Adding Kinetic Ions and Wave-Particle Interactions to the Polar Wind Outflow Model

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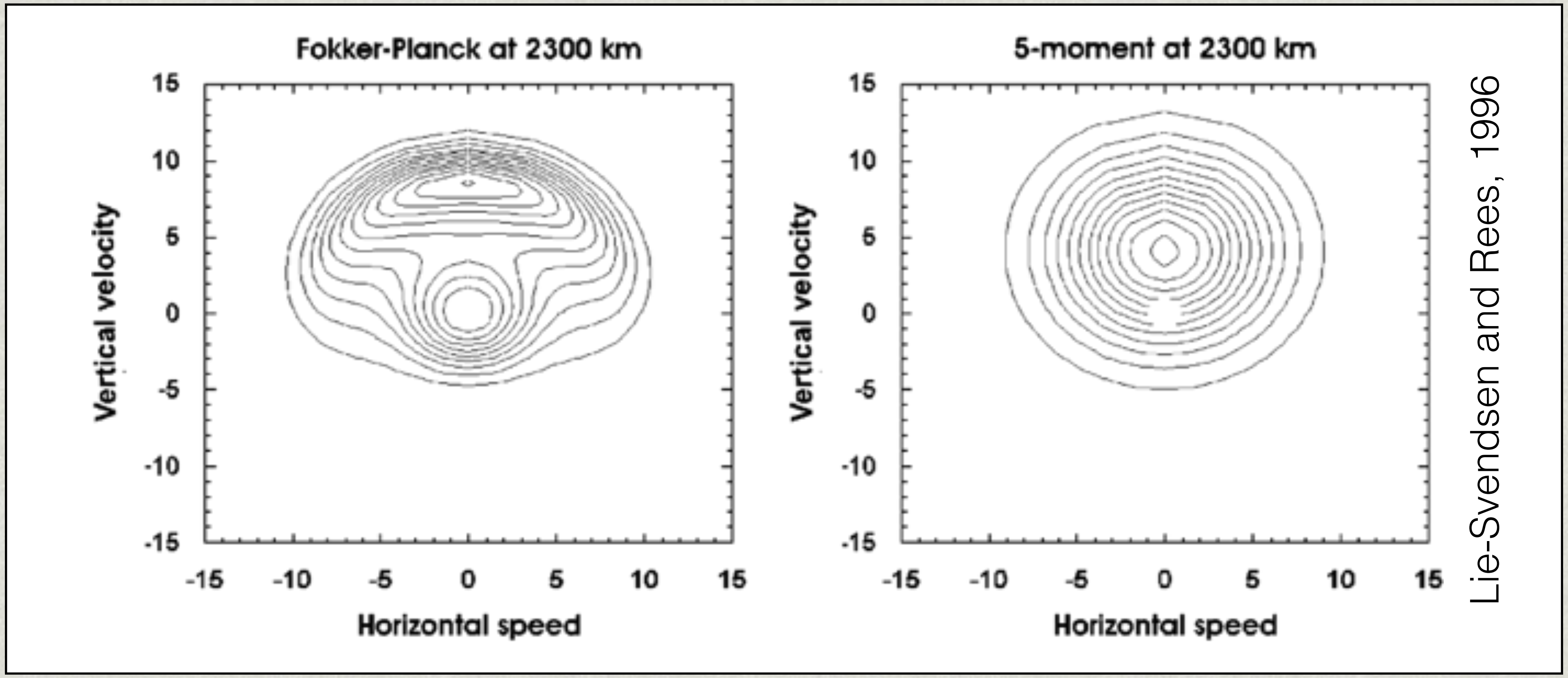
Thanks to:
S. Solomon for making GLOW available
NASA LWS & HGCR programs

Overview

- Motivation: Importance of kinetic effects in outflow
- New developments in PWOM
- Fast global kinetic outflow solution
- Results
  - Single field line: cusp
  - Multiple field lines: convection+cusp
  - Consequences for the magnetosphere

Glocer A., G. Toth, and M.-C.H. Fok (2018), Including Kinetic Ion Effects in the Coupled Global Ionospheric Outflow Solution, Journal of Geophysical Research, 123, doi:10.1002/2018JA025241.

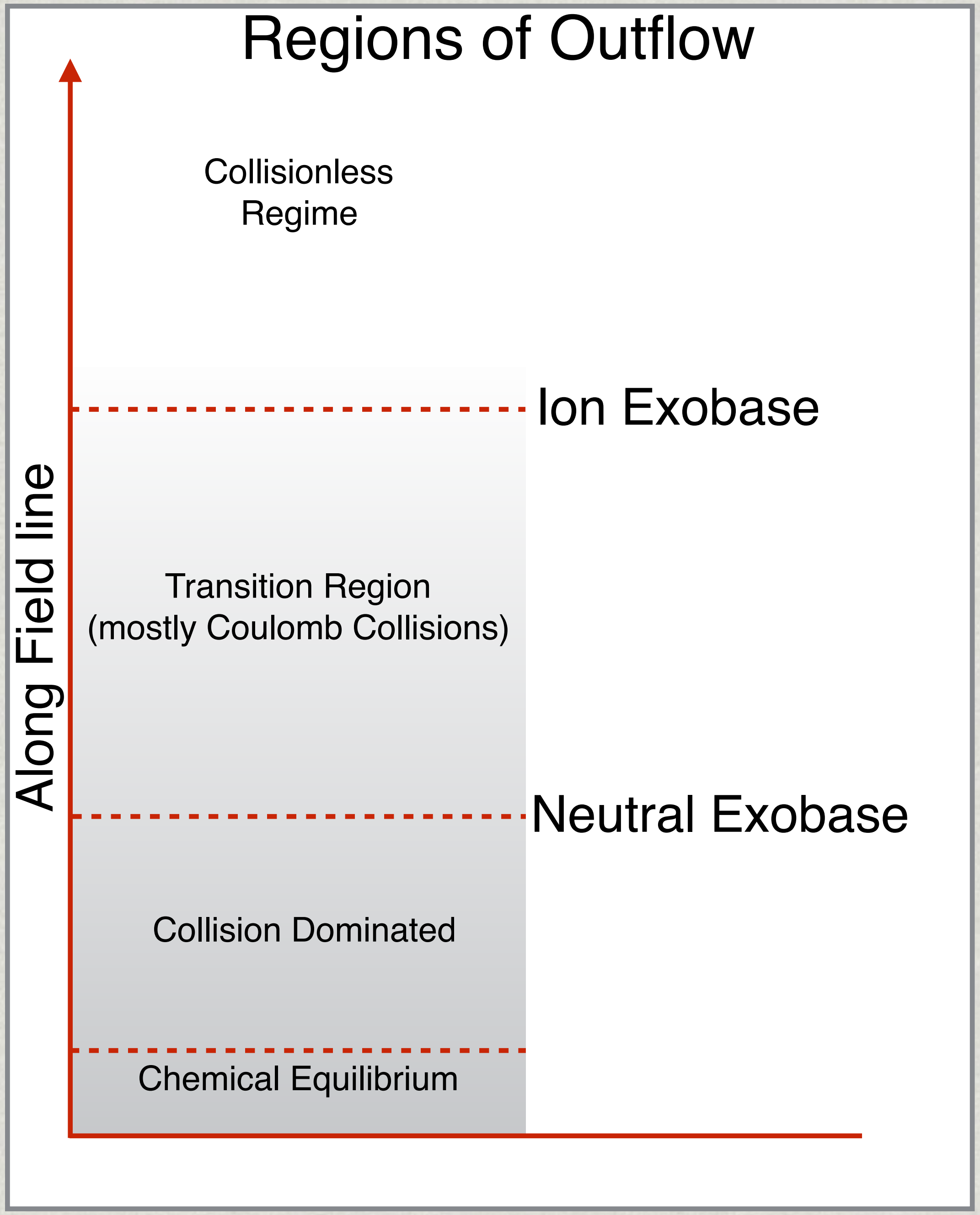
Going Beyond Hydrodynamics for Ionospheric Outflow



Lie-Svendsen and Rees, 1996

- Dessler and Cloutier (1969): hydrodynamic models do not explain neutral exosphere well so why would it work for polar wind?
- Marubashi (1970): fluxes from hydrodynamic model are comparable to kinetic models, but over estimate collisions
- Other issues: non-Maxwellian distributions and WPI.
- Extended hydrodynamic and kinetic models important for modeling outflow.

Where is the Hydro approach valid?



Regions of Outflow

Along Field line

Collisionless
Regime

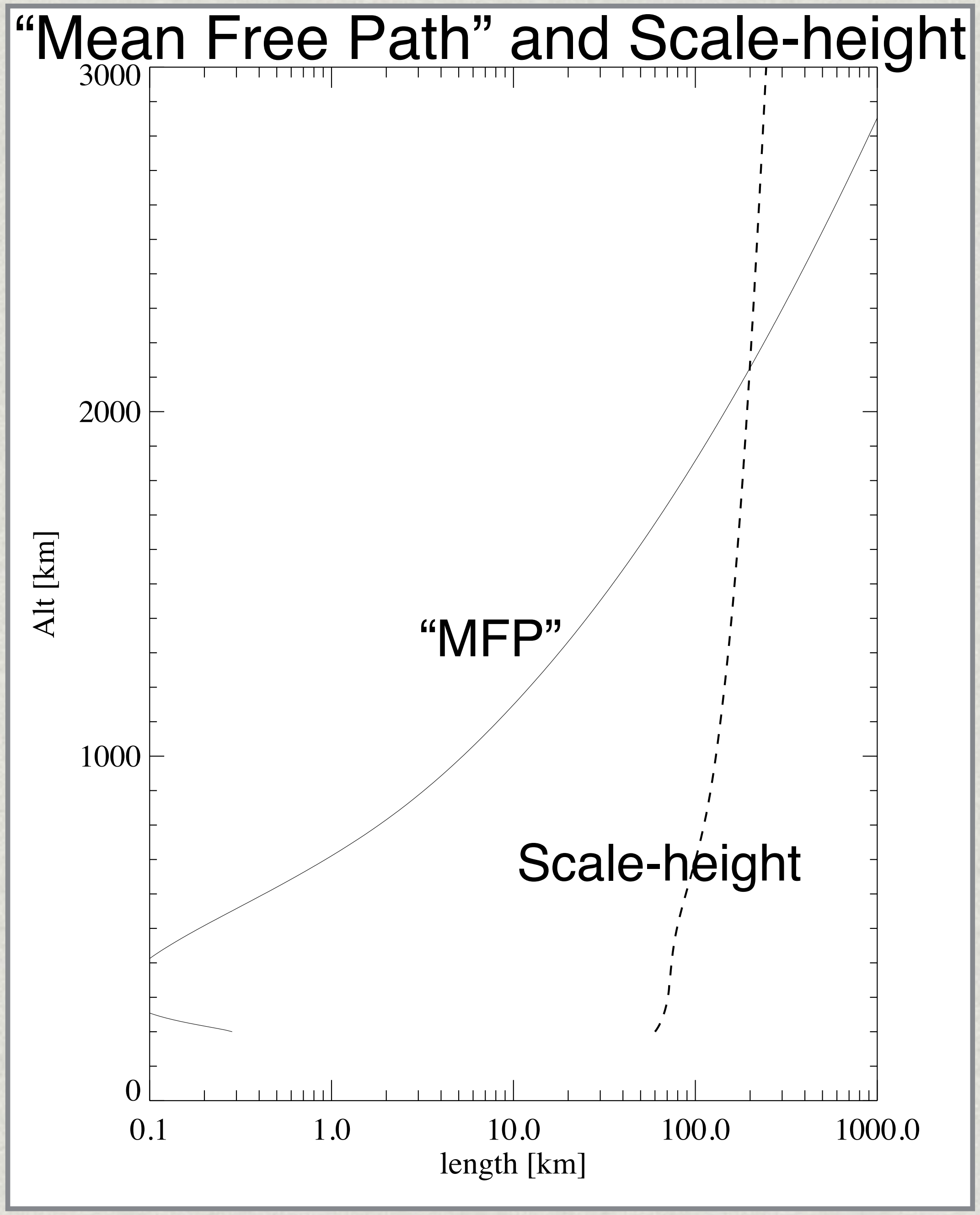
Ion Exobase

Transition Region
(mostly Coulomb Collisions)

Neutral Exobase

Collision Dominated

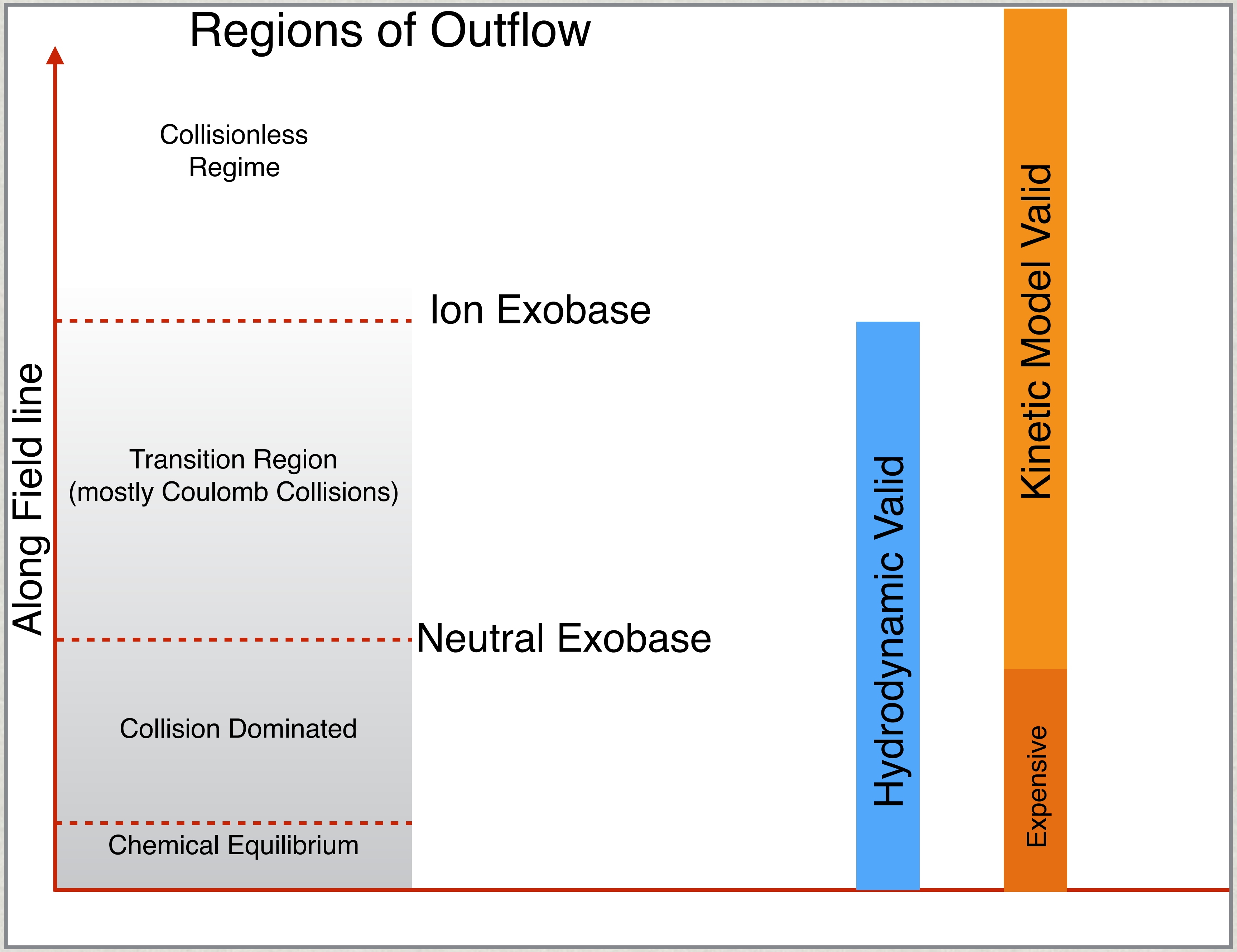
Chemical Equilibrium



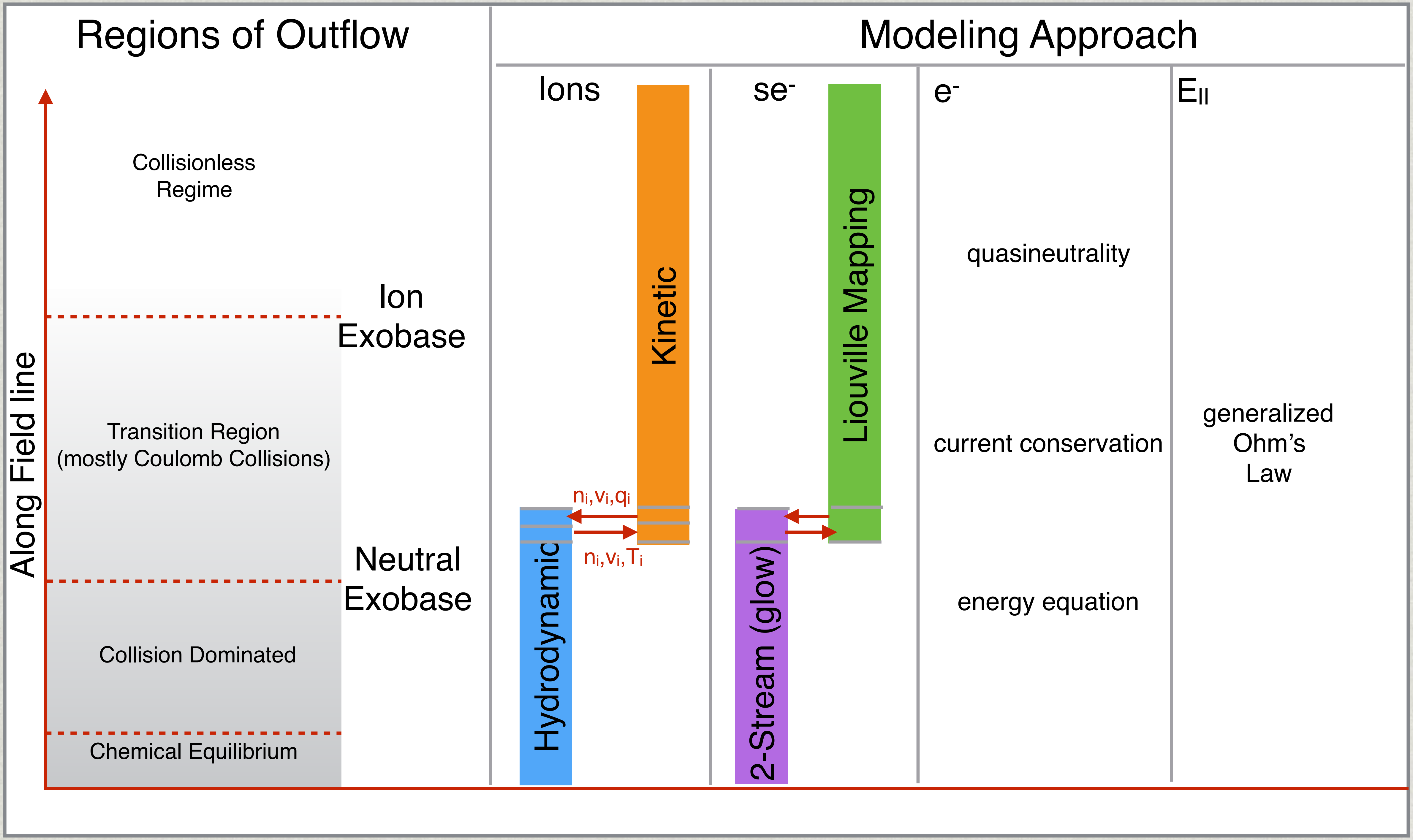
“Mean Free Path” and Scale-height

- Ion exobase or baropause (Spitzer (1949) and Jeans (1954)) where MFP = Scale-height

