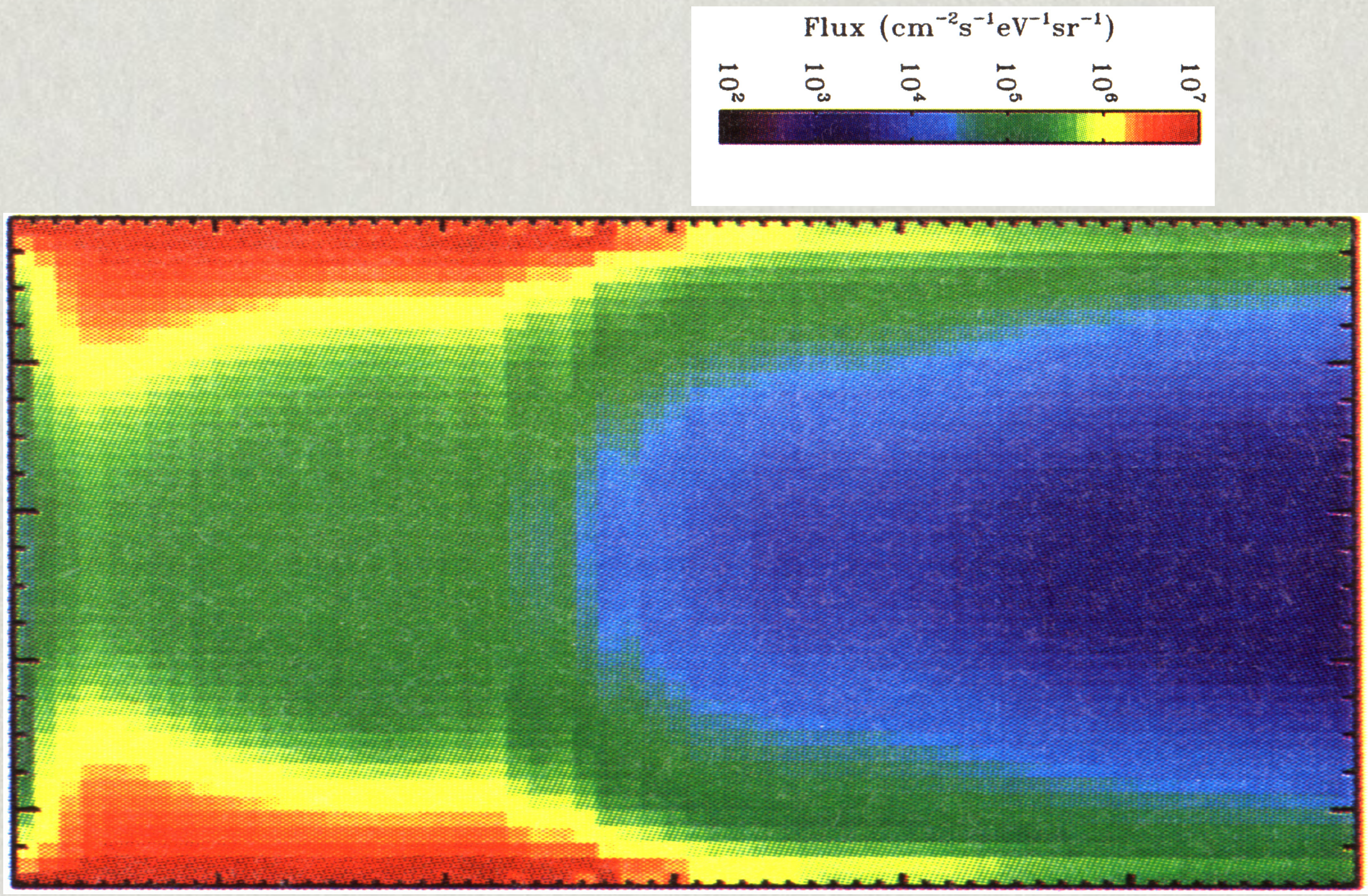


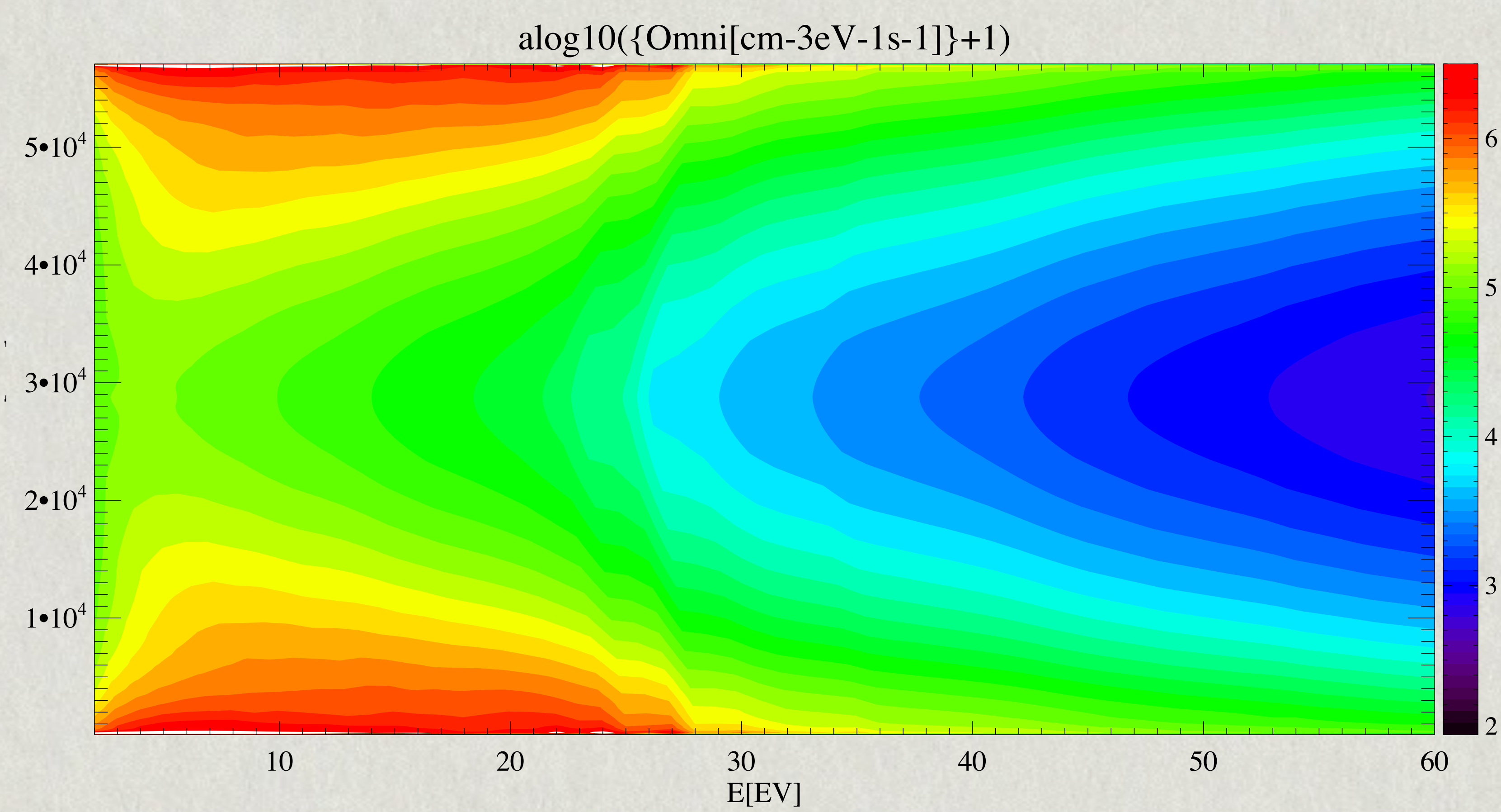

- Absolutely no PA scattering results from numerical diffusion in these coords.
- Verification: Specify upward flux in ionosphere of $1\times10^5$ (red) and see nothing in trapped region.

