Alfvenic Aurora: An Overview

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PPPL Research and Review Seminar
Sept. 8, 2017

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Somewhere to start...

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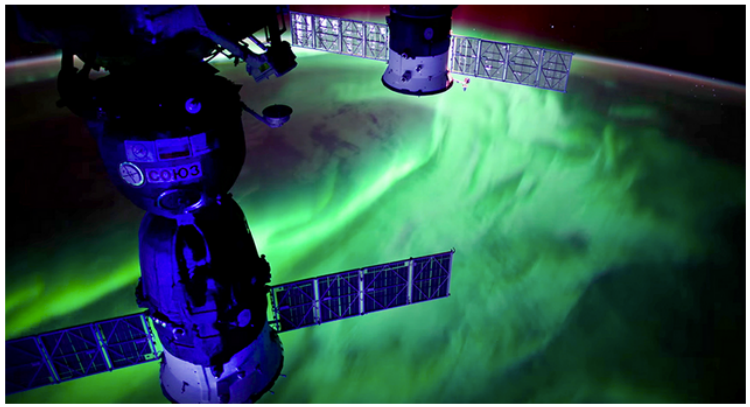
DOI:10.1063/PT.5.7357

16 Mar 2017 in Research & Technology

A step toward deciphering auroras

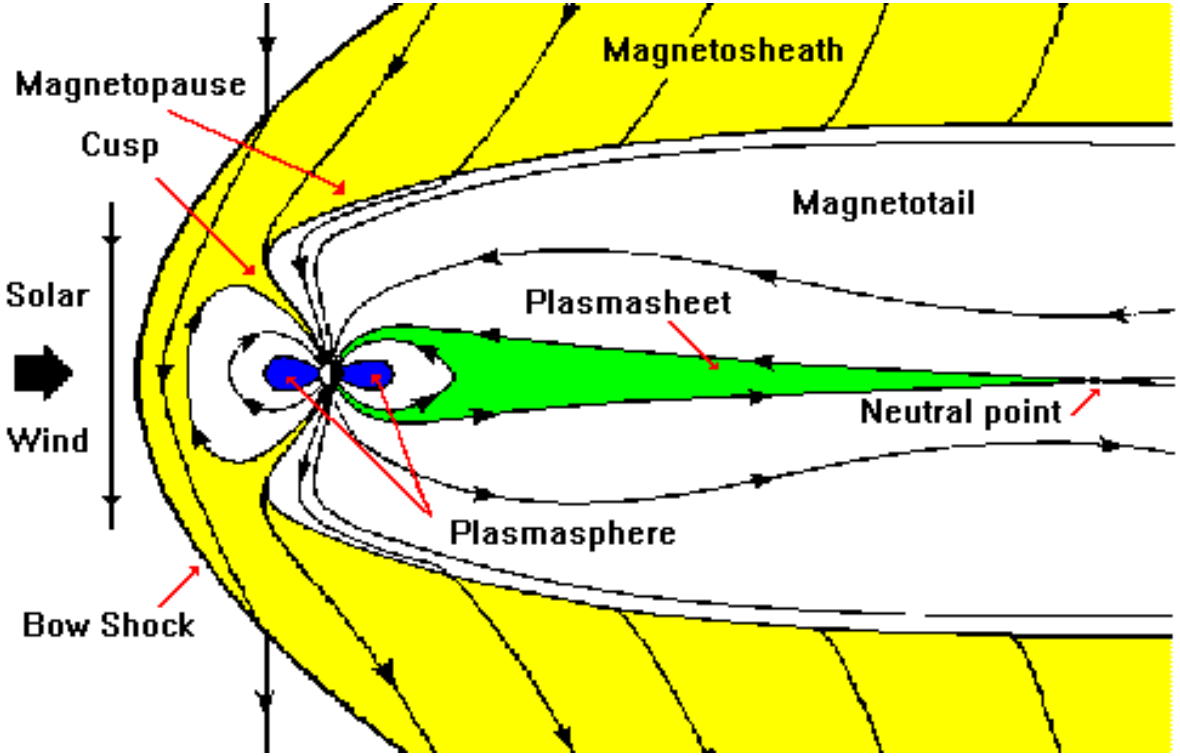
Electrons get jolted by the plasma waves that are thought to drive the colorful phenomenon.

Andrew Grant



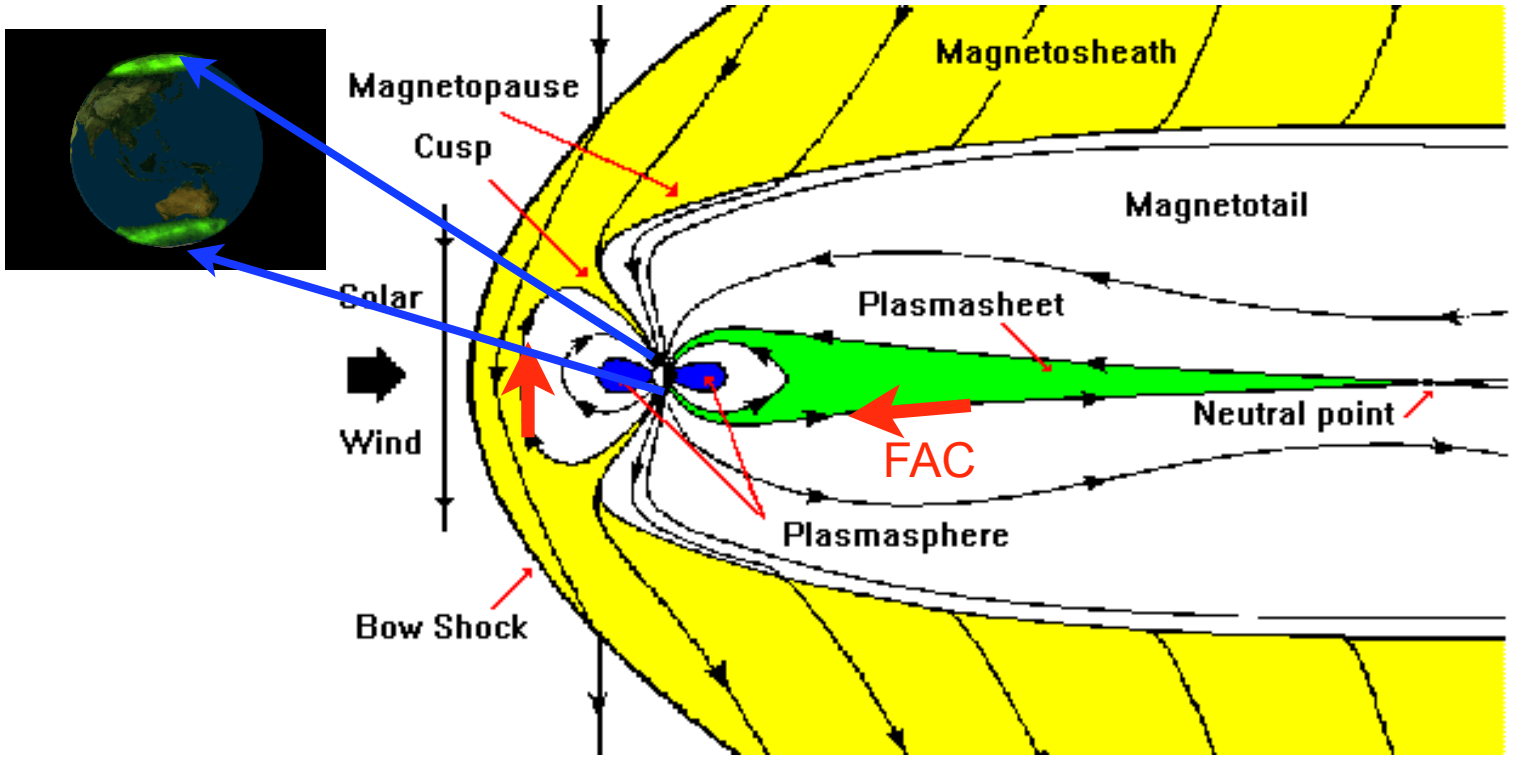
An aurora viewed from the International Space Station. Credit: NASA