Appropriate Descriptions

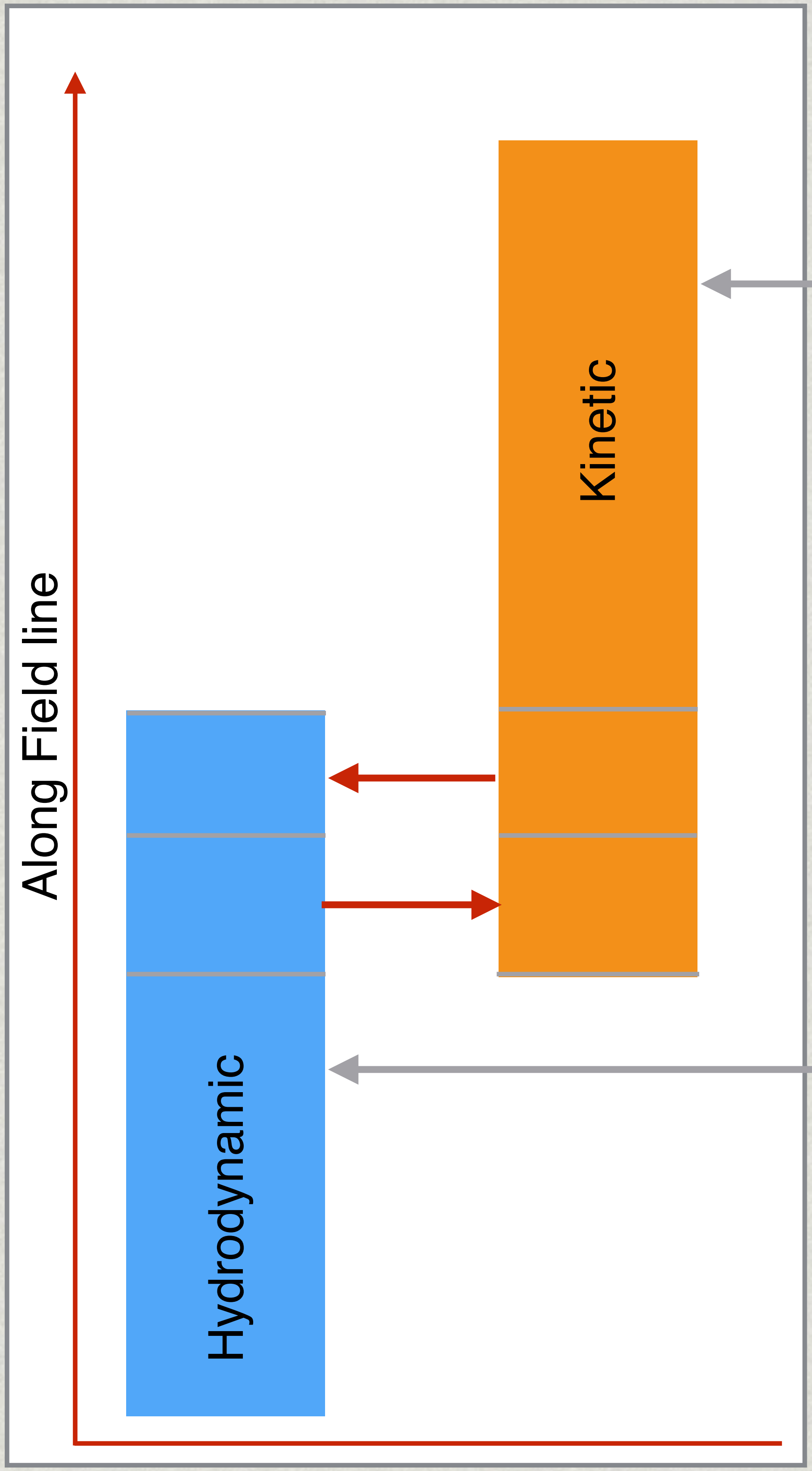


Combined Fluid-Kinetic PWOM



- New model capability to enable global kinetic studies of ion outflow.
- Similar in concept to DyFK & GPW models but with some advantages

Fluid & Kinetic Ion Description



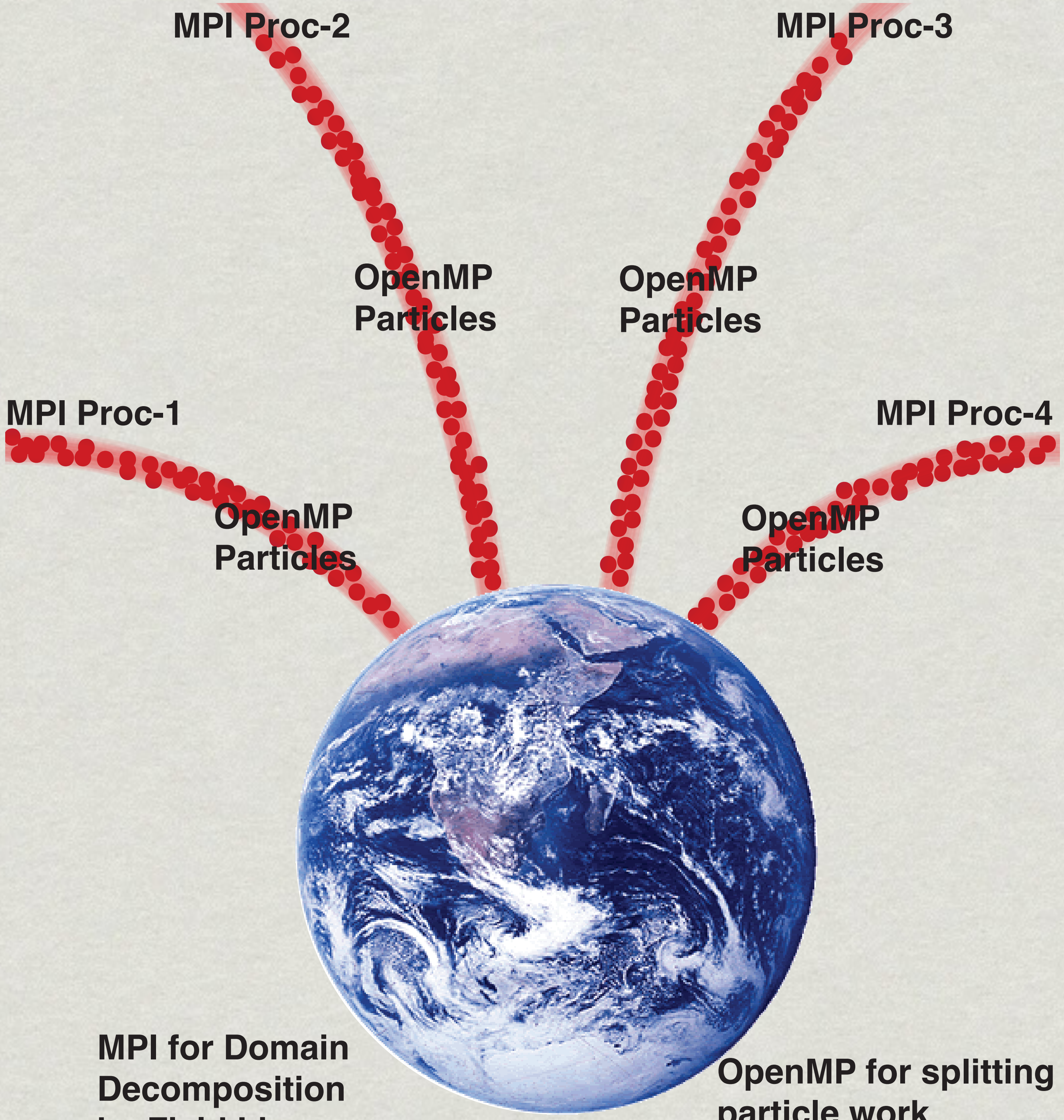
Kinetic Solution

- Gyroaveraged particle EoM (rk4)
- O+, H+, and He+
- Ion-Ion non-linear collisions (Takizuka and Abe [1977])
- Resonant WPI (Barakat and Bargouthi, [1994])
- Particle splitting & joining (Lapenta, [2002])

Hydrodynamic Solution

- Gyrotropic multi-fluid + heat flux
- O+, H+, and He+
- Chemistry and photoionization source terms
- Ion-Ion, Ion-neutral collisions

Fast Global Solution



MPI Proc-2

MPI Proc-3

OpenMP
Particles

OpenMP
Particles

MPI Proc-1

MPI Proc-4

OpenMP
Particles

OpenMP
Particles

MPI for Domain
Decomposition
by Field Line

OpenMP for splitting
particle work

PWOM Parallelization

Summary of modeling Approach

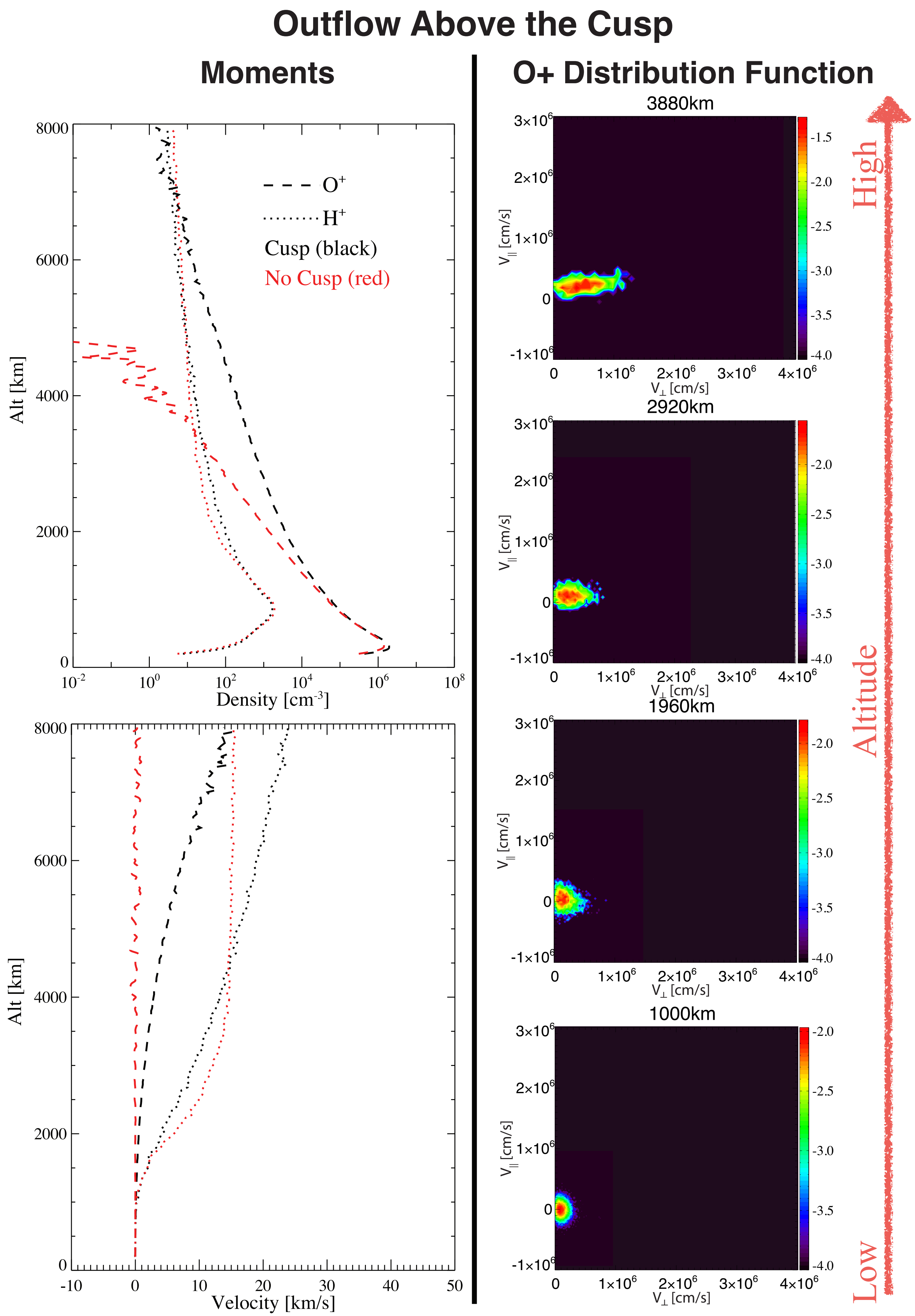
- Combined Fluid-Kinetic Approach: Fluid at low alt & Hybrid PIC at high alt
- Includes
  - Collisions
  - Hot e-
  - Wave-Particle Interactions
- Multiple layers of parallelization for fast execution

Results

- sunlit cusp field line
- Multiple field lines: convection+cusp
- Consequences for the magnetosphere

Sunlit Cusp Field line

- After 25 minutes of resonant WPI.
- WPI yields higher n, v, and T at higher altitudes.
- “Classic” conic distribution function visible in the O+.



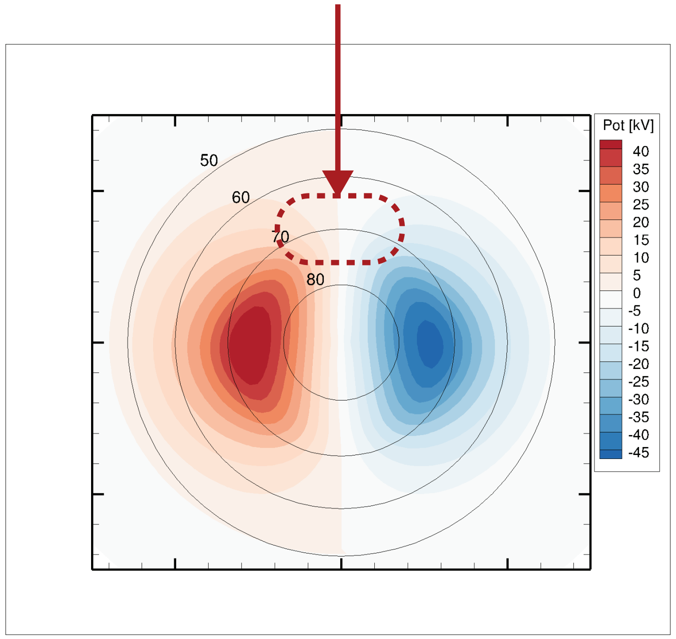
Outflow Above the Cusp

Moments

O+ Distribution Function

Multiple field lines: convection+cusp

Typical 2-cell Convection

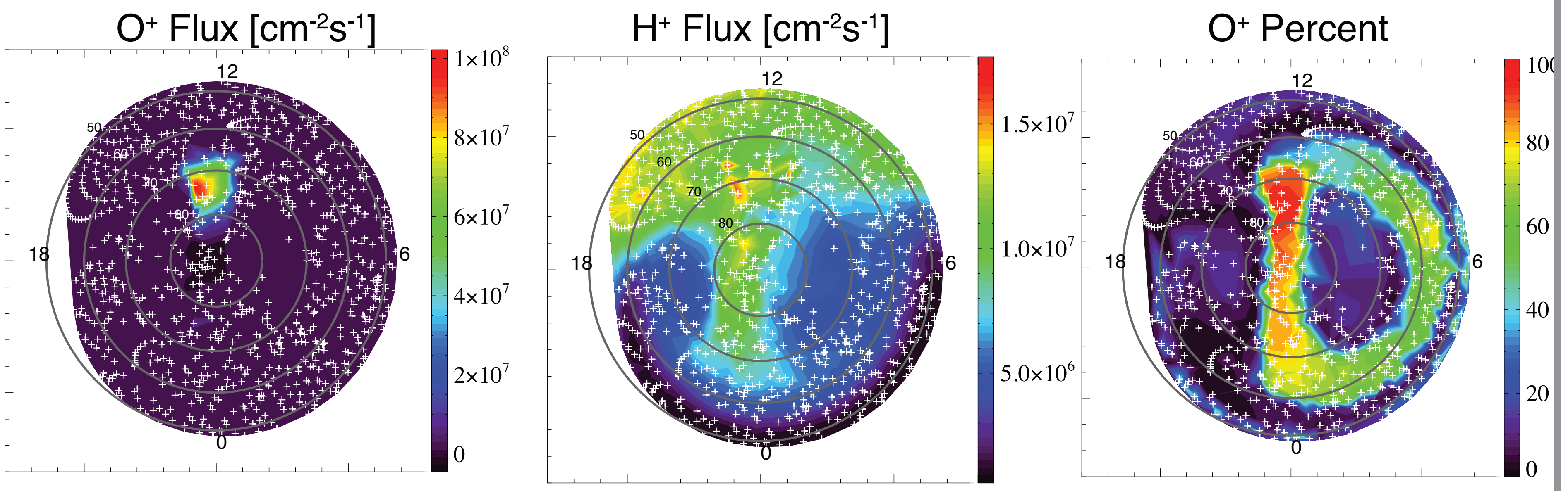


Imposed Cusp Region

Precipitation (1 erg cm^{-2} s^{-1}, E_0=100 eV)