# Region of Existence for SEs

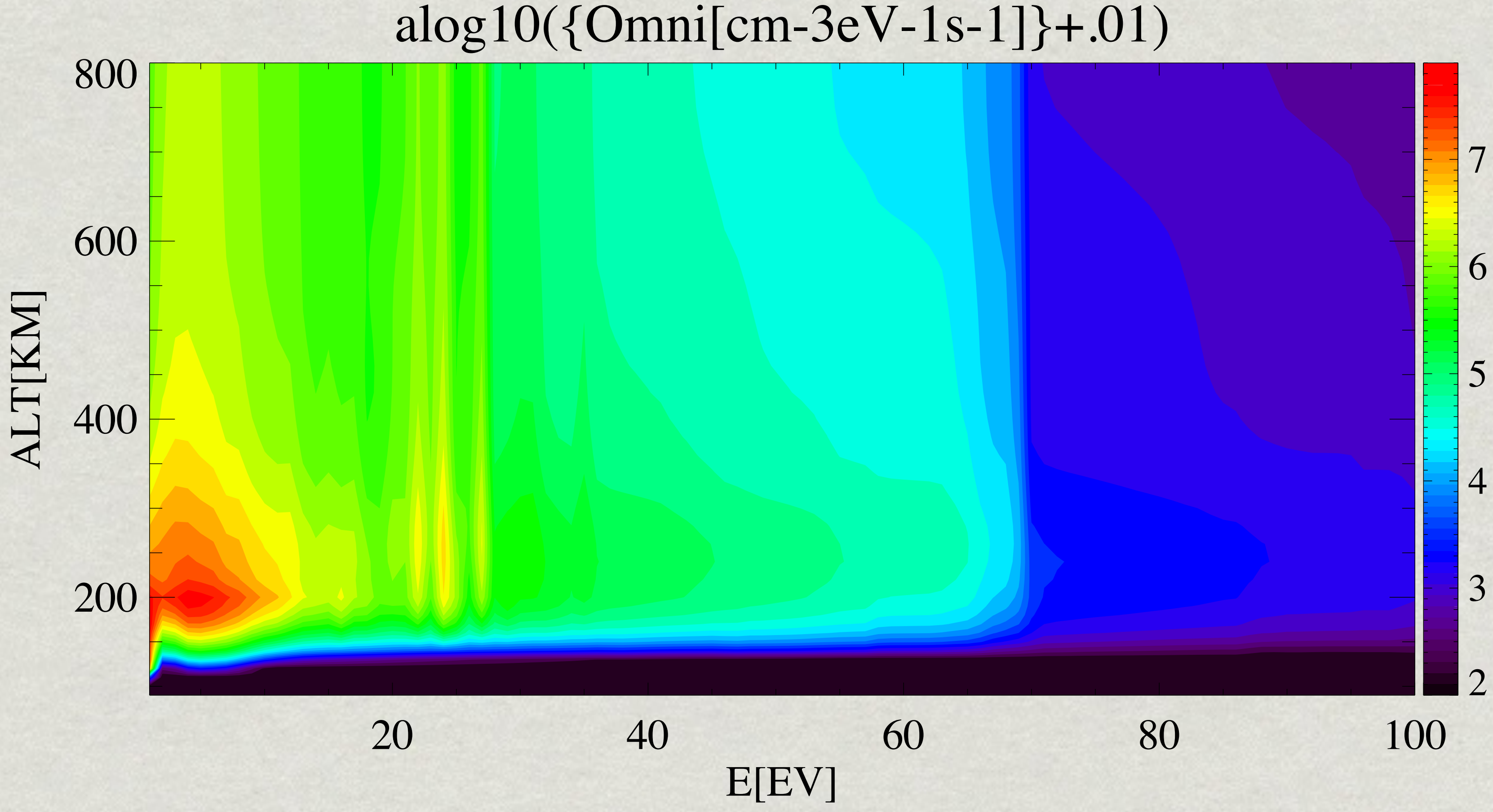


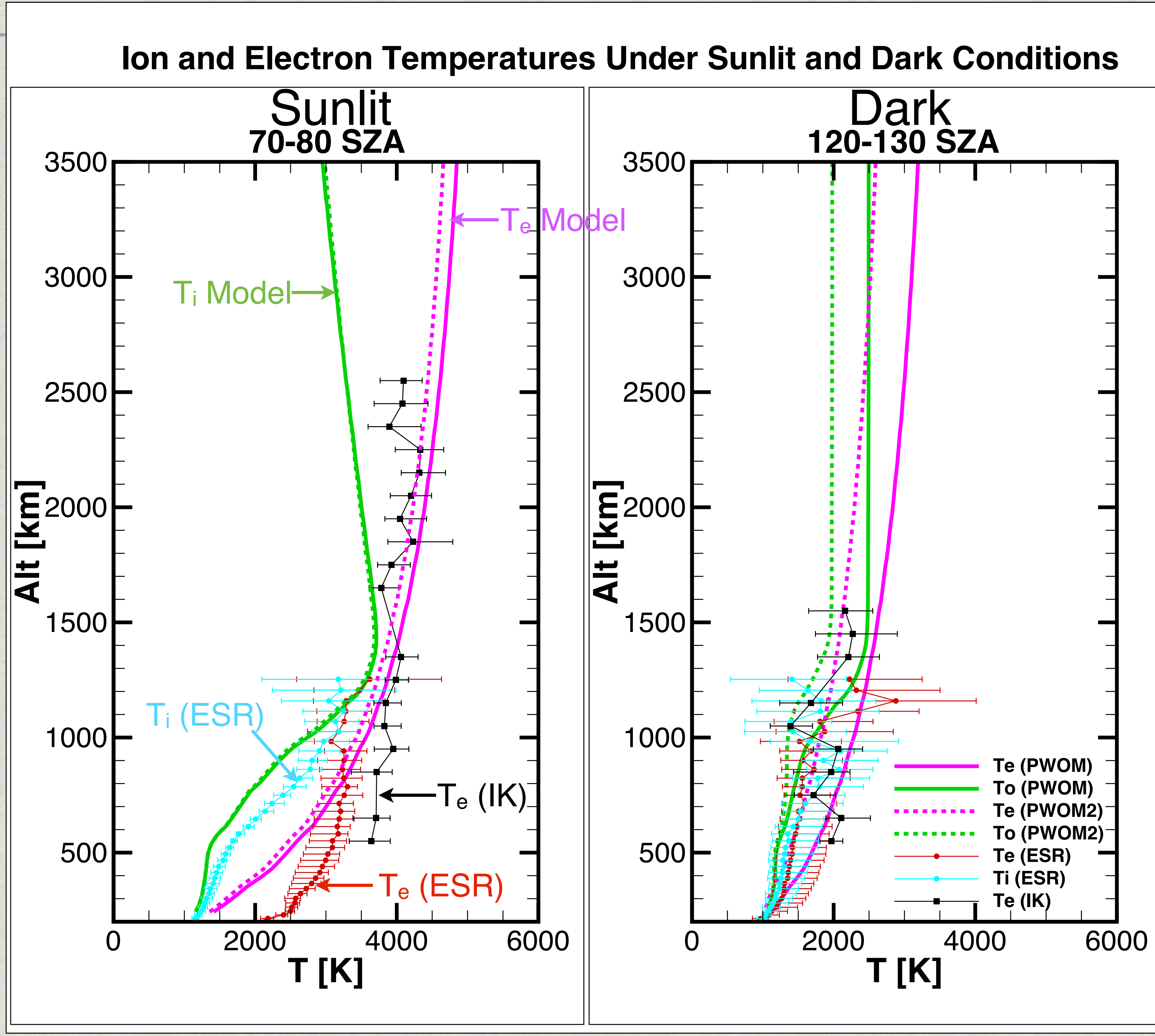

- Effects with scattering


Flux (cm-2s-1eV-1sr-1)
10^2
10^3
10^4
10^5
10^6
10^7


alog10({Omni[cm-3eV-1s-1]}+1)
5•10^4
4•10^4
3•10^4
2•10^4
1•10^4
10
20
30
40
50
60
E[EV]
6
5
4
3
2

# ionospheric flux






- Including SEs renders the choice of topside e- heat flux unnecessary.

*Glocer et al.*, [2012]