Magnetosphere-Ionosphere Coupling



Magnetosphere-Ionosphere Coupling

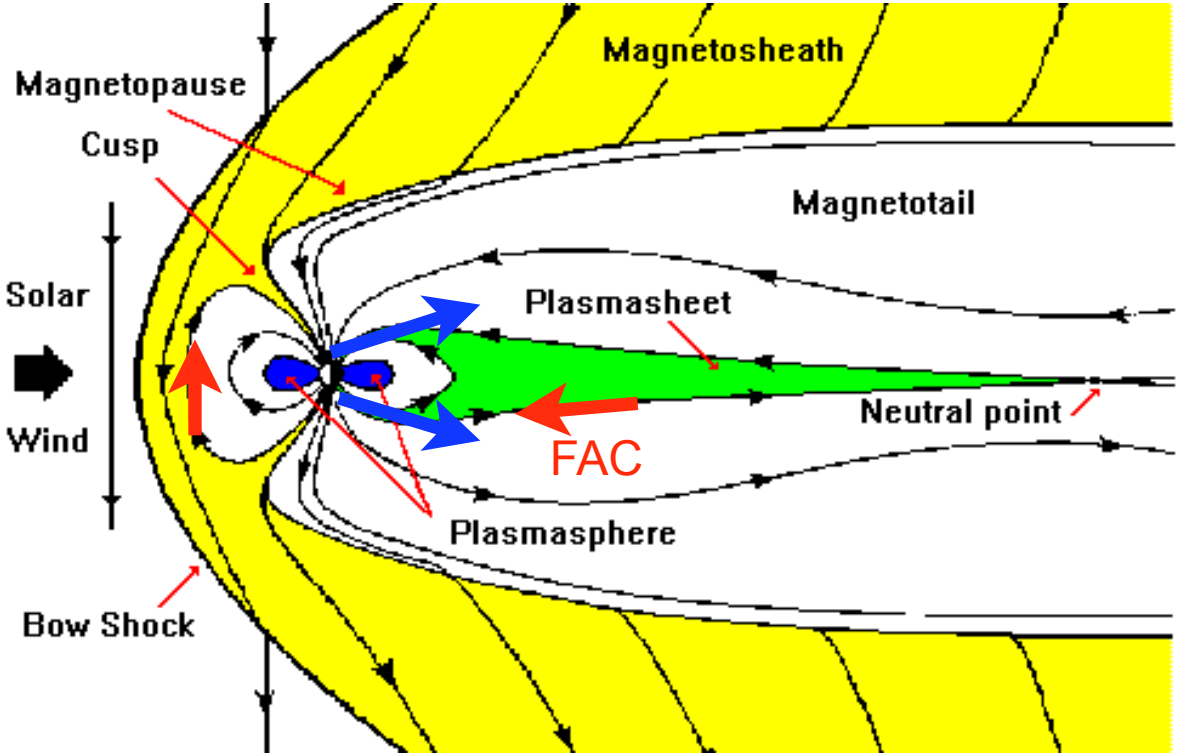
FACs carry electron flux into ionosphere



Electron flux interacts with atmospheric gases to produce aurora

Magnetosphere-Ionosphere Coupling

Poynting and Electron flux also drive outflow of heavy ions



Which alters the magnetospheric configuration

Auroral Morphology

- **Monoenergetic Aurora** are associated with:
  - quasi-static global Field Aligned Currents (FACs).
  - Low frequency global scale Alfven waves (Damiano and Wright, 2008; Damiano and Johnson, 2012, 2013).

- **Broadband Aurora (aka Alfvenic aurora)** are associated with:
  - dispersive scale Alfven waves ($\lambda_\perp \sim c/\omega_{pe}$, ρ_s or ρ_i) and can drive substantial ionospheric outflow.

- **Diffuse Aurora** associated with:
  - EMIC and whistler waves (radiation belts).

Motivation: Understanding how Alfven wave energy couples to electron precipitation that drives the broadband aurora.

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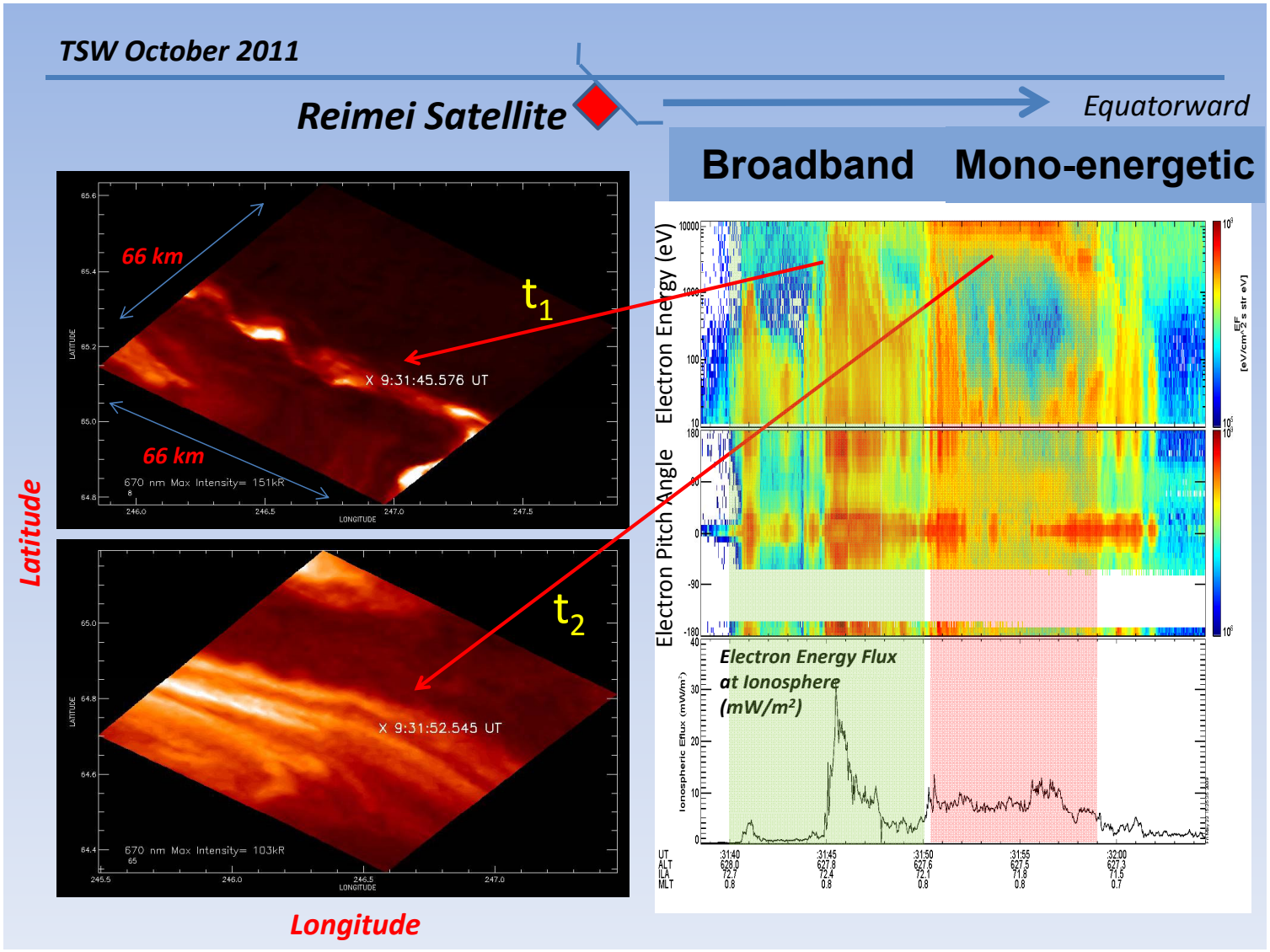
Characteristics of Monoenergetic and Broadband Aurora

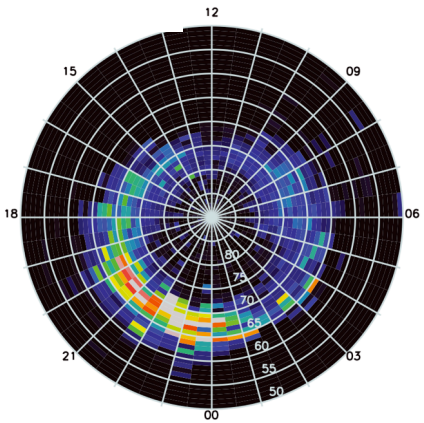


(Courtesy C. Chaston)

Alfvenic Aurora

Broadband e^- precipitation correlated with Alfvenic Poynting flux.

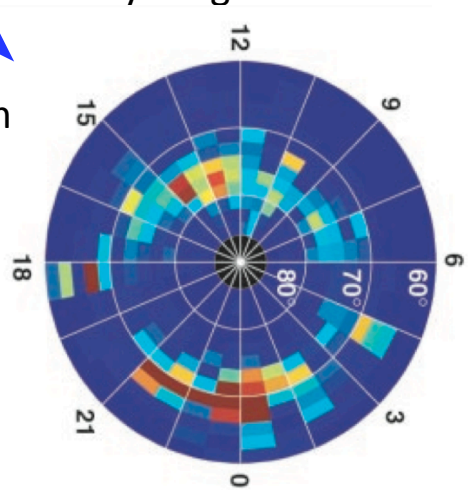
Broadband electron energy flux



(Wing et al., 2013)

Sun

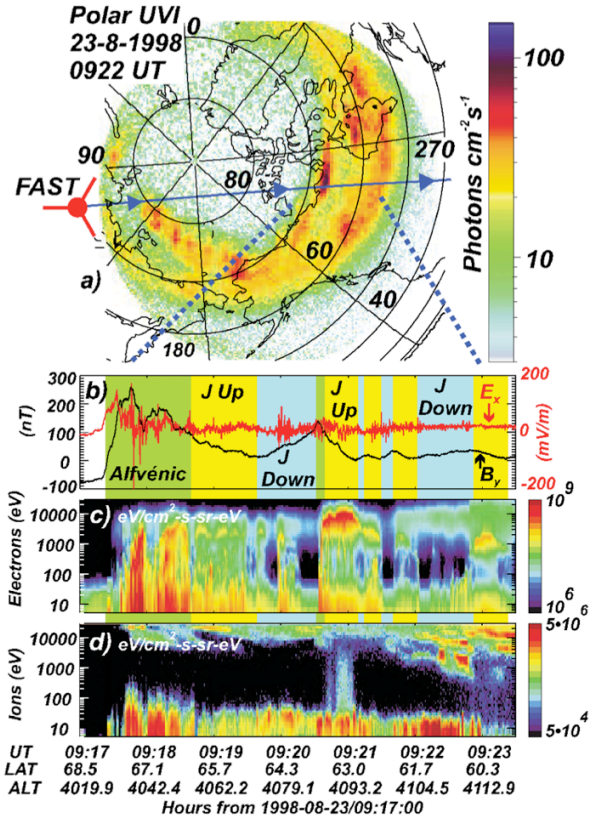
Downward Alfvenic Poynting flux



(Keiling et al., 2003)

Poynting flux associated with ~Hz frequency dispersive Alfven waves ($\lambda_{\parallel} \sim R_E$, $\lambda_{\perp} \sim \lambda_e$, ρ_s, ρ_i).