Wave Heating

PWOM output at 6000 km

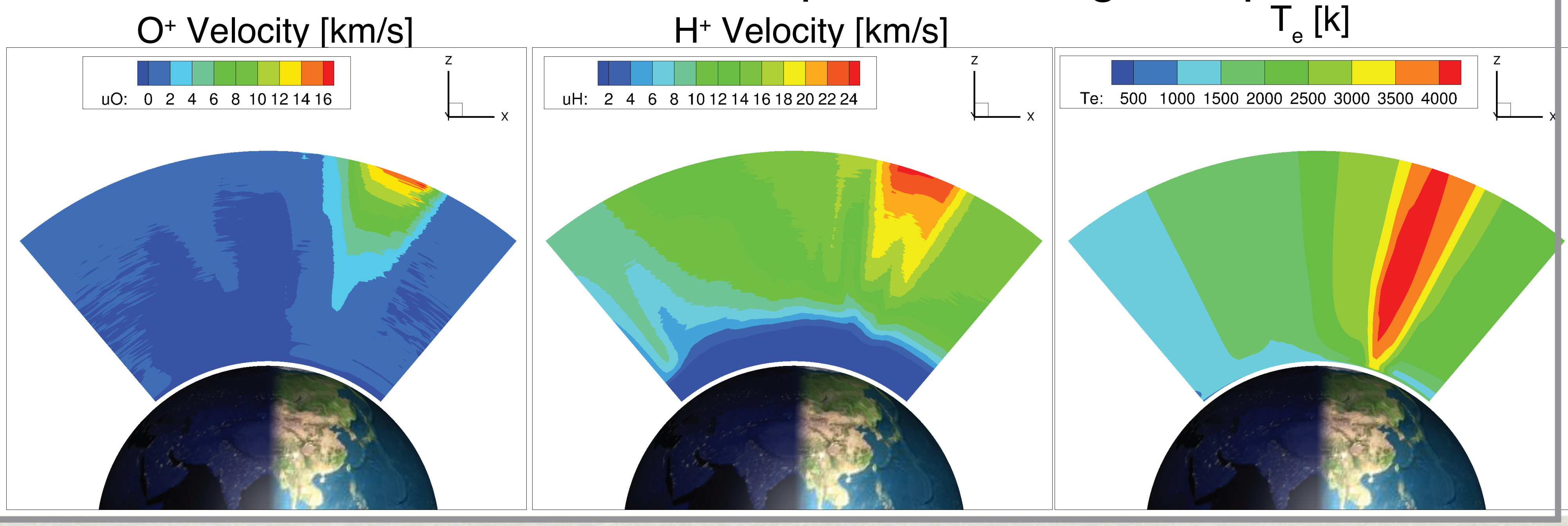


O$^+$ Flux [cm^{-2}s^{-1}]

H$^+$ Flux [cm^{-2}s^{-1}]

O$^+$ Percent

PWOM output cut through cusp



O$^+$ Velocity [km/s]

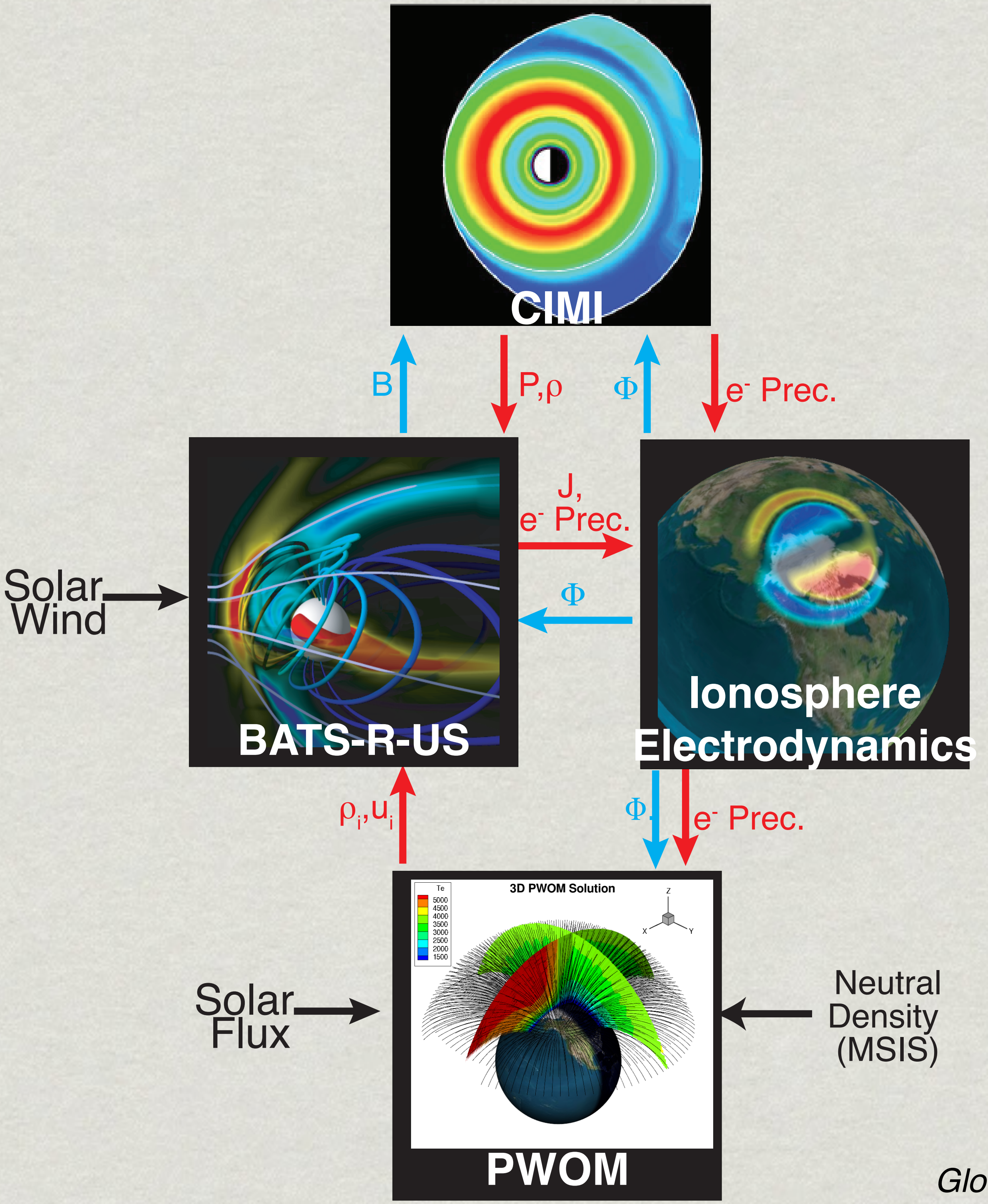
H$^+$ Velocity [km/s]

T_e [k]

~4M particles per line x 900 lines =3.6B particles

Consequences for the Magnetosphere

Model Coupling: Particle - Fields



CIMI

B

P,ρ

Φ

e^- Prec.

Solar Wind

BATS-R-US

J, e^- Prec.

Φ

Ionosphere Electrodynamics

ρ_i,u_i

Φ

e^- Prec.

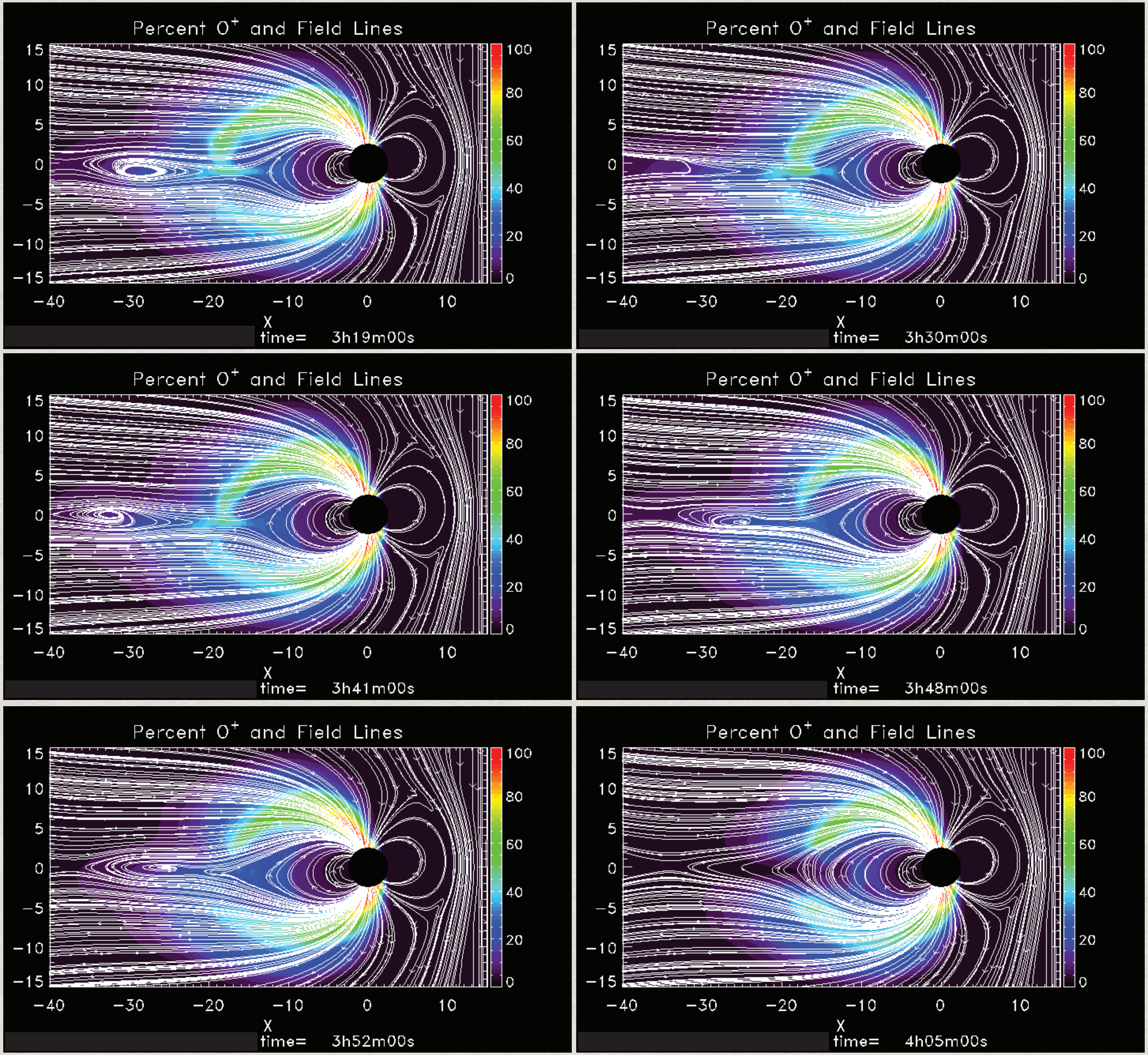
Solar Flux

PWOM

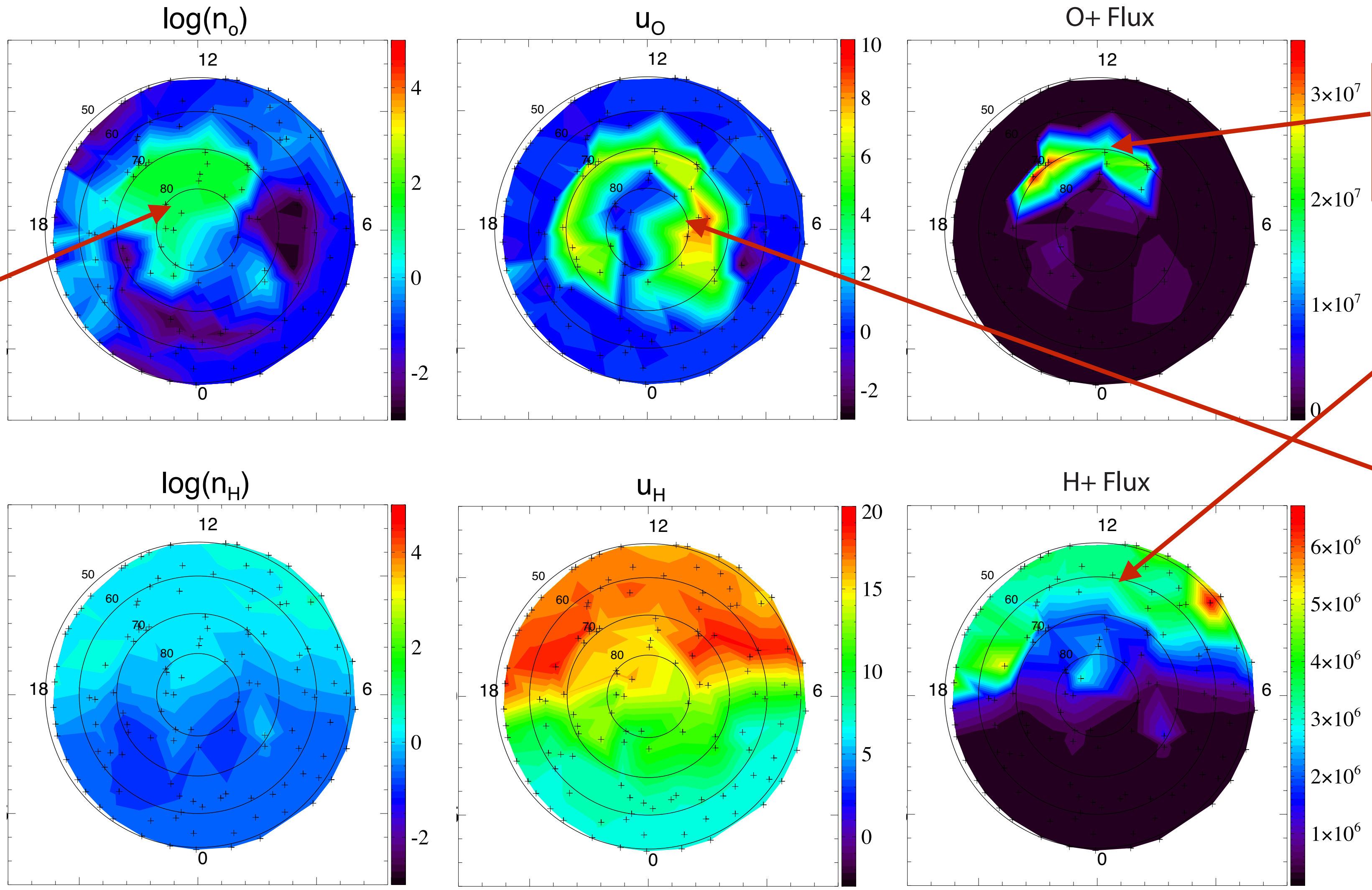
Neutral Density (MSIS)

Glocer et al., [2009,2013]