Alfvenic aurora associated with significant ionospheric outflow

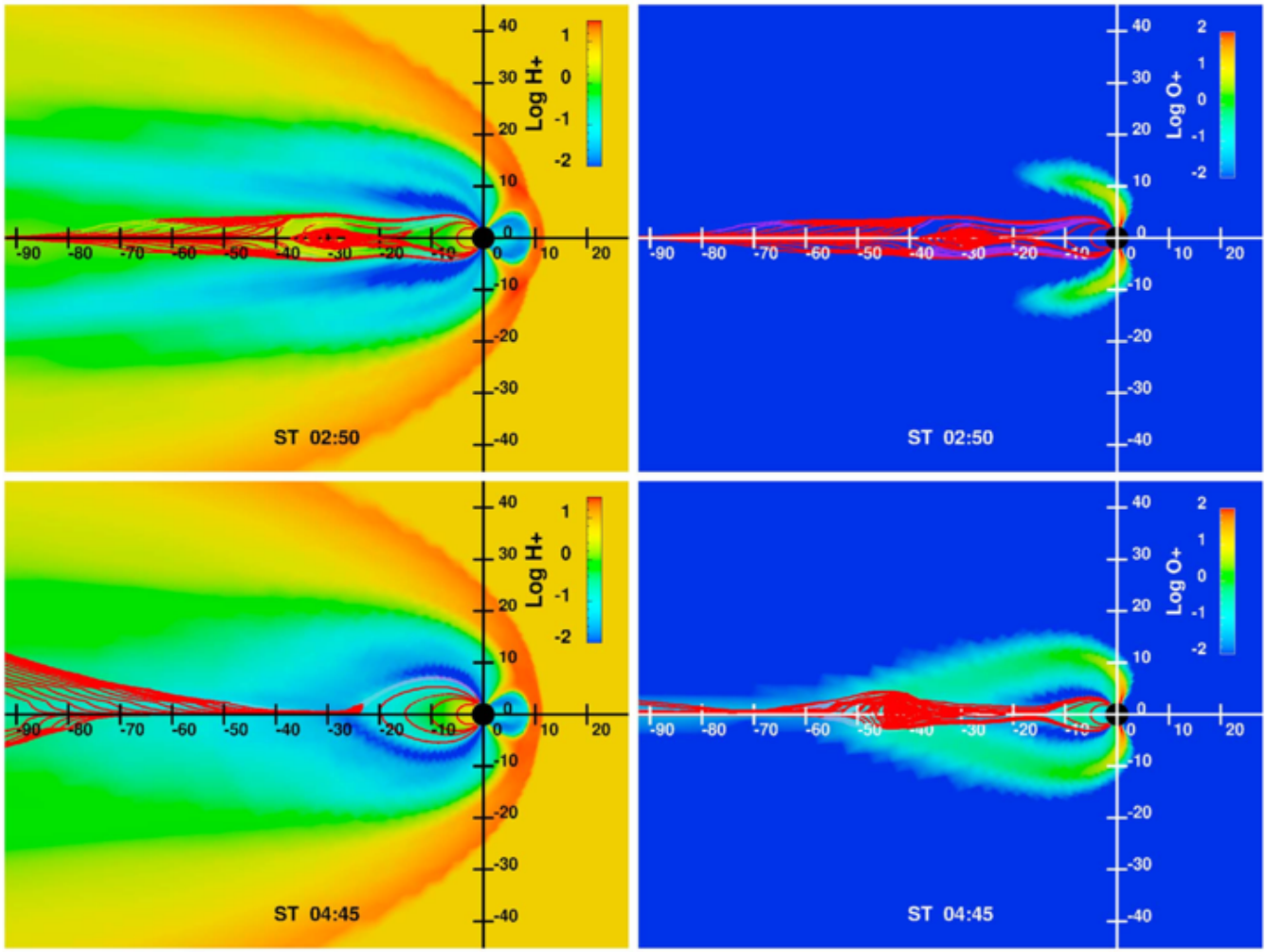


(Chaston et al., 2008)

Outflow can alter magnetotail configuration

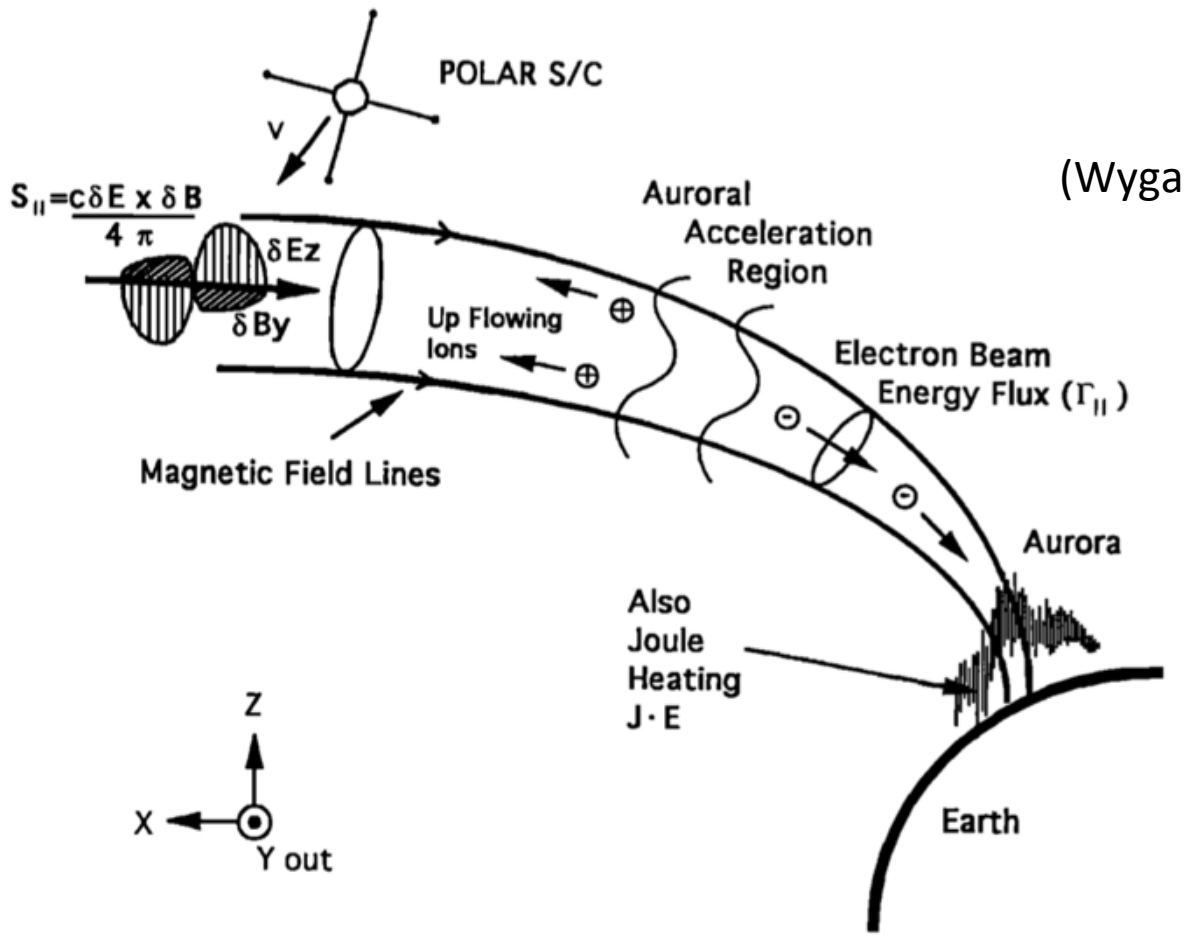
Magnetosphere-ionosphere is a tightly coupled system.

no O^+ outflow | with O^+ outflow



(Wiltberger et al., 2010)

Global picture



(Wygant et al., 2000)

Poynting flux converted to particle energization and and dissipated in ionospheric joule heating.

Need $E_{||}$ to accelerate electrons - dispersive Alfven waves

Two limits in which Alfven waves carry significant parallel electric field:

1) **Inertial Alfven wave limit:** ($\lambda_\perp \sim \lambda_e = c/\omega_{pe}$, $v_{Te} << V_A$, *Goertz and Boswell*, 1979).

$$\omega = k_{||} V_A \rightarrow \omega = k_{||} V_A / \sqrt{1 + k_\perp^2 \lambda_e^2}$$

2) **Kinetic Alfven wave:** ($\lambda_\perp \sim \rho_s$, ρ_i, $v_{Te} >> V_A$; *Hasegawa*, 1976).

$$\omega = k_{||} V_A \rightarrow \omega = k_{||} V_A \sqrt{1 + k_\perp^2 \left(\rho_s^2 + \frac{3}{4} \rho_i^2 \right)}$$

ω -> $\omega(k_\perp)$ - wave can now disperse perpendicular to the magnetic field

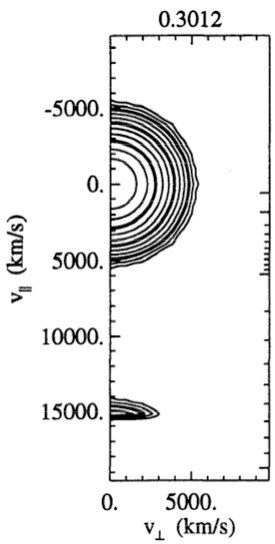
$$E_{||} = \underbrace{\boxed{\lambda_e^2 \frac{\partial j_{||}}{\partial t}}}_{\text{IAW}} - \underbrace{\boxed{\frac{\nabla_{||} P_e}{en}}}_{\text{KAW}}$$

Generalized Ohm's Law

Electron acceleration in dispersive scale Alfven waves

Path along field line is a highly variable plasma environment

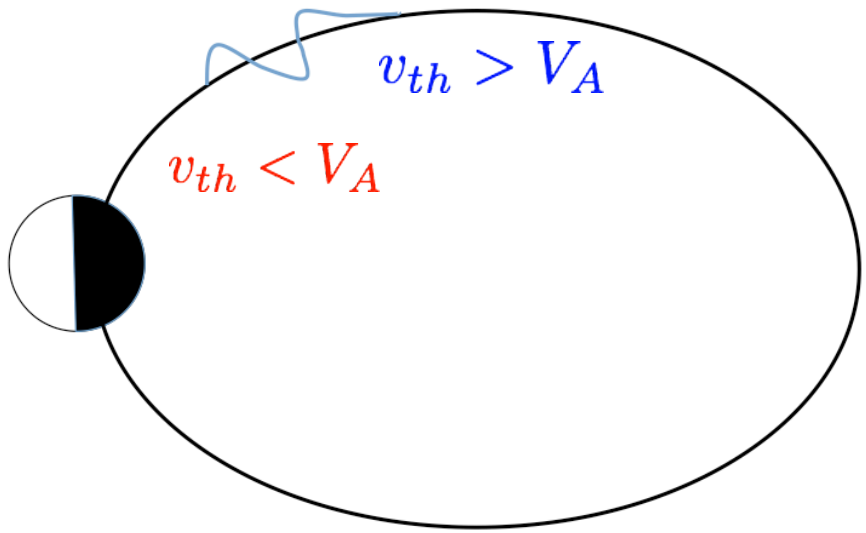
IAW regime



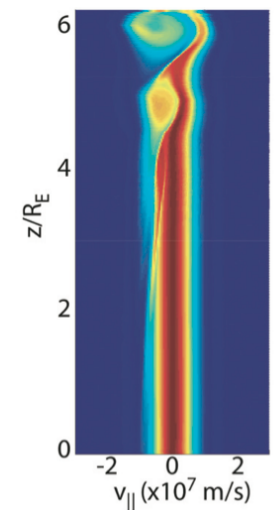
(Kletzing et al., 1994)

Fermi acceleration

Alfven wave



KAW regime



(Watt and Rankin, 2010)

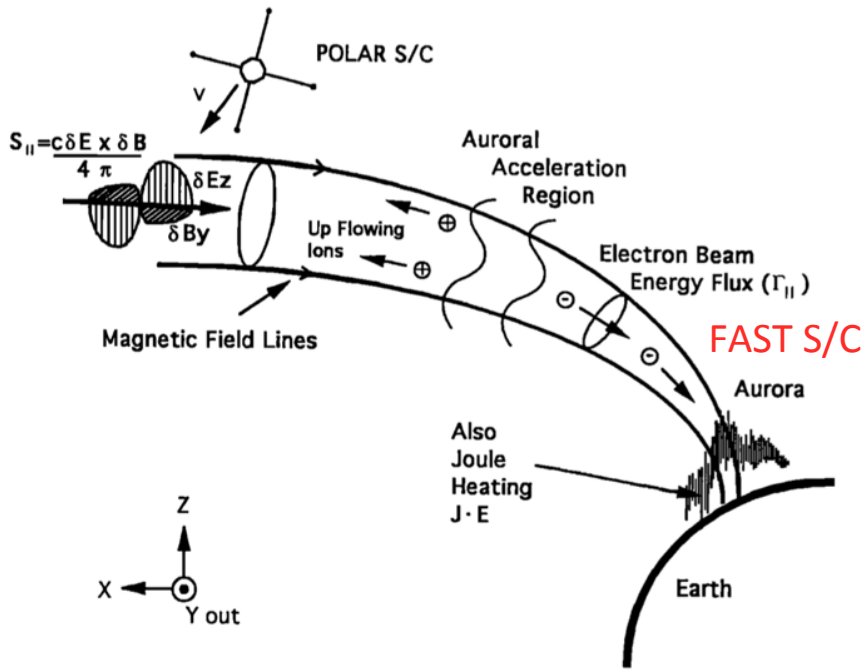
Particle trapping

Significant body of previous work - (e.g. *Kletzing,* 1994; *Chaston et al.,* 2000, 2002; *Watt et al.*, 2004, 2006, 2009). Local simulations show good correspondence between observed and modeled features. ***However, we need to put things in a more global context to facilitate a better understanding...but first a closer look at the individual regimes.***

IAW regime

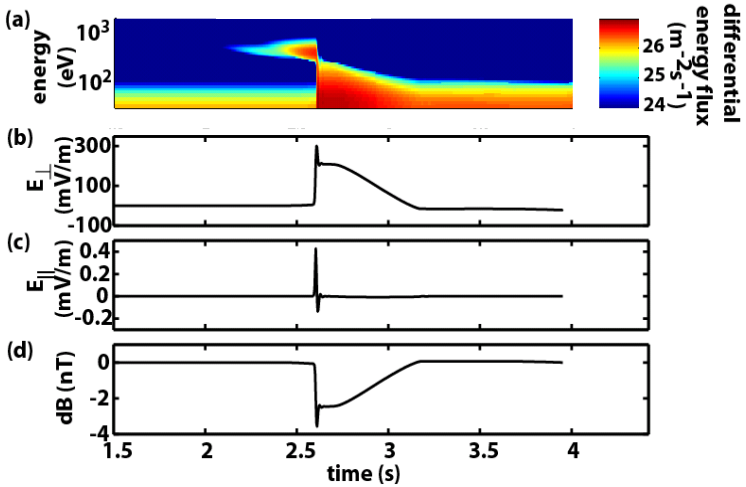
Inertial Alfven waves: Comparison of simulations and observations

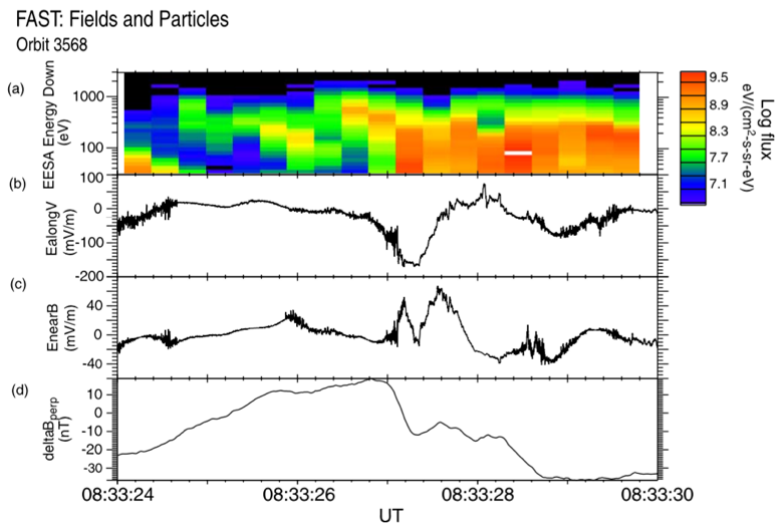
(e.g. Watt and Rankin, JGR, 2005)



FAST (Fast Auroral SnapshoT) spacecraft

1D Vlasov simulations

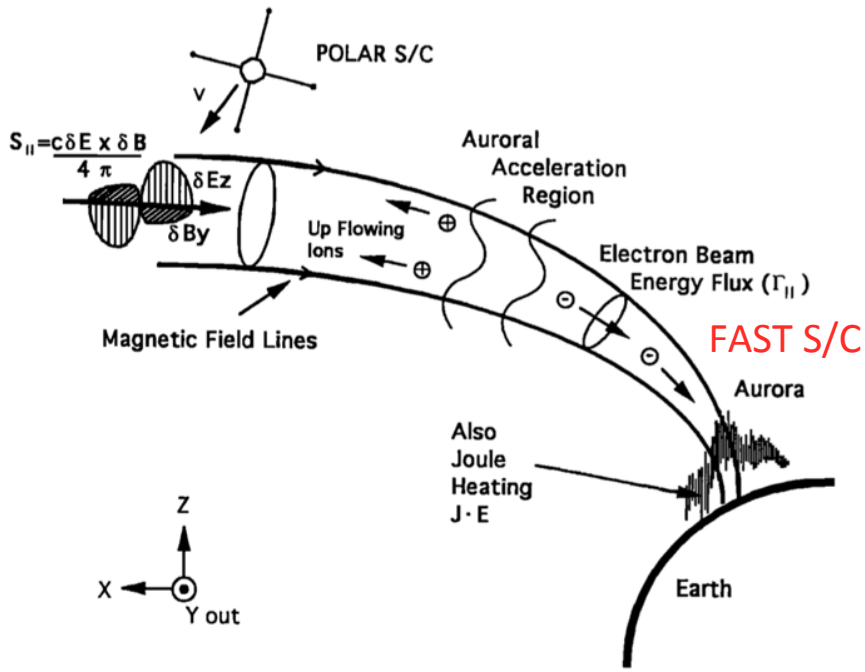




Both resonant and non-resonant acceleration. Non-resonant acceleration/deceleration of bulk distribution to carry parallel current can be viewed as a ``sloshing" motion.