Coupled BATS-R-US + Kinetic PWOM



PWOM Output at 6000 km - Time=4hr

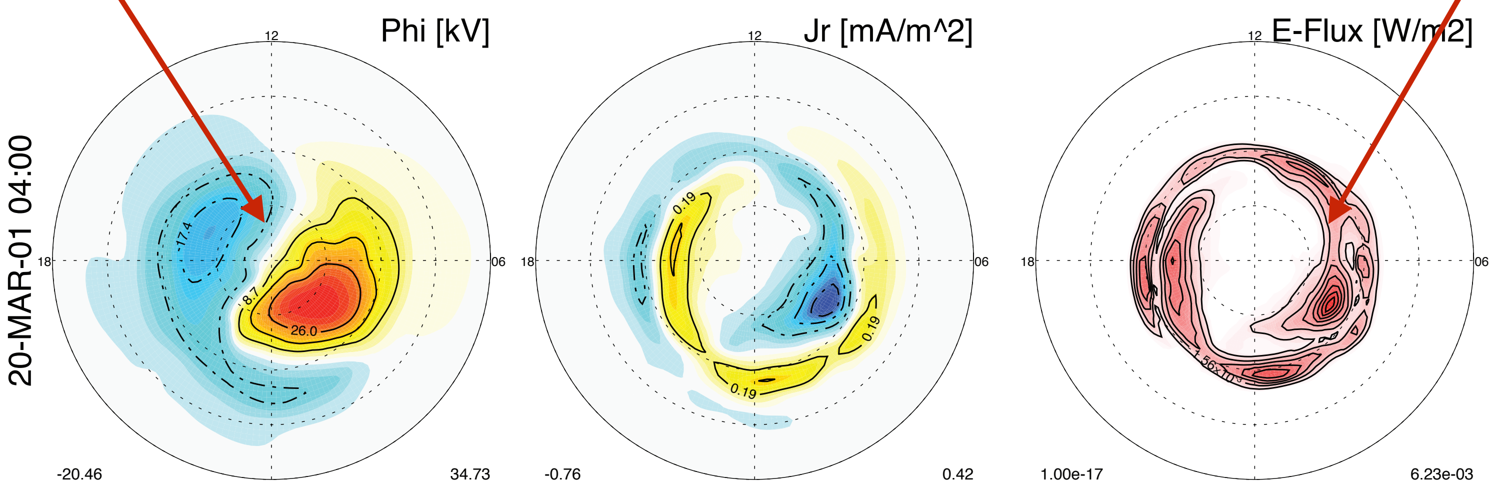


Outflow flux mostly on dayside

Density skewed by convention

O+ velocity driven by WPI above aurora

Ionosphere Electrodynamics Output



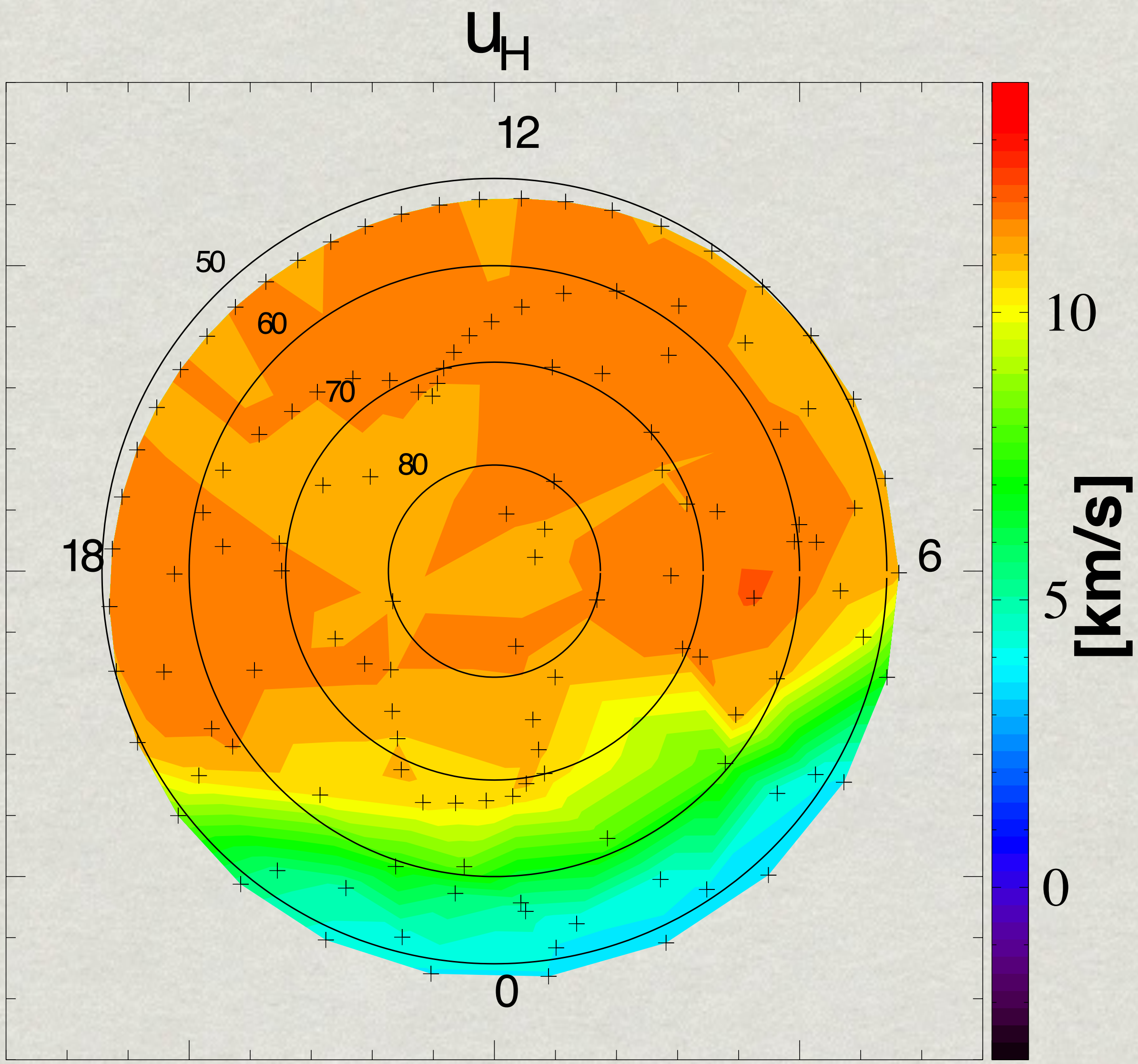
Summary

- New PWOM features enable treatment of most major outflow mechanisms.
  - Expansion to kinetic ion treatment above 1000km
  - Inclusion of resonant wave-particle interactions
- Parallelization of PWOM results in global kinetic simulations of ionospheric outflow.
- Coupling with SWMF enables comprehensive treatment of magnetospheric composition.
- PWOM to CCMC, in progress
- Glocer A., G. Toth, and M.-C.H. Fok (2018), Including Kinetic Ion Effects in the Coupled Global Ionospheric Outflow Solution, *Journal of Geophysical Research*, 123, doi:10.1002/2018JA025241.

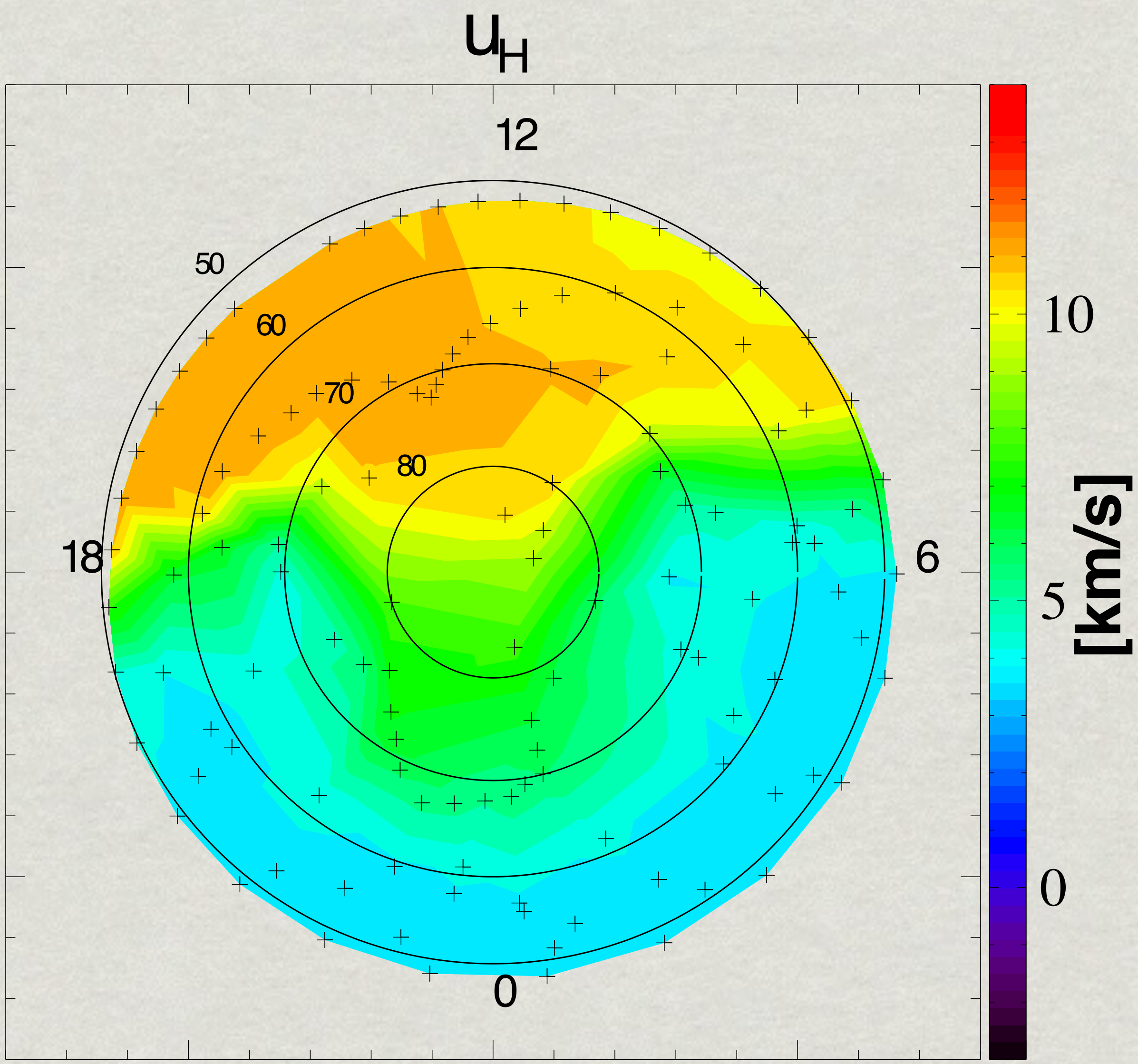
End

Comparing Outflow in Each Hemisphere

Northern Hemisphere



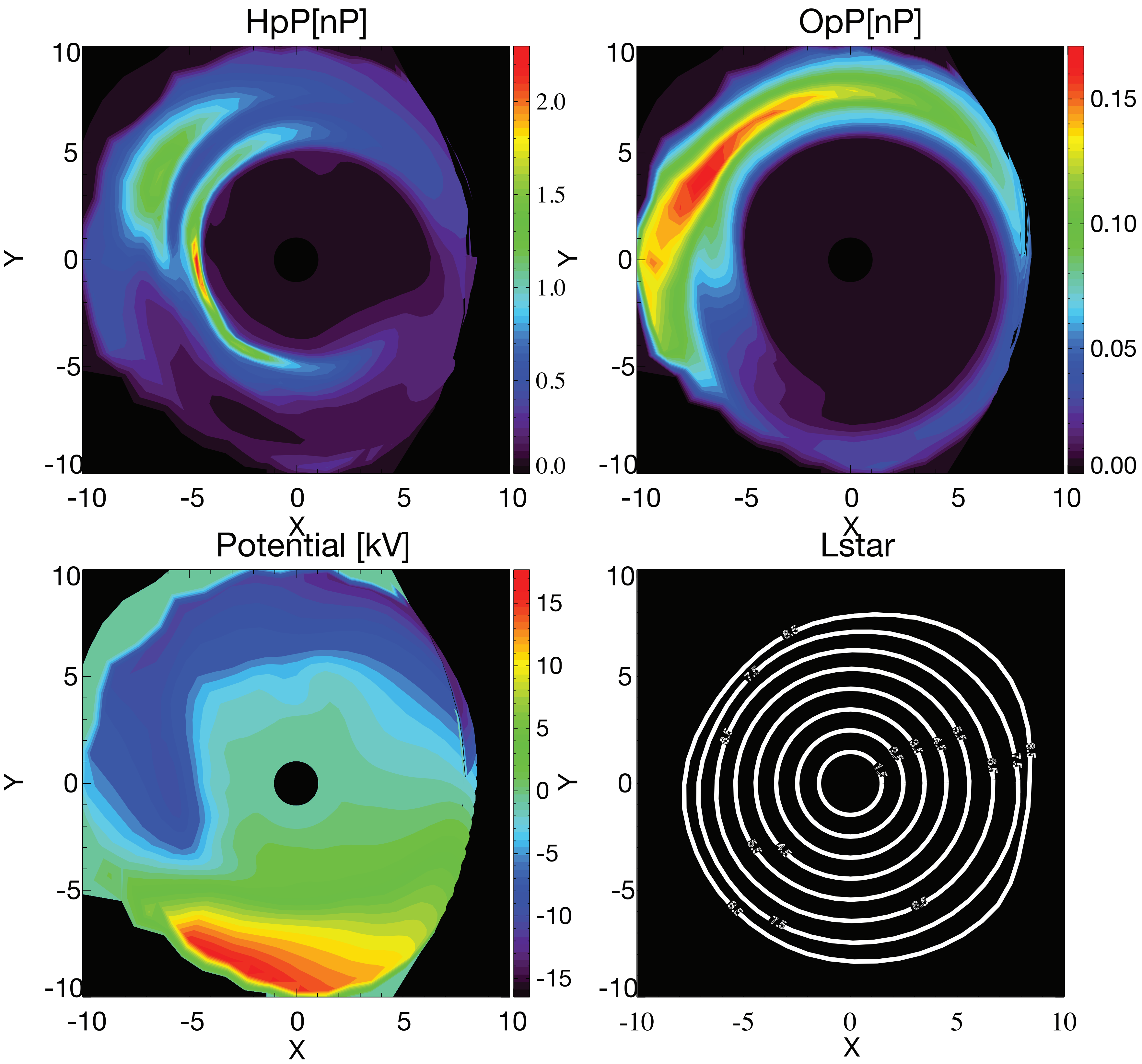
Southern Hemisphere



Simulation Setup

- Constant solar wind conditions:
  1. n=5/cc
  2. v=400km/s
  3. Bz=-5nT
- Cusp/Auroral WPI is turned on based on precipitation threshold

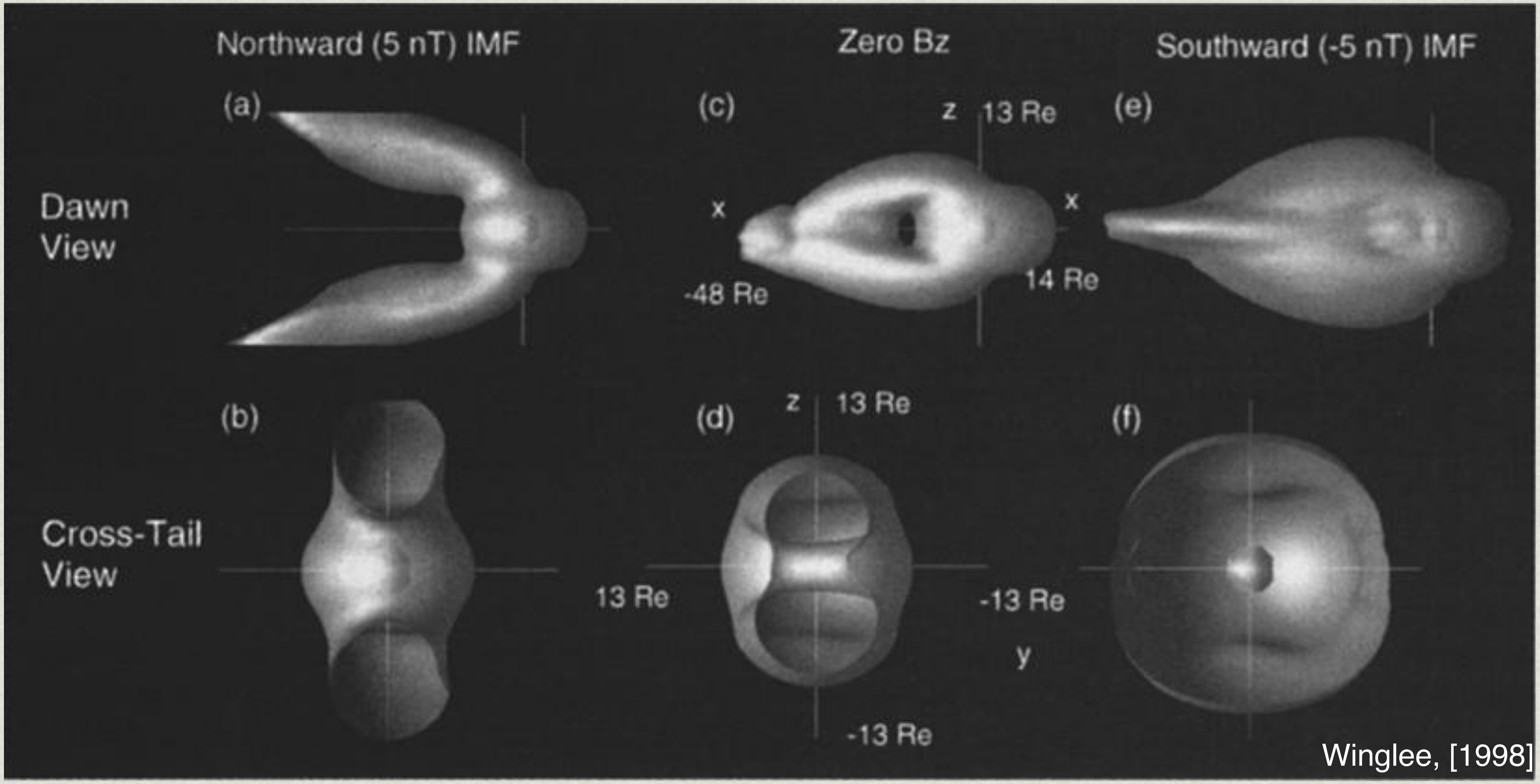
CIMI Output (Ring Current P)



Two sources of magnetospheric plasma

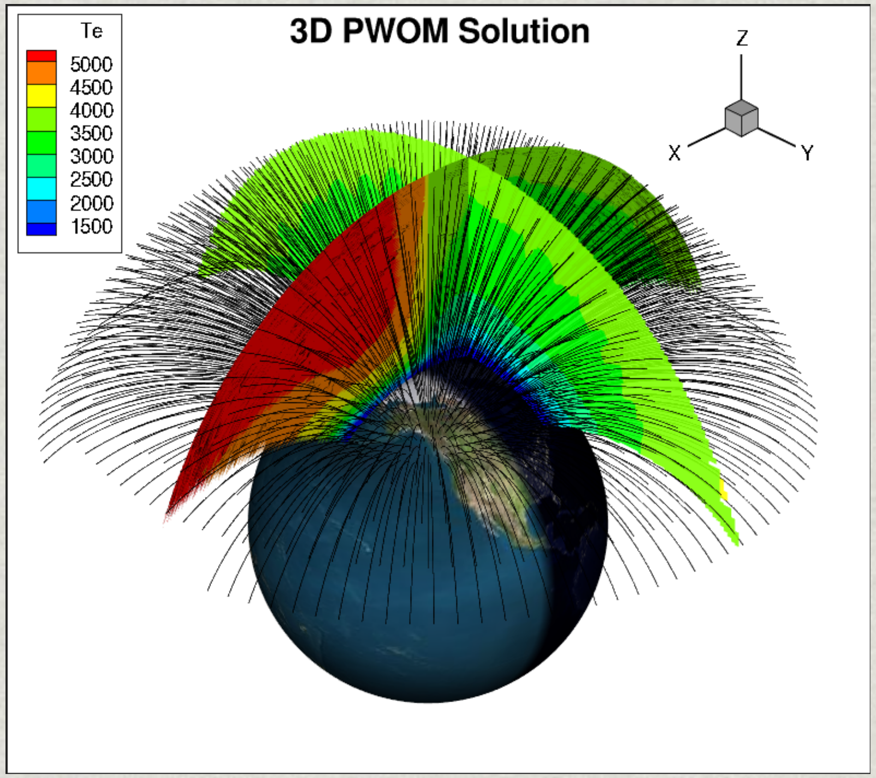
Ionosphere and Solar Wind

Geopause: Boundary Between Sources



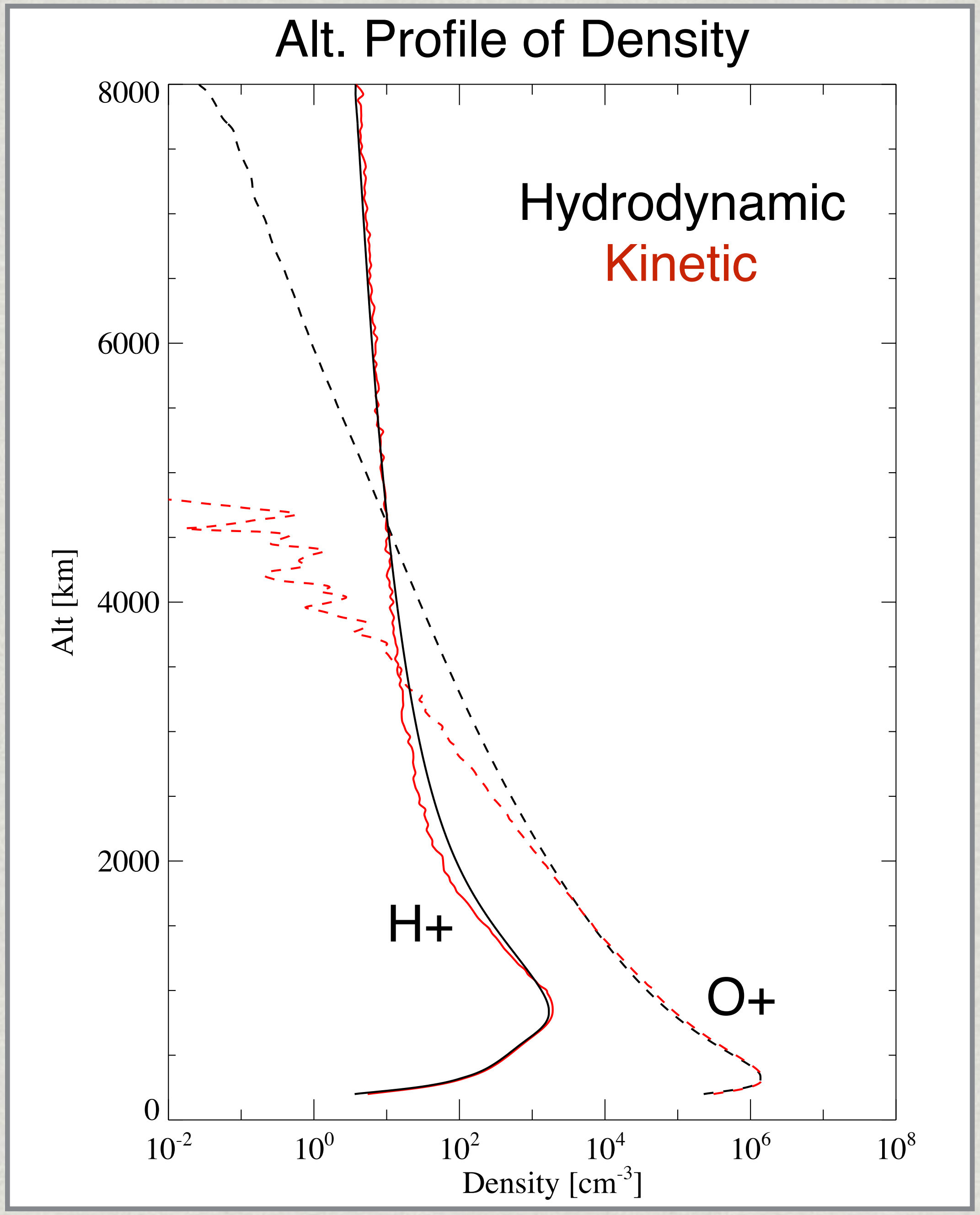
Winglee, [1998]