Inertial Alfven waves: Comparison of simulations and observations

(e.g. Watt and Rankin, JGR, 2005)



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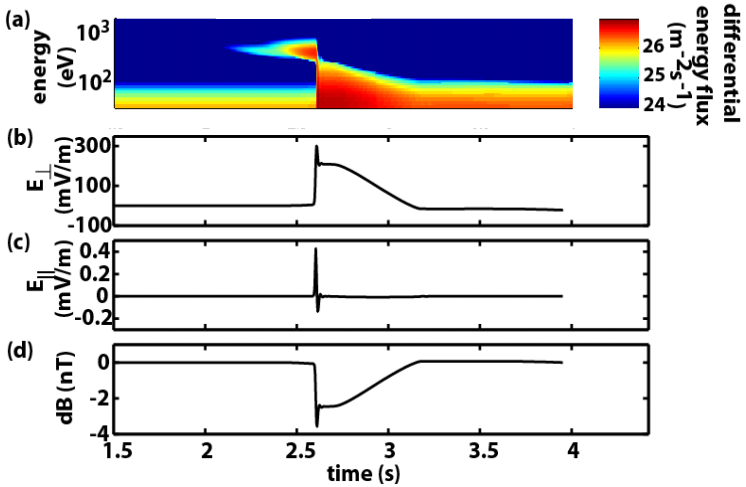
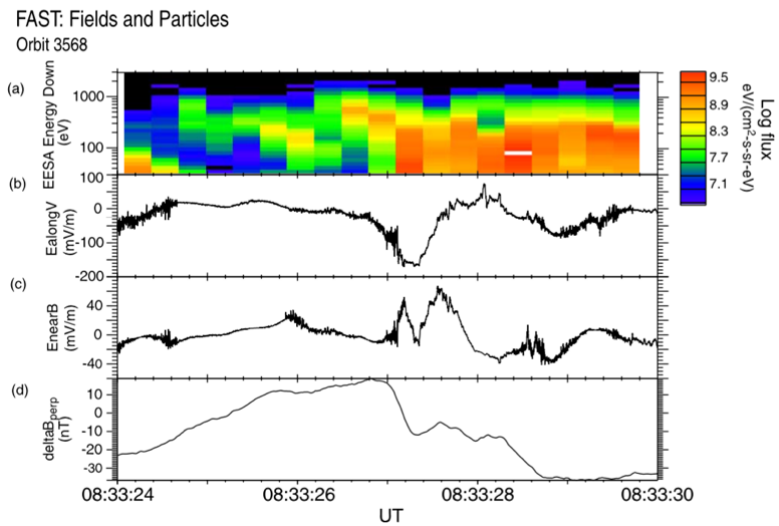
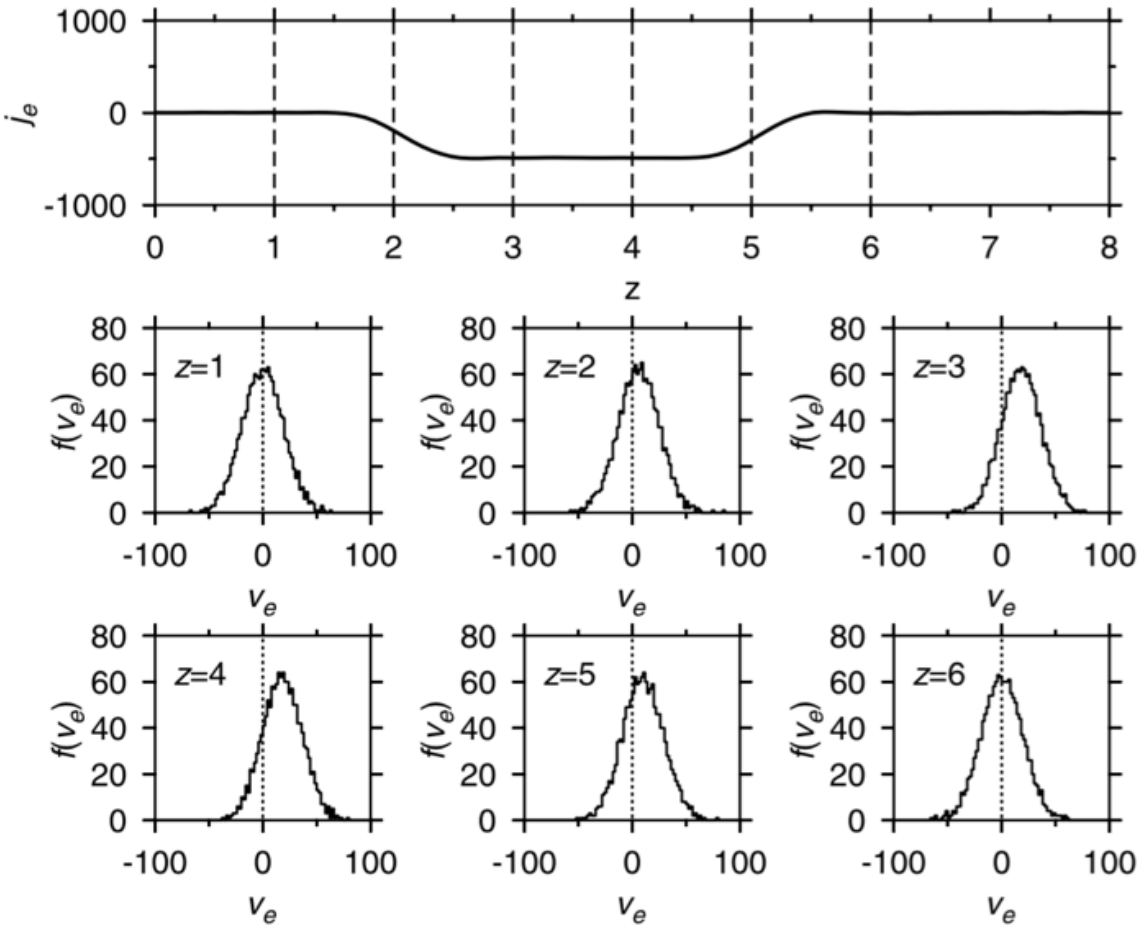




Resonant acceleration might account for a low flux of high energy electrons ~ keV. Non-resonant acceleration represents a large flux of low energy electrons.

Non-resonant acceleration of bulk - “sloshing”

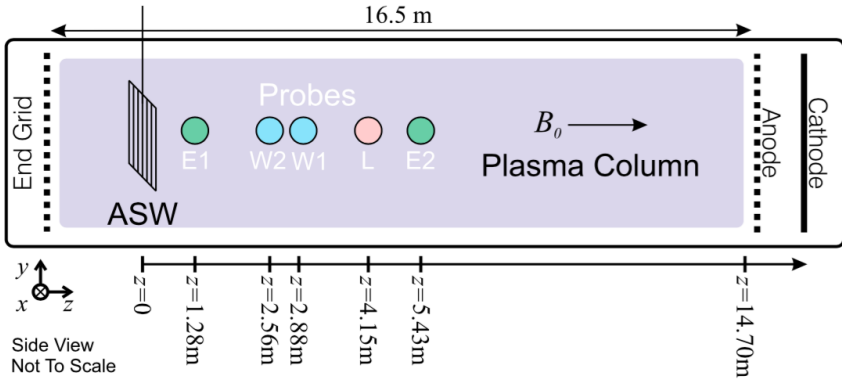


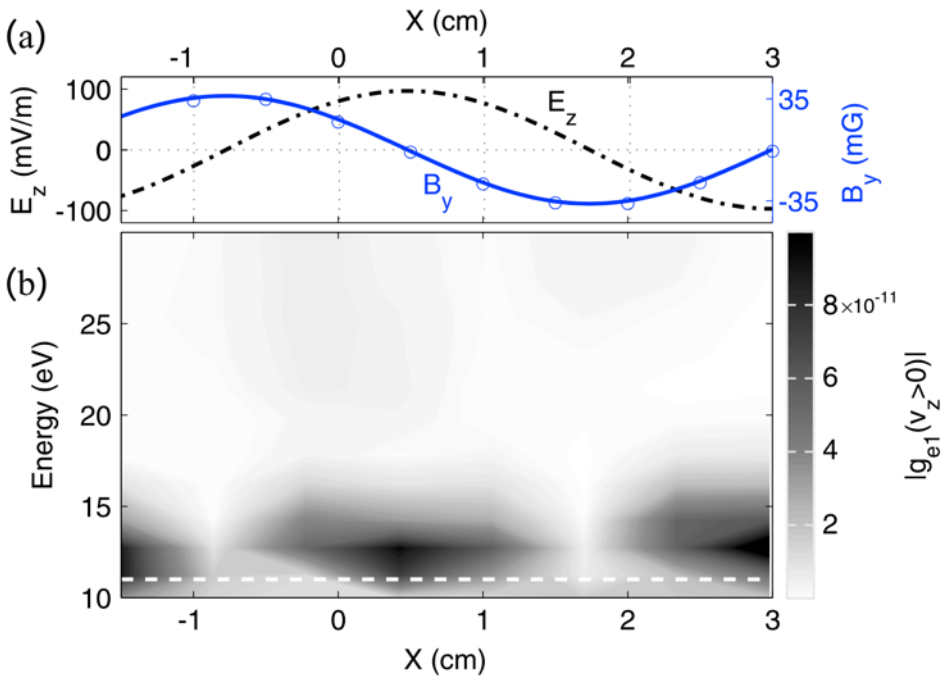
$$j_e = -n_e e v_{||}$$

(e.g. Damiano and Wright, JGR, 2005)

Direct measurement of electron sloshing of an IAW

Experiments done using Large Plasma Device (LaPD) at UCLA



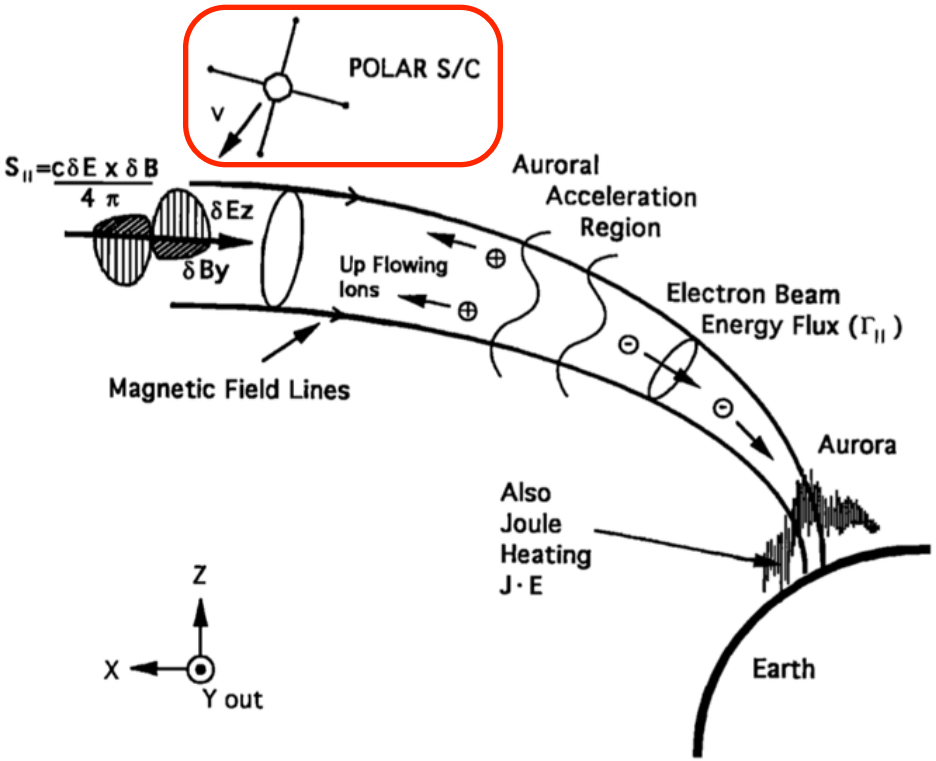


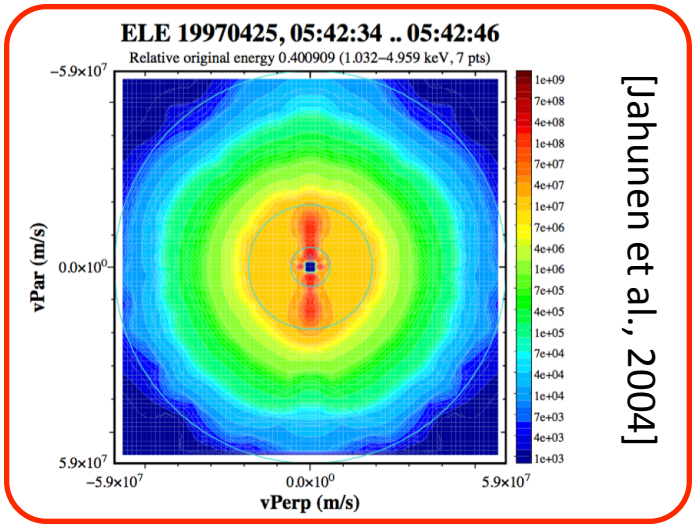
(Schroeder, J. W. R., et al., GRL. (2016); Schroeder, J.W.R., et al., Phys. Plasmas, 2017)

Next step: Experimental verification of resonant Fermi acceleration.

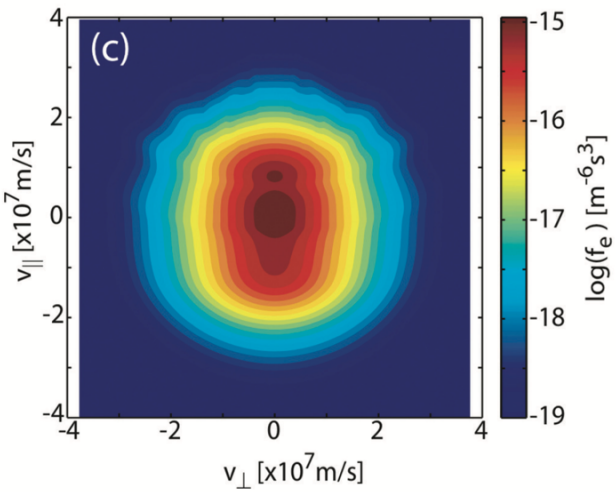
KAW regime

Kinetic Alfven wave regime





[Jahunen et al., 2004]

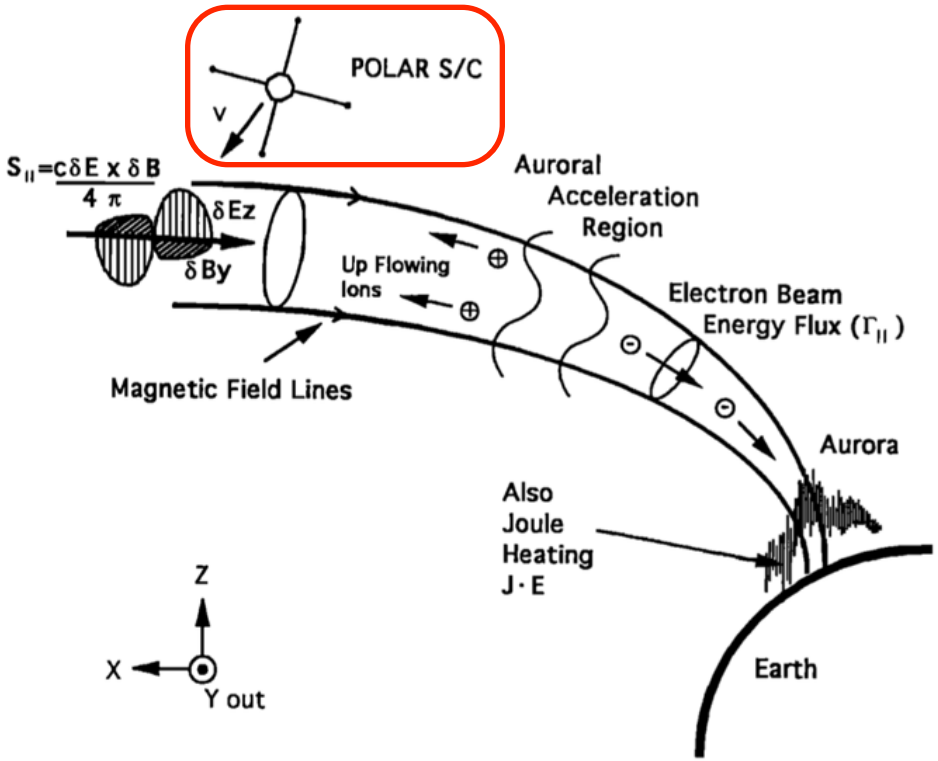


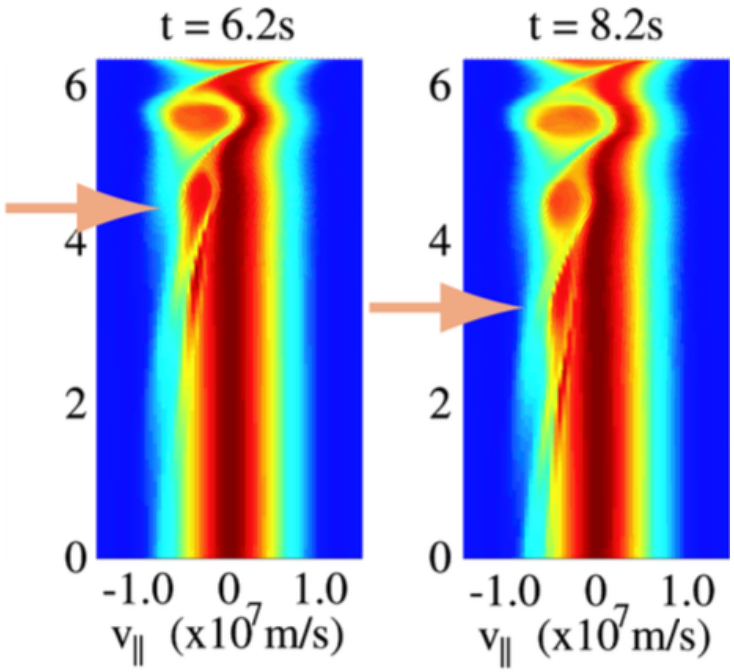
[Watt and Rankin, 2012]

1D Vlasov simulations

Electrons resonant close to core of distribution -> can become trapped in wave parallel electric field .