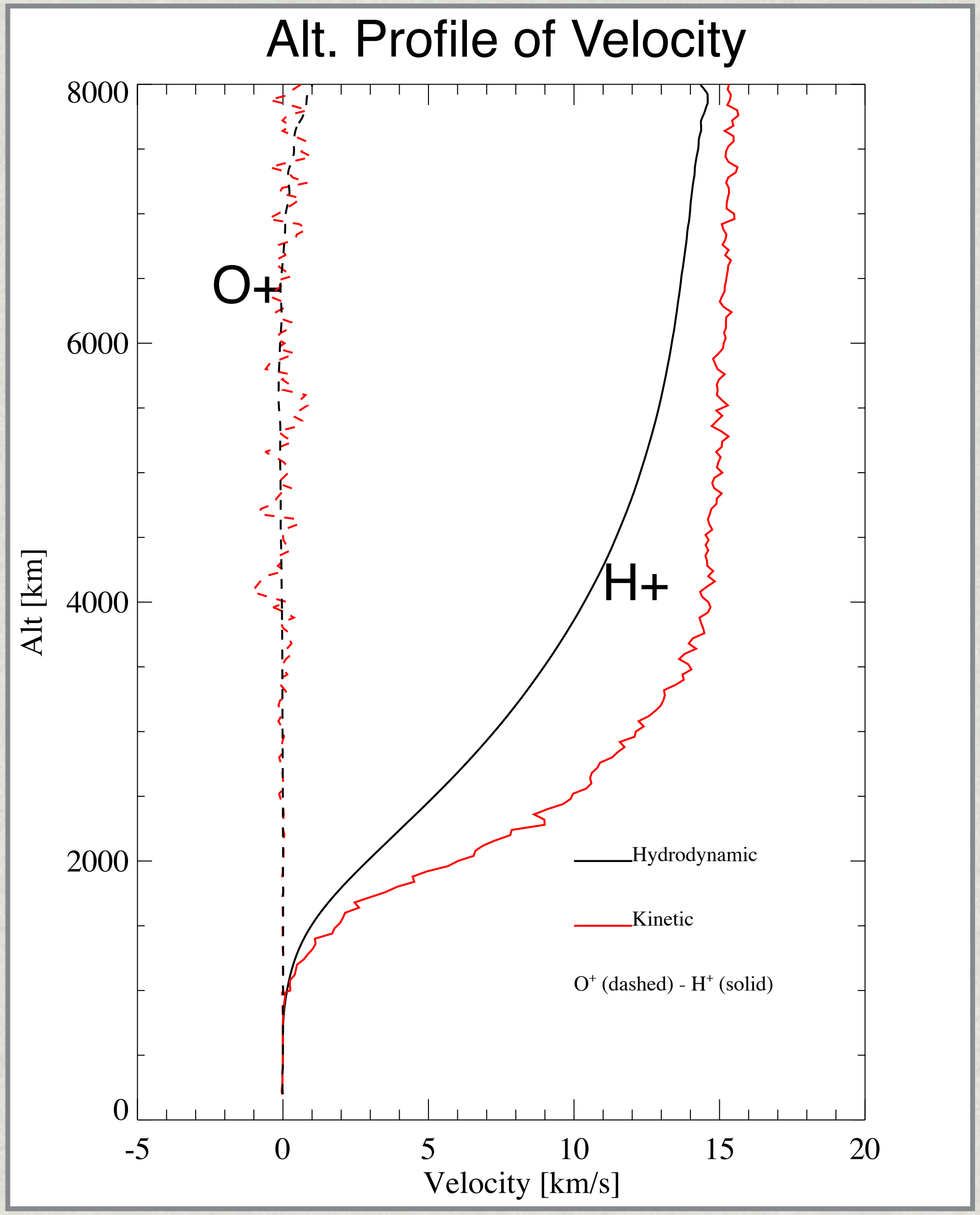
Polar Wind Outflow Model (PWOM)



- Determines transport of plasma from ionosphere to magnetosphere
  - The lower boundary is at 200km, and the upper boundary is at a few R_e
  - Multiple convecting field-lines solutions are obtained
  - **NEW:** 3 treatments of super thermal electron population
  - **NEW:** Transition to kinetic ion description above 1000km based on Macro-PIC approach with Monte Carlo collisions
  - **NEW:** Expansion of model to Jupiter and exoplanet problems

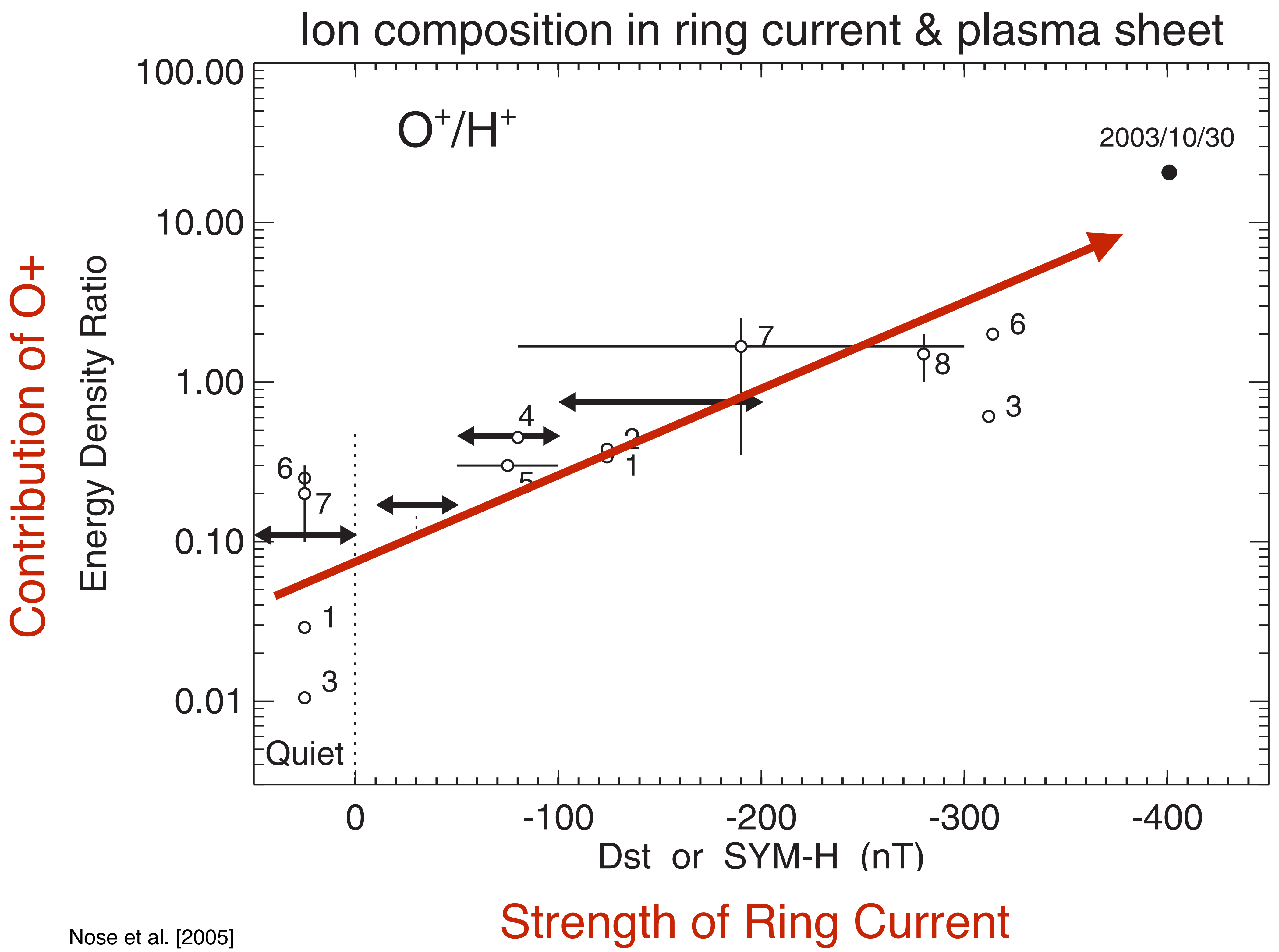
Sunlit Polar Field Line





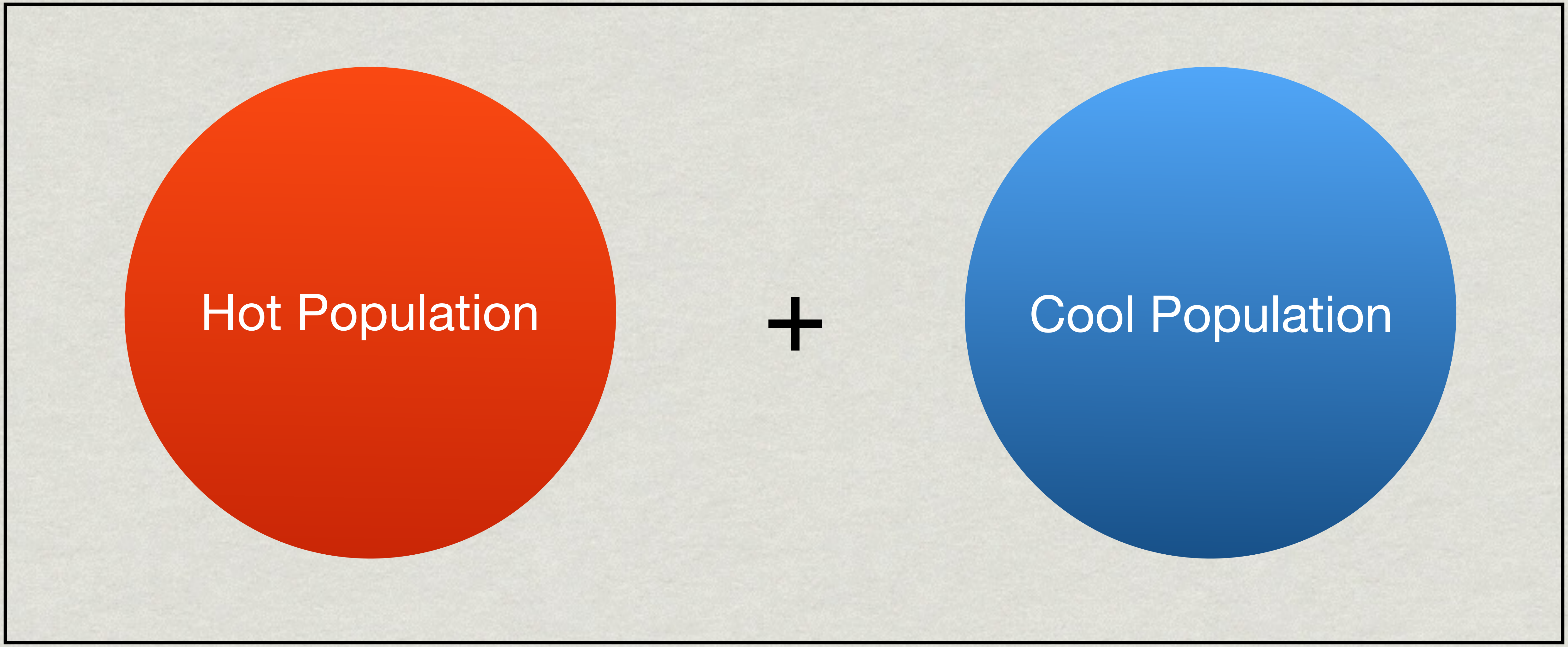
- Comparing hydrodynamic and kinetic solutions

Ionospheric Plasma has System Wide Effects



Nose et al. [2005]

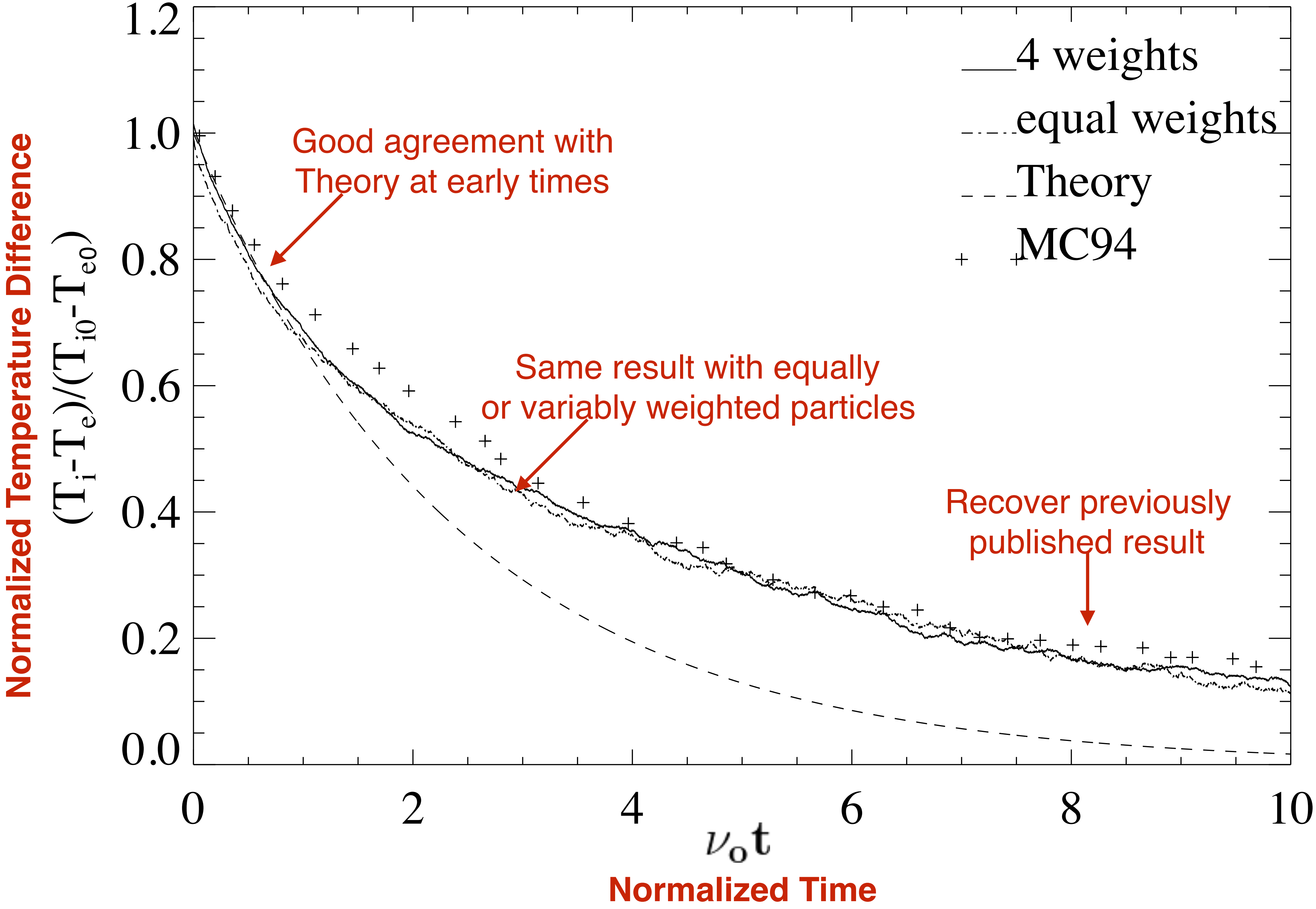
Verifying The Particle Collision Operator



<u>Equilibration of Temperature: Tracking temperature difference over time</u>

- Compare with analytical theory and previously published work
- Verify collision operator for variably weighted particles
- Two cases: Variably weighted and equally weighted particles.

Model Verification: Equilibration of Temperature



Good agreement with Theory at early times

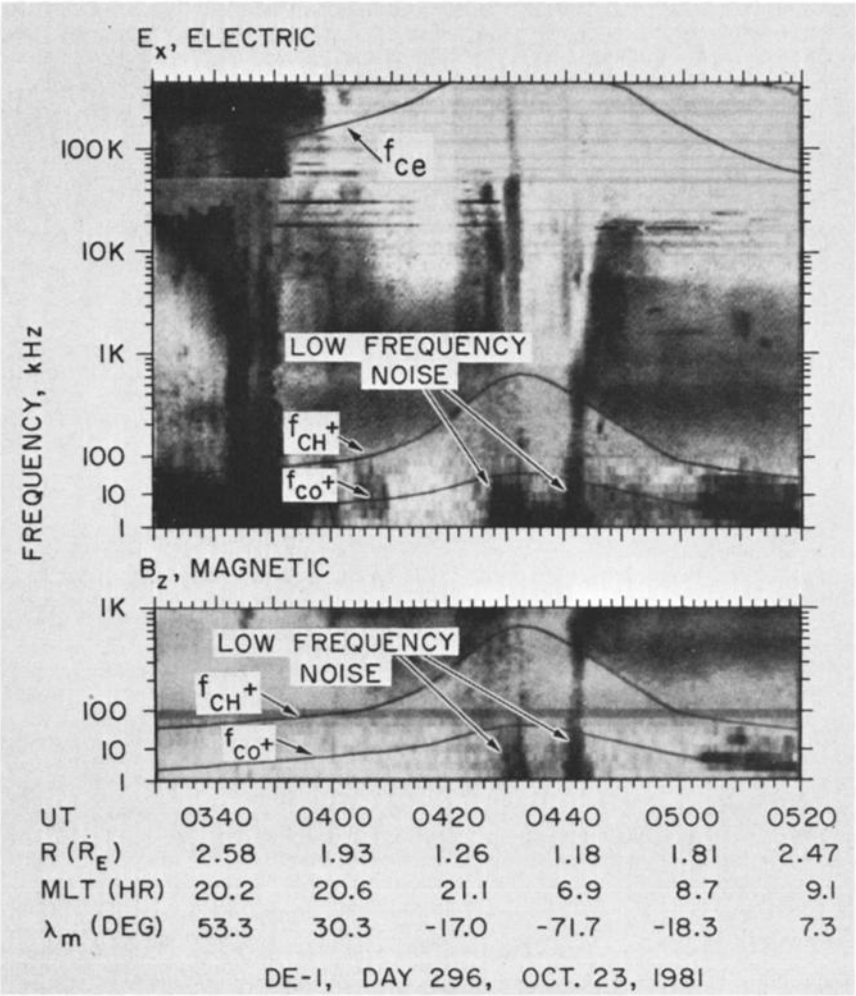
Same result with equally or variably weighted particles

Recover previously published result

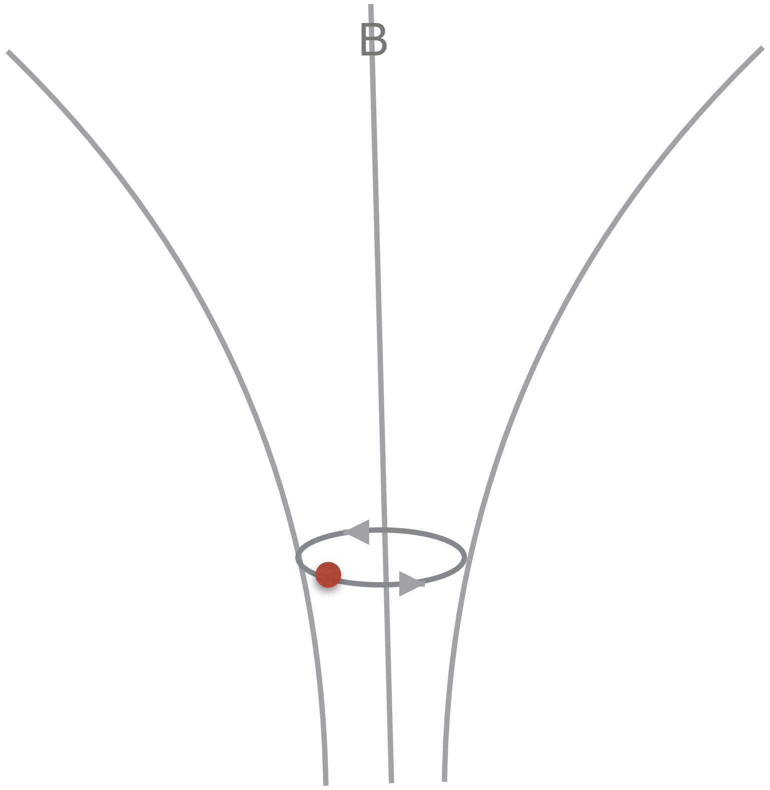
Normalized Temperature Difference

Normalized Time

Turbulent Wave Spectra + Heating Perpendicular to B = Generation of Ion Conic



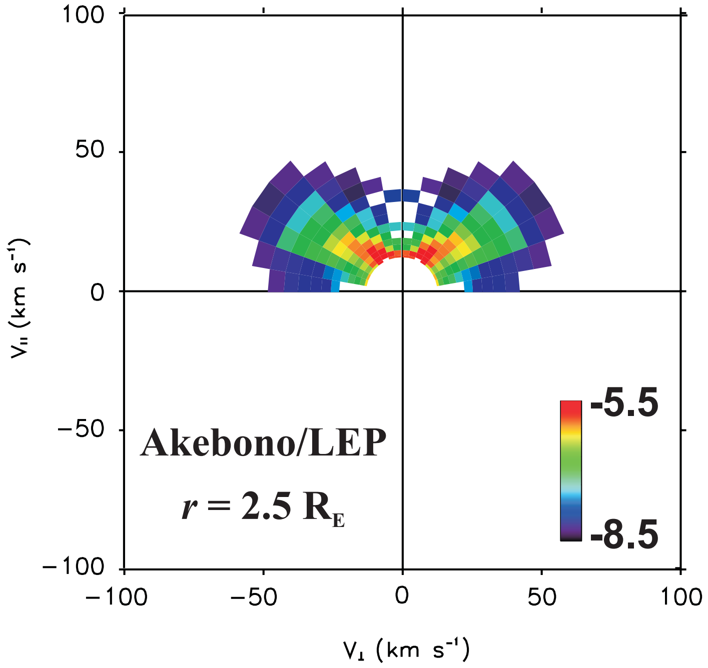
Gurnett et al., [1984]



$$m_i \frac{v_{i\parallel}}{dt} - q_i E_\parallel + \frac{G m_i M_{planet}}{r^2} + \boxed{\mu_i \nabla_\parallel B} = 0$$

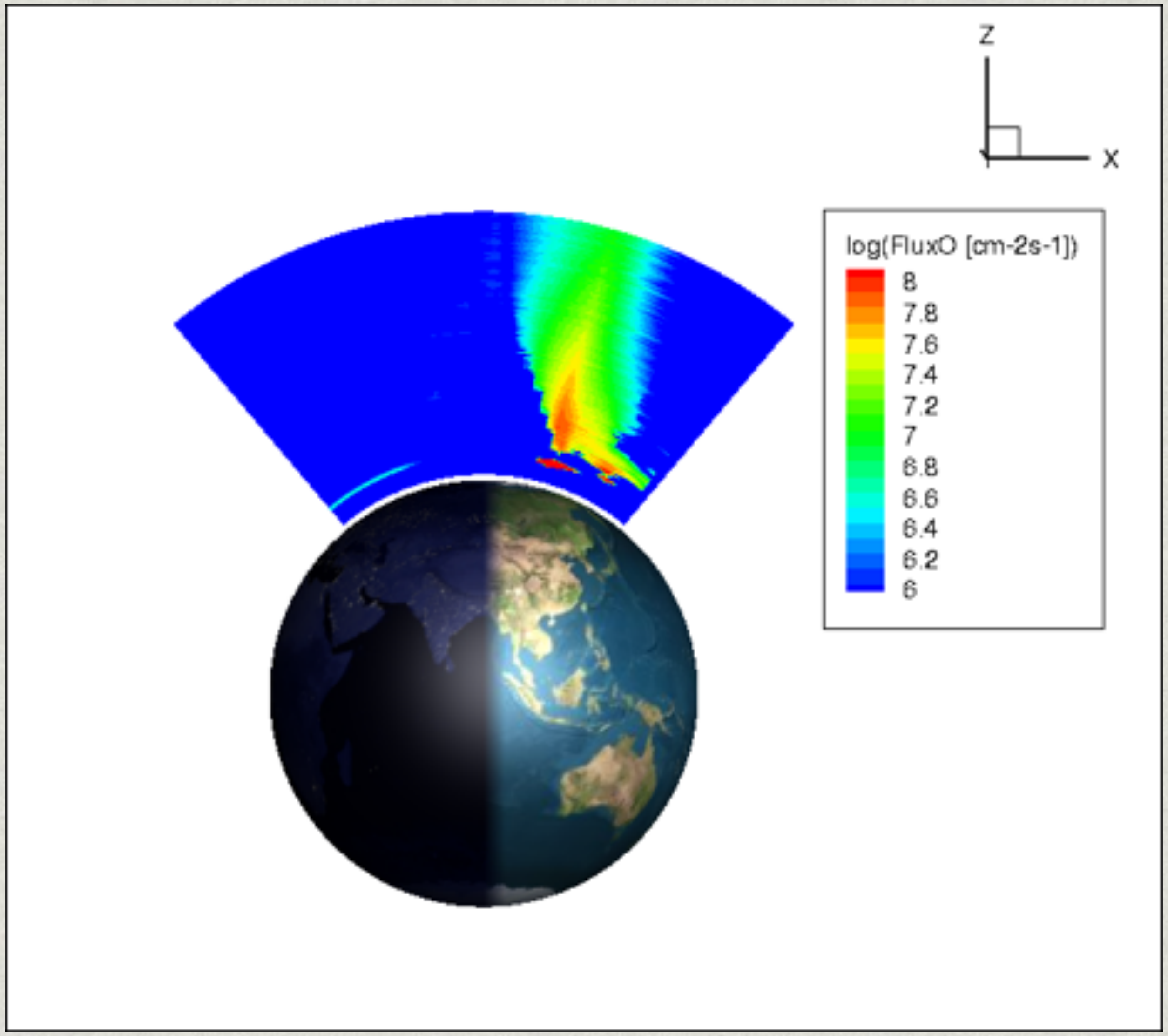
$$\mu_i = \frac{1/2 m_i v_\perp^2}{B}$$

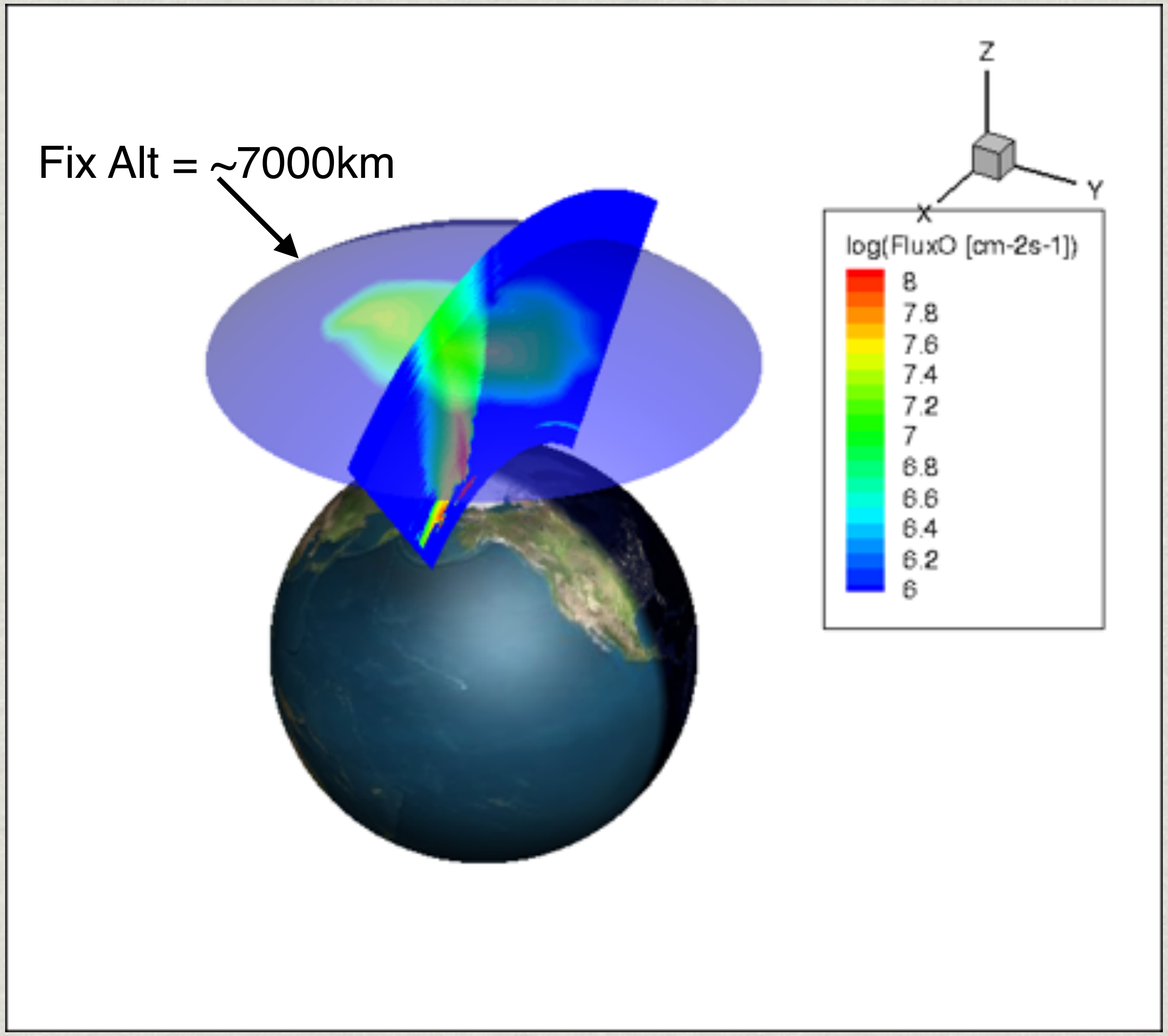
Mirror Force



Bouhram et al., [2004]

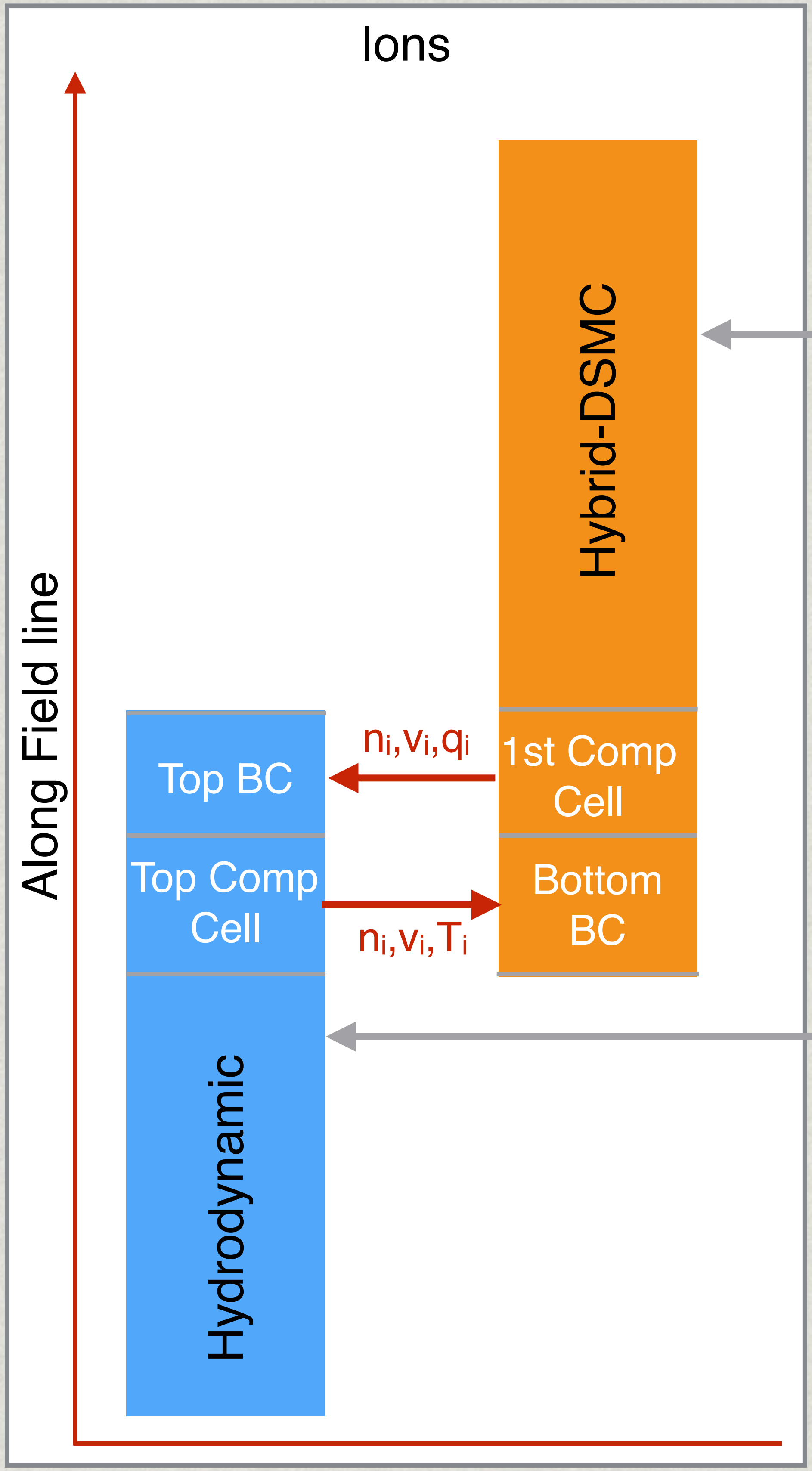
3D View of Outflow





- Majority of the O+ outflow is driven from the dayside, not the aurora

Combined Fluid-Kinetic PWOM



$$m_i \frac{v_{i\|}}{dt} - q_i E_{\|} + \frac{G m_i M_{planet}}{r^2} + \mu_i \nabla_{\|} B = 0$$