Kinetic Alfven wave regime





1D Vlasov simulations
(Watt and Rankin, PRL, 2009)

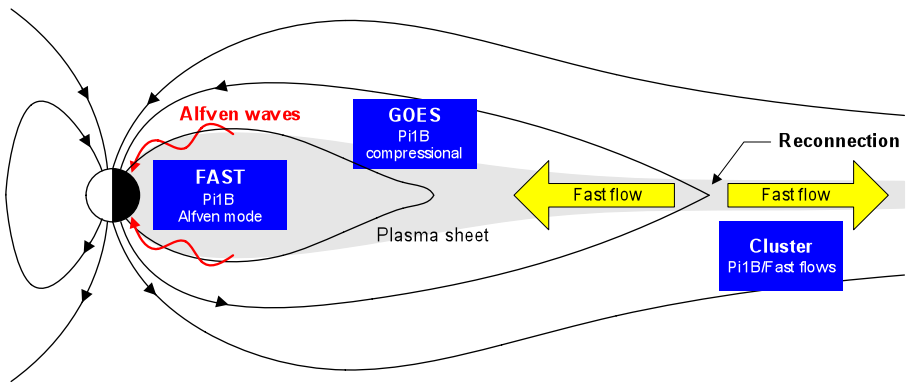
Trapped electrons gain energy as wave moves along field line (V_A increases). $E_{\parallel}$ -> 0 at the transition between KAW and IAW regimes and electrons become untrapped.

Starting to try to put it all together...

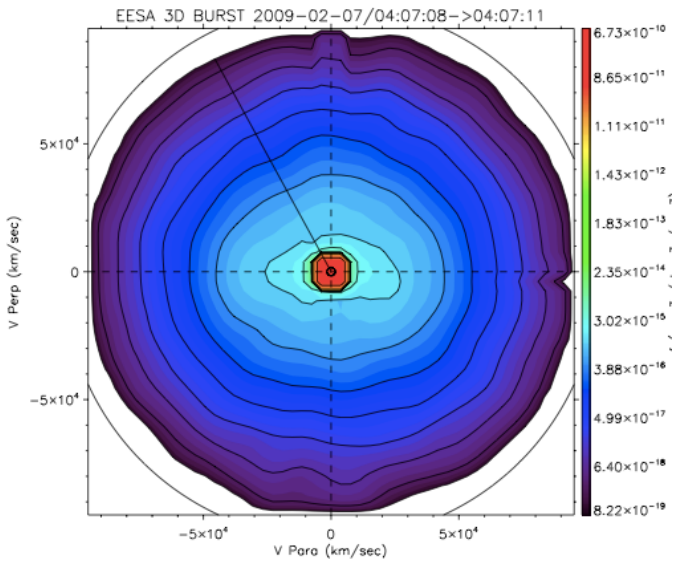
Taking a step back to the global picture

Broadband aurora increase rapidly at sub storm onset (e.g. Wing et al., 2013).

KAWs ubiquitous in plasma sheet in regions of flow breaking (e.g. *Chaston et al.*, 2012, 2014)



(Lessard et al., 2006, 2011)



From THEMIS (Courtesy C. Chaston)

How does KAW energy in the plasma sheet connect to energized electrons at the ionosphere?

Hybrid Gyrofluid-Kinetic-Electron model

(*Damiano et al.*, 2007; *Damiano et al.*, 2015; *Cheng and Johnson*, 1999)

Fluid equations

Momentum equation

$$\rho \frac{\partial \tilde{\mathbf{V}}_\perp}{\partial t} = (\mathbf{B}_0 \cdot \nabla)\mathbf{B}_\perp$$

where $\tilde{\mathbf{V}}_\perp = (1 - 1.25\rho_i^2 \nabla_\perp^2)\mathbf{V}_\perp$

Faraday's Law

$$\frac{\partial \mathbf{B}_\perp}{\partial t} = -\nabla \times \mathbf{E}$$

Perpendicular Ohm's law

$$\mathbf{E}_\perp = \mathbf{B_0} \times (\mathbf{1} - \rho_\mathbf{i}^\mathbf{2} \nabla_\perp^\mathbf{2})\tilde{\mathbf{V}}_\perp$$

Parallel Ohm's law

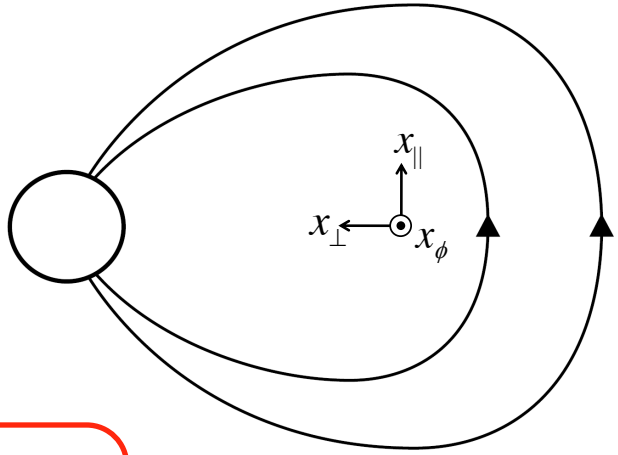
$$E_{||} = \boxed{\frac{m_e}{ne^2}\frac{\partial j_{||}}{\partial t}} - \boxed{\frac{1}{ne}\nabla_{||} P_{e_{||}}} - \boxed{\frac{1}{ne}\frac{P_{e_{||}} - P_{e_\perp}}{B_o}\nabla_{||} B_o}$$

IAW KAW Mirror force

Guiding center equations

$$m_e \frac{dv_{||}}{dt} = -eE_{||} - \boxed{\mu_m \nabla_{||} B_o}$$

$$h_{||}\frac{dx_{||}}{dt} = v_{||}$$

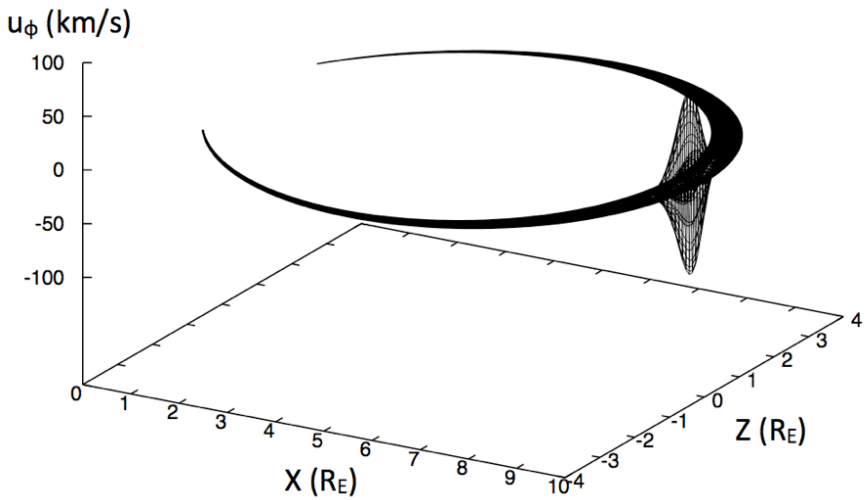


Term most important for global scale waves

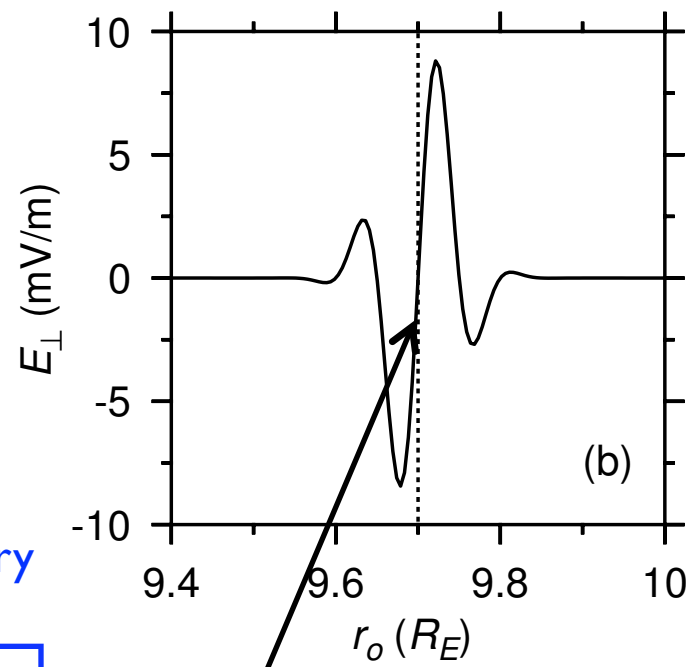
Moments of electron distribution function calculated via PIC techniques