$$\mu_i = \frac{1/2 m_i v_\perp^2}{B}$$

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

Continuity

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

Momentum

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

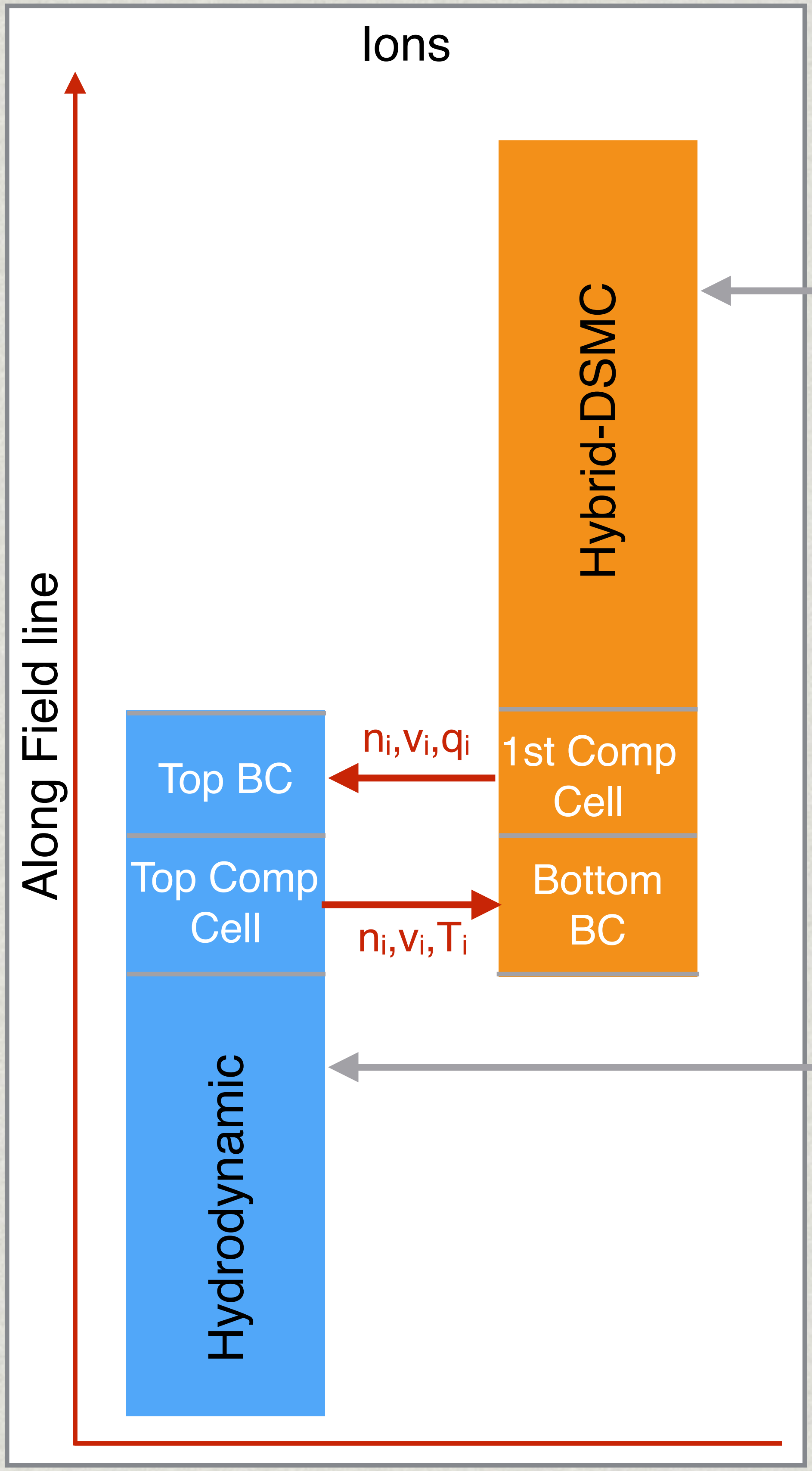
Energy

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

$E_{\|}$

Gombosi et al. (1989)

Combined Fluid-Kinetic PWOM



Particle EOM + Collisions

$$m_i \frac{v_{i\|}}{dt} - q_i E_\| + \frac{G m_i M_{planet}}{r^2} + \mu_i \nabla_\| B = 0$$

$$\mu_i = \frac{1/2 m_i v_\perp^2}{B}$$

Gyrotropic Fluid Transport

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

Continuity

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

Momentum

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

Gombosi et al. (1989)

Energy

Field-Aligned Transport Equations

Continuity

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

Momentum

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

Energy

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

Ambipolar E-Field

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

Gombosi et al. (1989)

Equations: Electrons + Superthermal electrons

Quasi-neutrality

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

Current conservation

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

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

Temperature

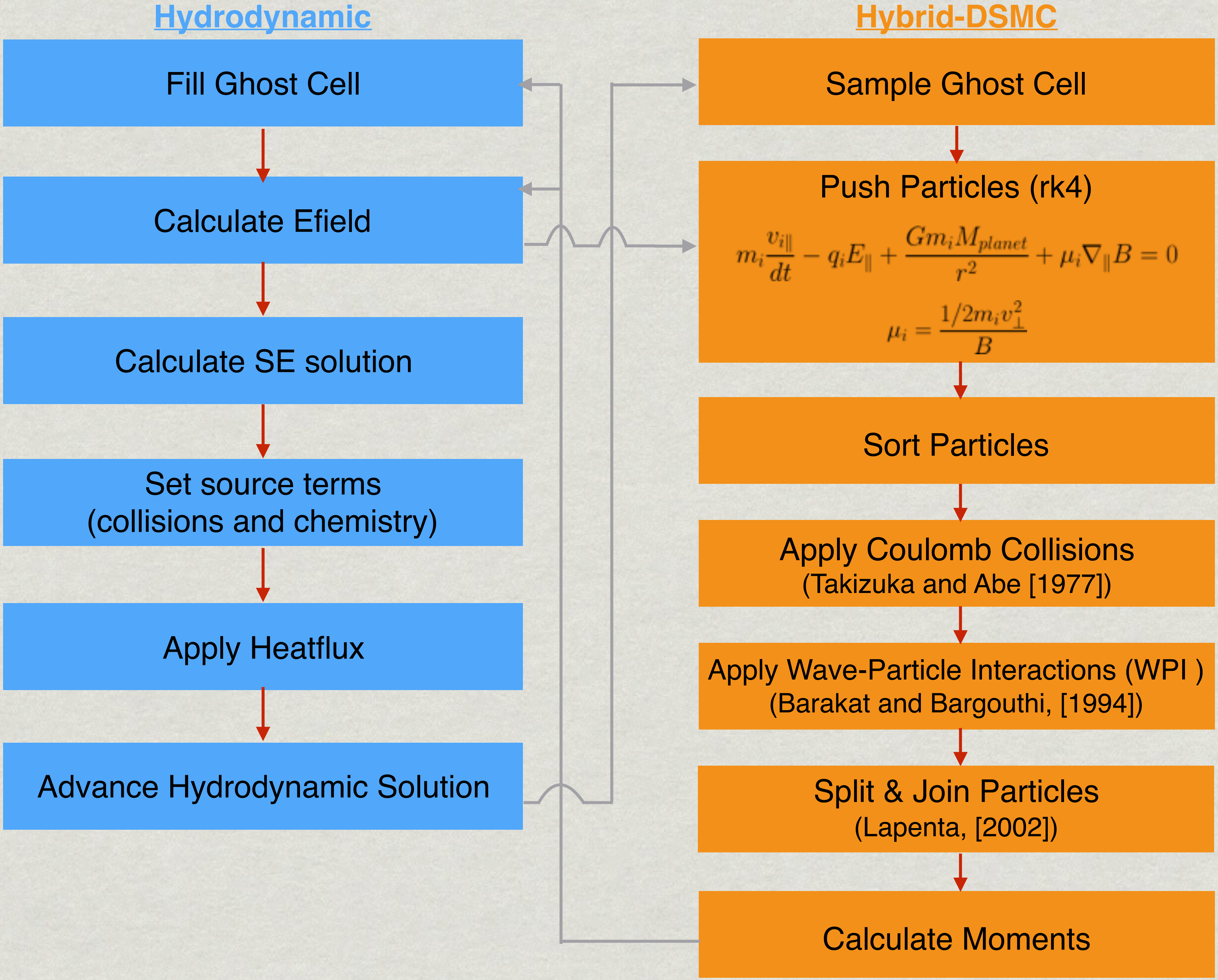
$$\rho_e \frac{\partial T_e}{\partial t} = (\gamma_e - 1) \frac{m_e}{kA} \frac{\partial}{\partial r} \left(A \kappa_e \frac{\partial T_e}{\partial r} \right) - \rho_e u_e \frac{\partial T_e}{\partial r} -$$

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

Superthermal e^-

Three choices (next slide)

Calculation Flow



Hydrodynamic

Fill Ghost Cell

Calculate Efield

Calculate SE solution

Set source terms
(collisions and chemistry)

Apply Heatflux

Advance Hydrodynamic Solution

Hybrid-DSMC

Sample Ghost Cell

Push Particles (rk4)

$$m_i \frac{v_{i\parallel}}{dt} - q_i E_\parallel + \frac{G m_i M_{planet}}{r^2} + \mu_i \nabla_\parallel B = 0$$

$$\mu_i = \frac{1/2 m_i v_\perp^2}{B}$$

Sort Particles

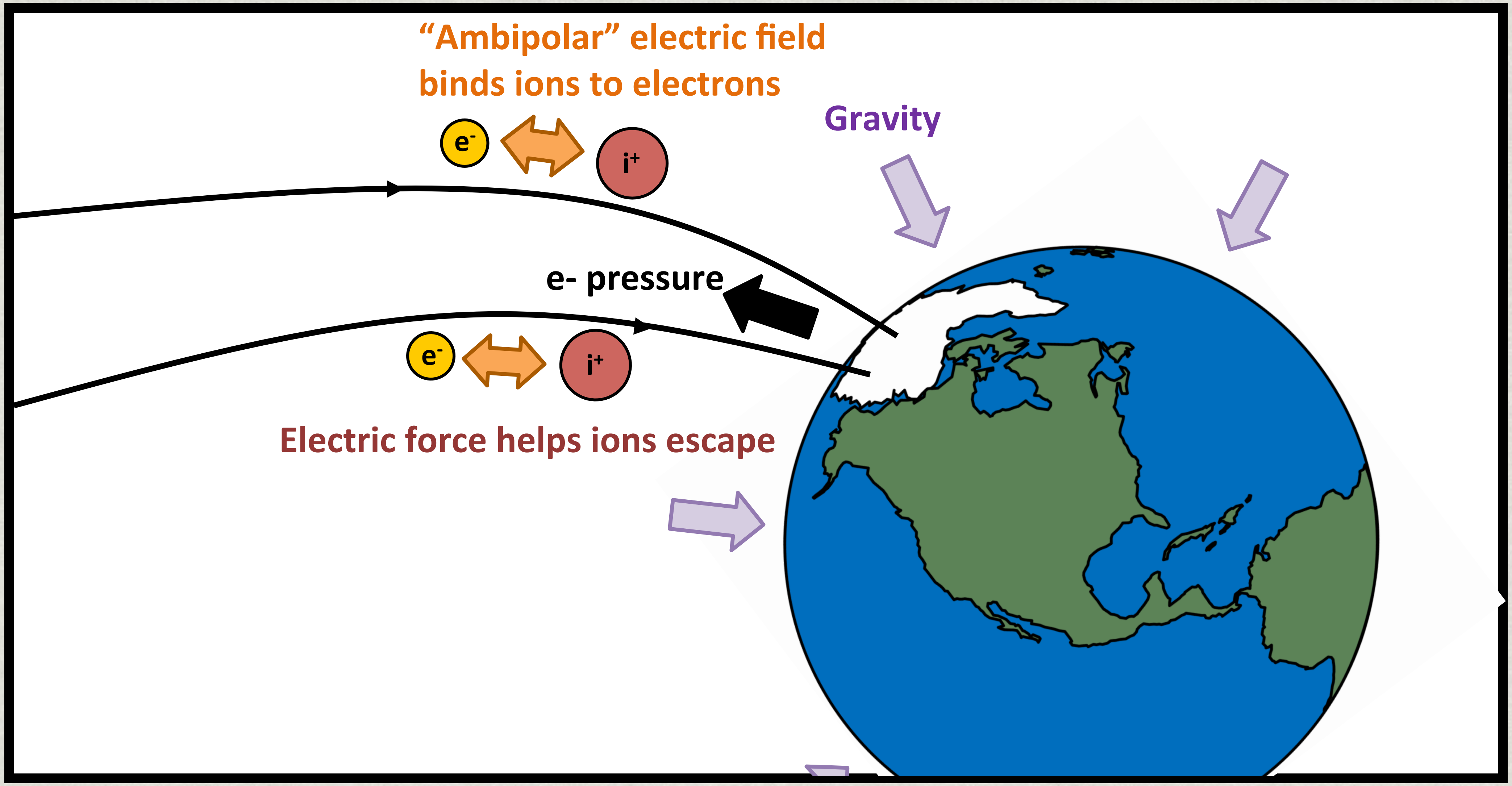
Apply Coulomb Collisions
(Takizuka and Abe [1977])

Apply Wave-Particle Interactions (WPI)
(Barakat and Bargouthi, [1994])

Split & Join Particles
(Lapenta, [2002])

Calculate Moments

Superthermal Electrons (SEs)



- Mechanisms by which SEs affect outflow
  - E||
  - Coulomb collisions

Equations: Electrons + Superthermal electrons

Quasi-neutrality

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

Current conservation

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

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

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$^-$

Three choices (next slide)

Three Treatments of SE population

- Externally imposed fluxes (Glocer et al., [2012])

- Two-Stream electrons from adapted GLOW model (Solomon et al.,[1988], Banks and Nagy [1970])

$$\frac{d\Phi^{+}(\epsilon, s)}{ds} = -\sum_{k} n_k(s)[\sigma_a{}^{k} + p_e{}^{k}\sigma_e{}^{k}]\Phi^{+}(\epsilon, s) + \sum_{k} n_k(s)p_e{}^{k}\sigma_e{}^{k}\Phi^{-}(\epsilon, s) + \frac{q(\epsilon, s)}{2} + q^{+}(\epsilon, s) \tag{1}$$

$$-\frac{d\Phi^{-}(\epsilon, s)}{ds} = -\sum_{k} n_k(s)[\sigma_a{}^{k} + p_e{}^{k}\sigma_e{}^{k}]\Phi^{-}(\epsilon, s) + \sum_{k} n_k(s)p_e{}^{k}\sigma_e{}^{k}\Phi^{+}(\epsilon, s) + \frac{q(\epsilon, s)}{2} + q^{-}(\epsilon, s) \tag{2}$$

THIS TALK

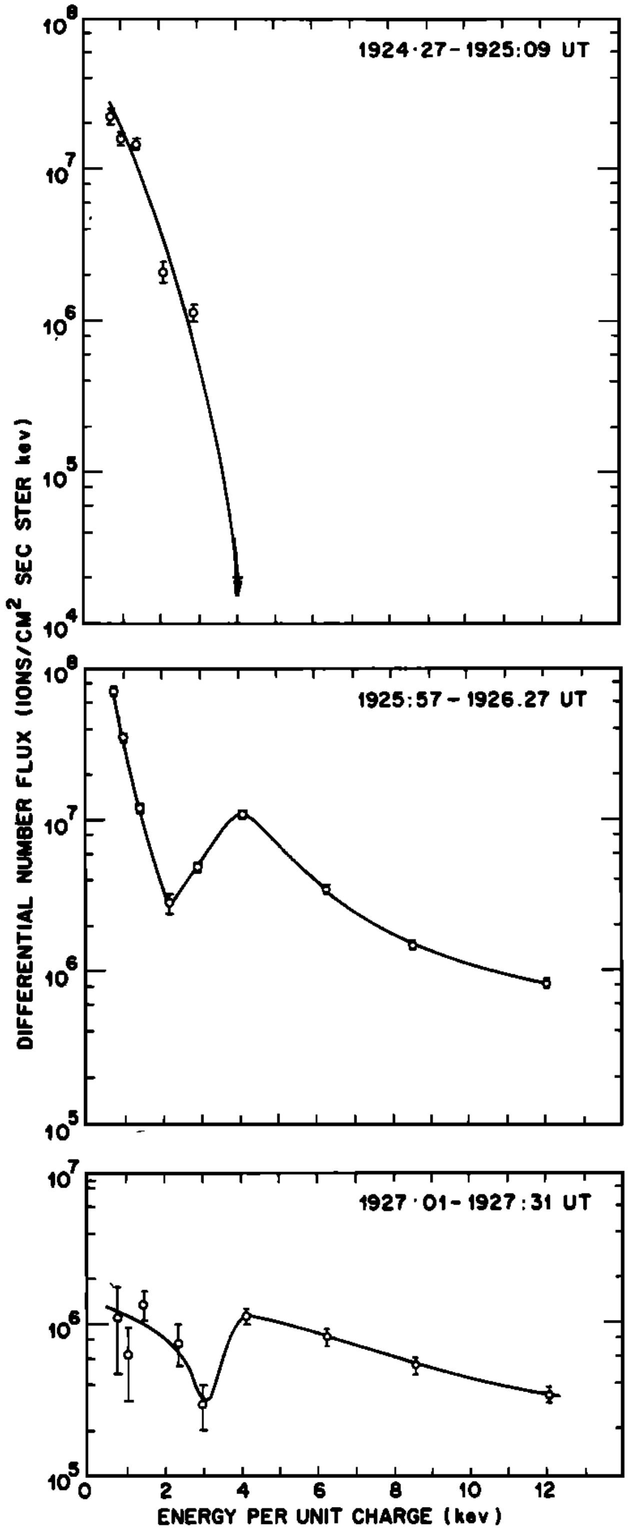
- Kinetic Model: STET (Khazanov et al., [1997], Liemohn and Khazanov, [1997])

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

O+ as a marker of outflow

First Measurements of O+ Raining Down from Magnetosphere

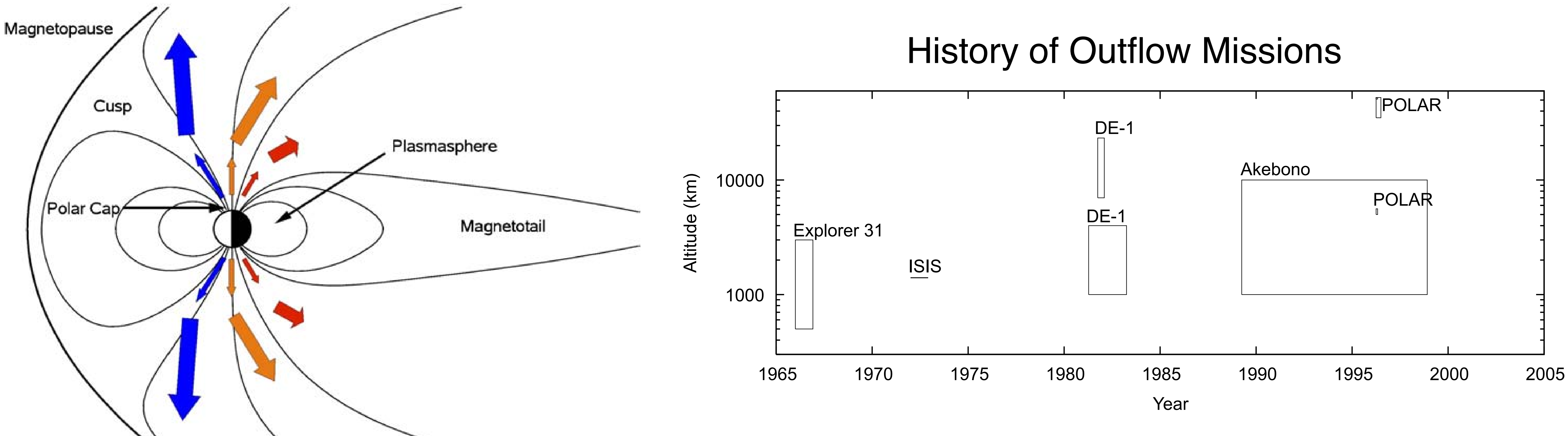
Differential O+ Flux



E/q

Shelley *et al.*, [1972]

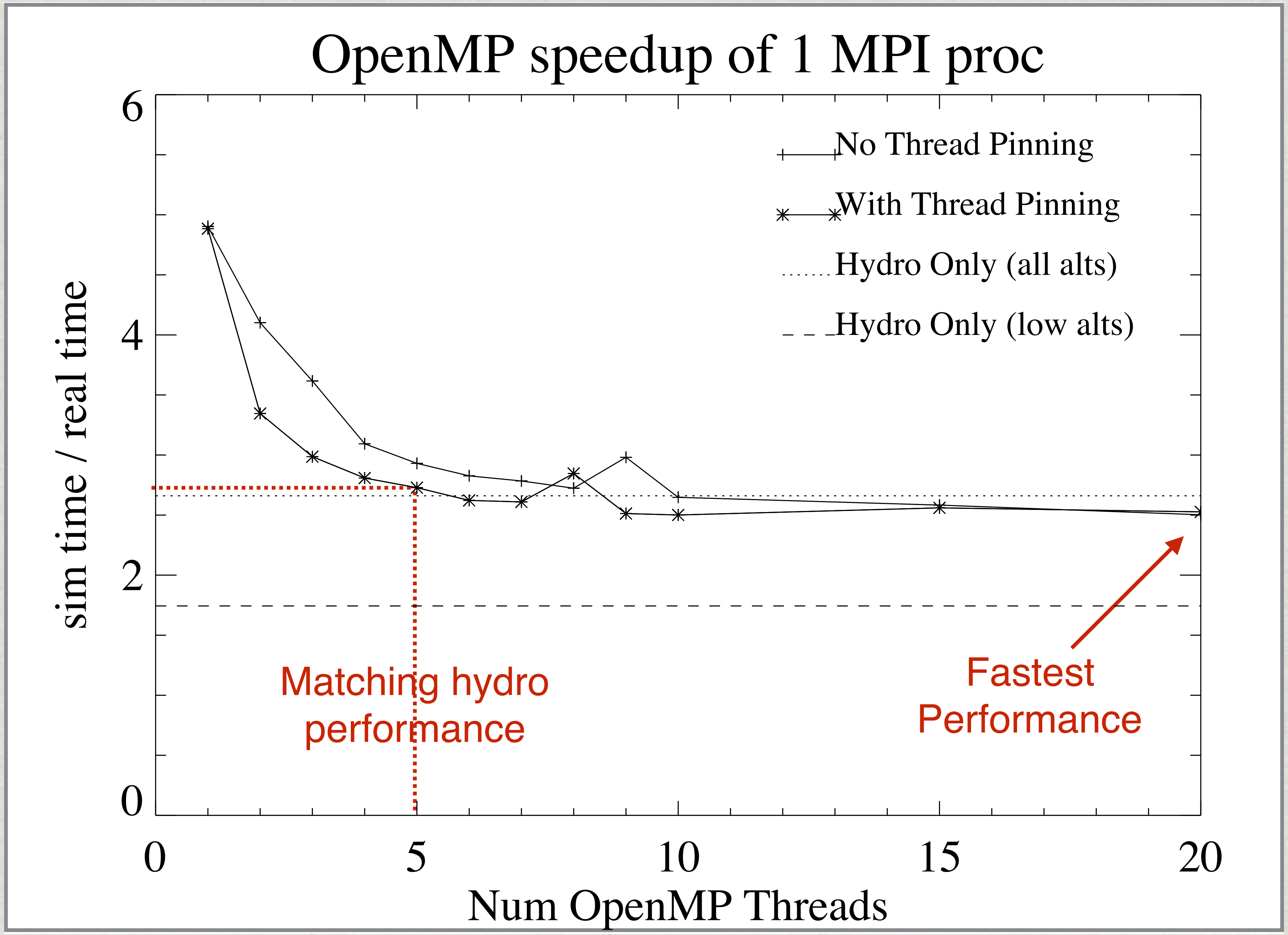
Background & importance of outflow



Yau et al., [2007]

- “Polar wind” outflow first postulated by *Axford* [1968] and *Banks and Holtzer* [1968]
- First in-situ measurements by the Explorer 31 satellite showing H^+ parallel velocities > 10km/s (Hoffman, 1970; Brinton et al., 1971)
- Outflows of H^+, O^+, He^+ frequently observed since (see one of many reviews by *Yau et al*., [2007], *Welling et al*., [2016], …)

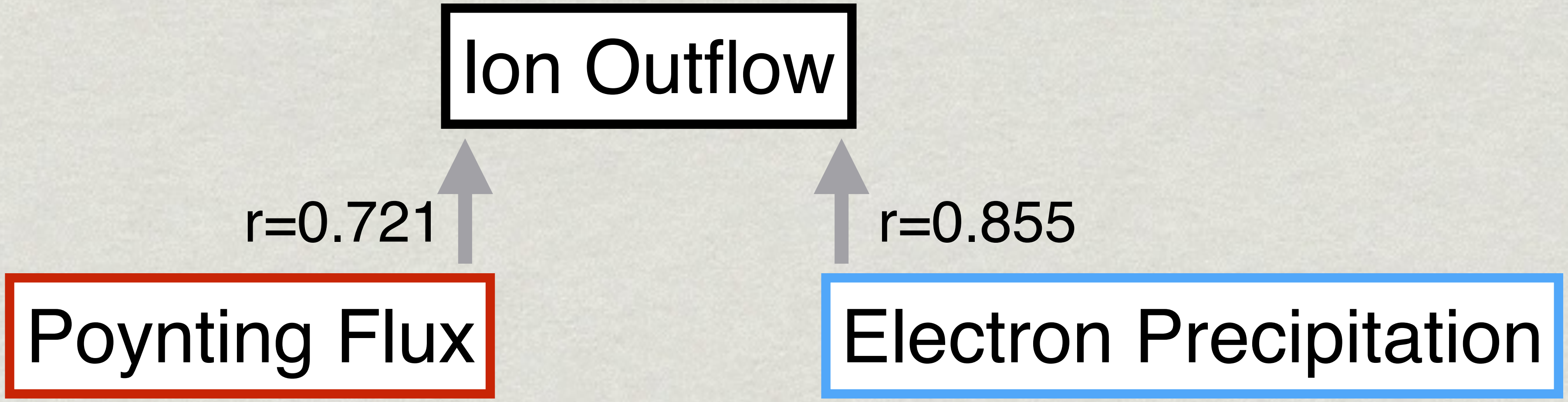
Parallel Performance



- This performance is true regardless of number of field lines since MPI parallelization is embarrassingly parallel.

Representing the Ionospheric Source

Empirical Model



Ion Outflow

r=0.721

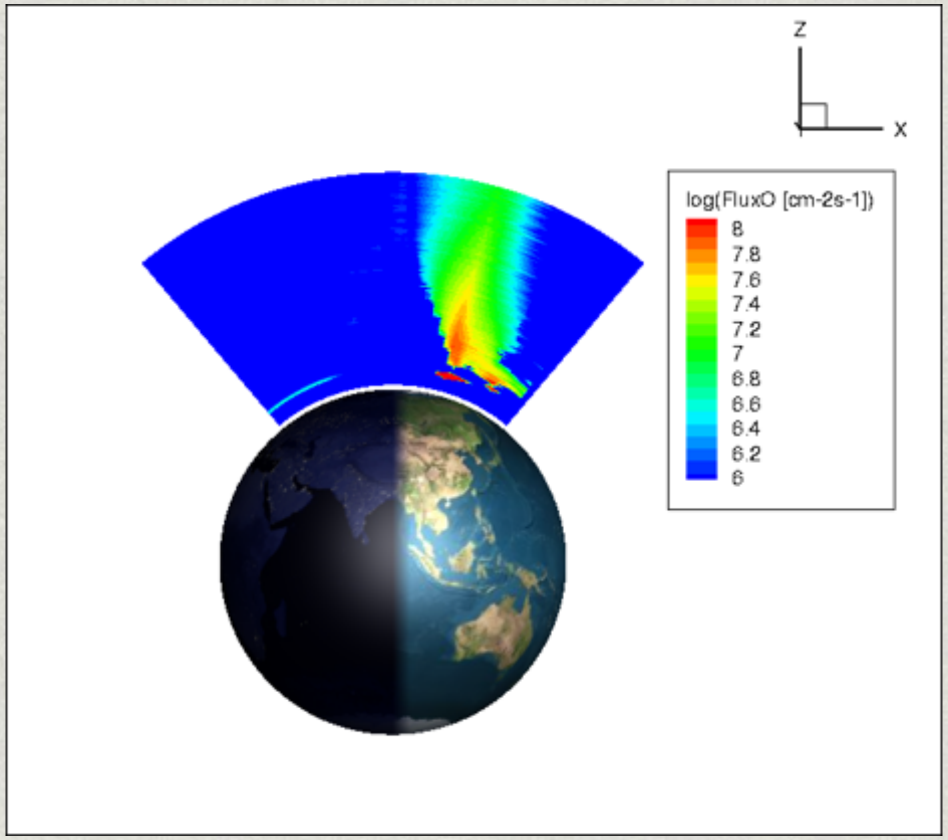
r=0.855

Poynting Flux

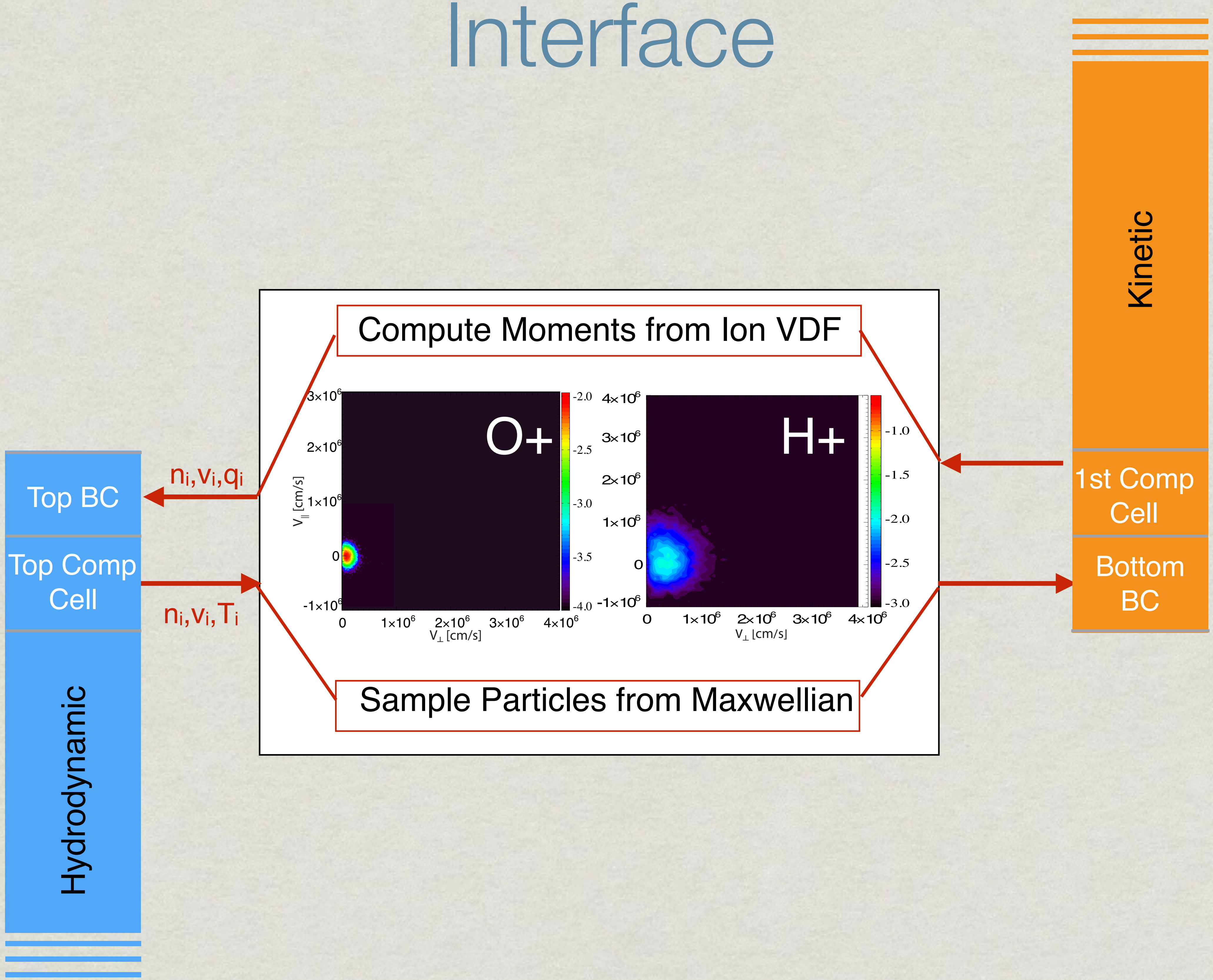
Electron Precipitation

Strangeway et al. [2005]

First Principles



Understanding the Hydro-Kinetic Interface



Kinetic

1st Comp Cell

Bottom BC

Top BC

Top Comp Cell

Hydrodynamic

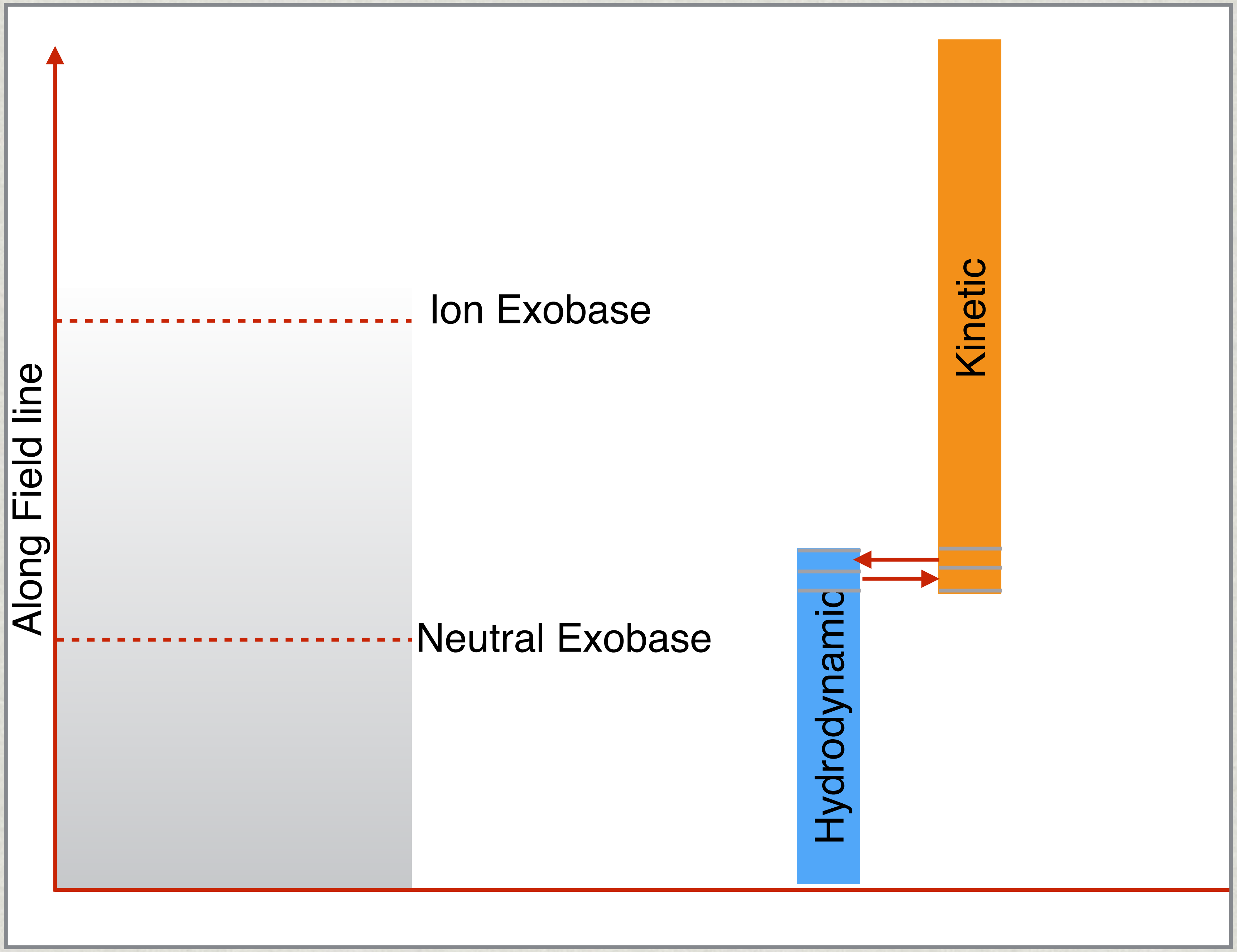
n_i, v_i, q_i

n_i, v_i, T_i

Compute Moments from Ion VDF

Sample Particles from Maxwellian

Location, Location, Location



- Fluid and Kinetic models are both valid descriptions while collisions are important