Kinetic Alfven wave pulse – initial perturbation example

Initialize KAW perturbation in the central plasma sheet



perpendicular $E_\perp$ profile at equator



Identical pulses propagate to each field-aligned boundary (at 1 R_E altitude above Earth surface).

$$\frac{k_\perp}{k_{||}} \sim 10$$

$\lambda_\perp \sim 0.1\ R_E$

Field line of maximum upward current

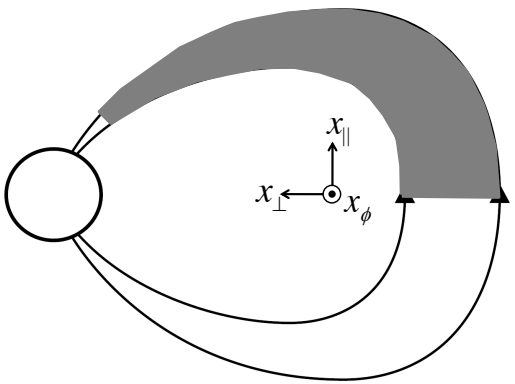
Two simulation cases:

1) T_i=0, T_e=100 eV

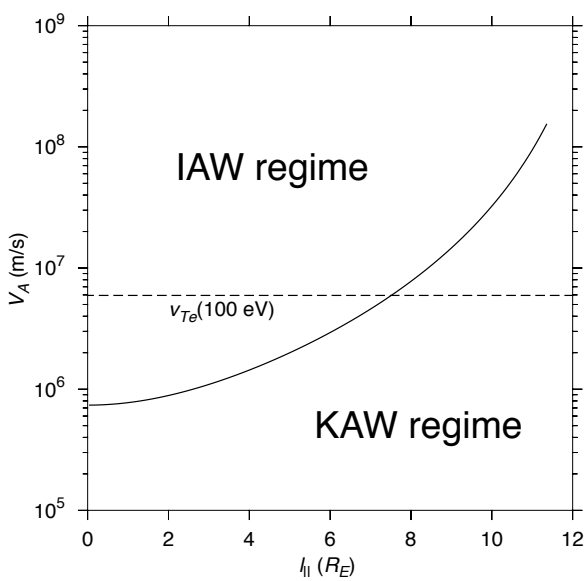
2) T_i=1 keV, T_e=100 eV

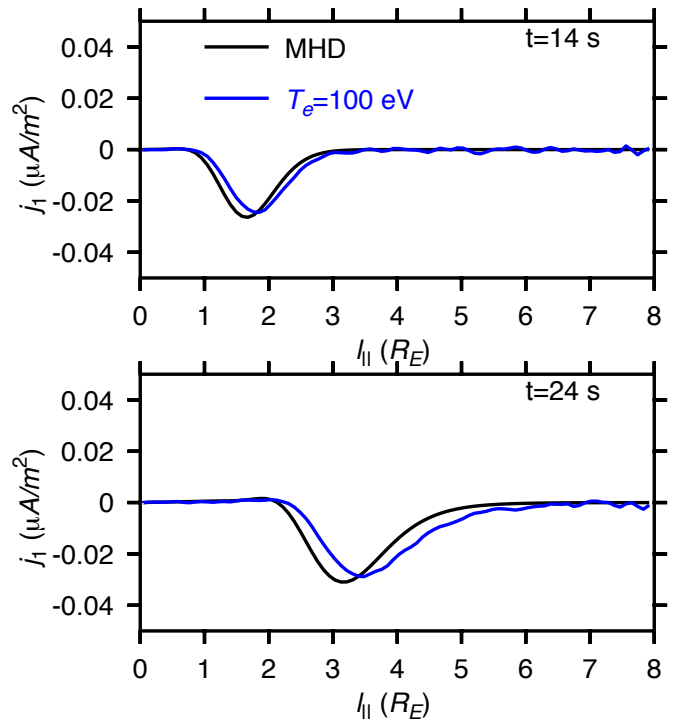
$$\frac{k_\perp}{k_{||}} \sim 10 - 100$$ (Chaston et al., 2014)

Pulse propagation



Consider slice along single field line in northern hemisphere. $l_{||}$ is distance along field line from equator.

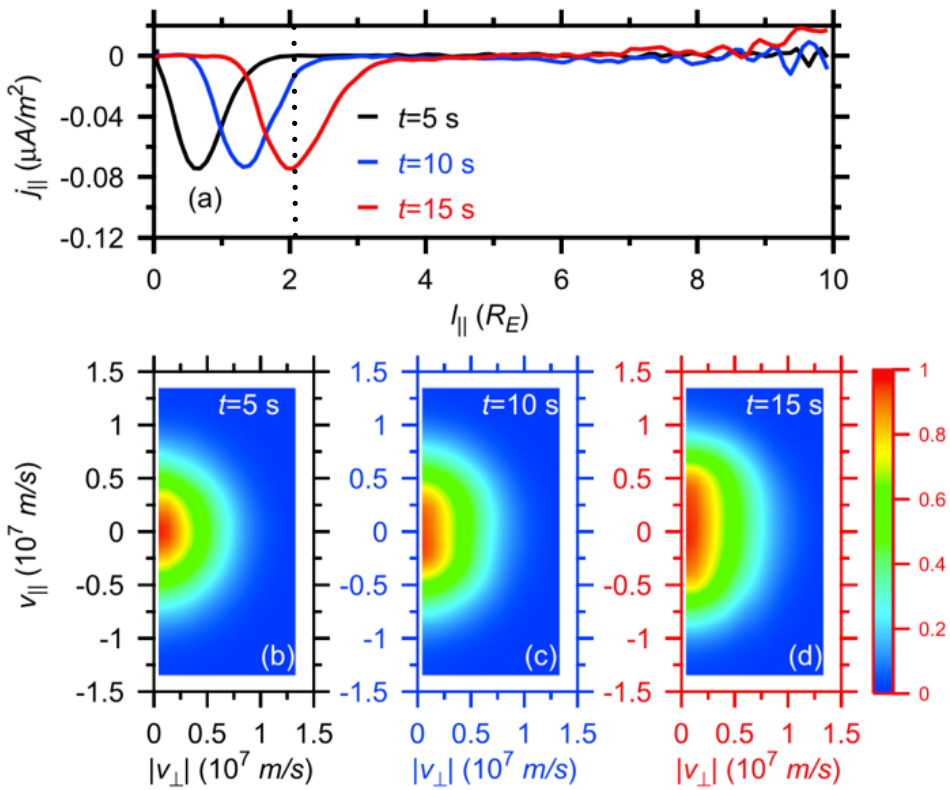




$$T_i = 0 \rightarrow \omega = k_{||} V_A \sqrt{1 + k_{\perp}^2 \rho_s^2}$$

Only minor divergence from MHD as $k_{\perp}\rho_s << 1$.

Electron trapping evident close to equatorial region



Parallel elongation defined by nonlinear trapping width (e.g. Wygant, 2002):

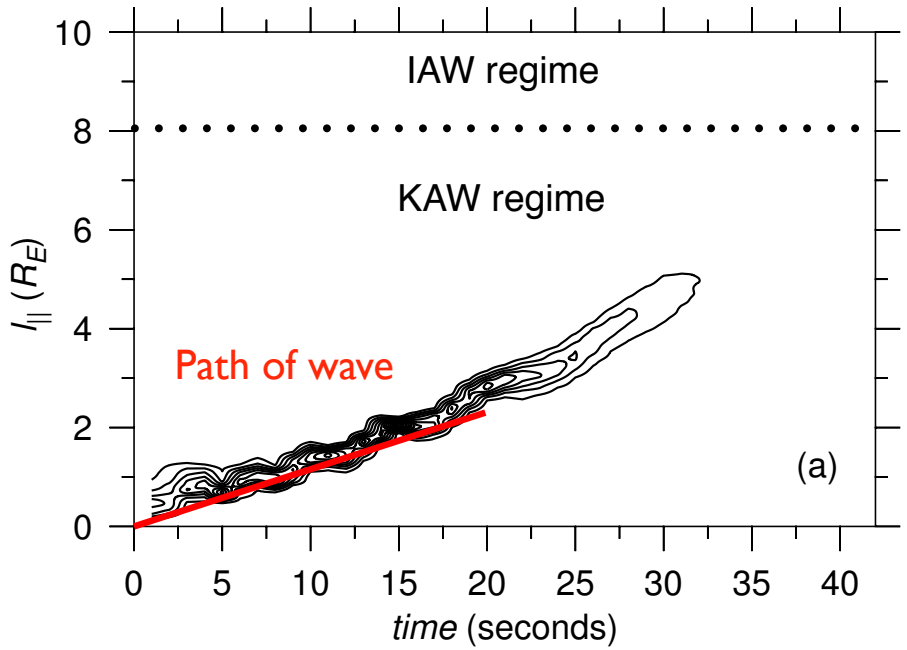
$$v_{tr} = \sqrt{\frac{2e\phi}{m_e}}$$

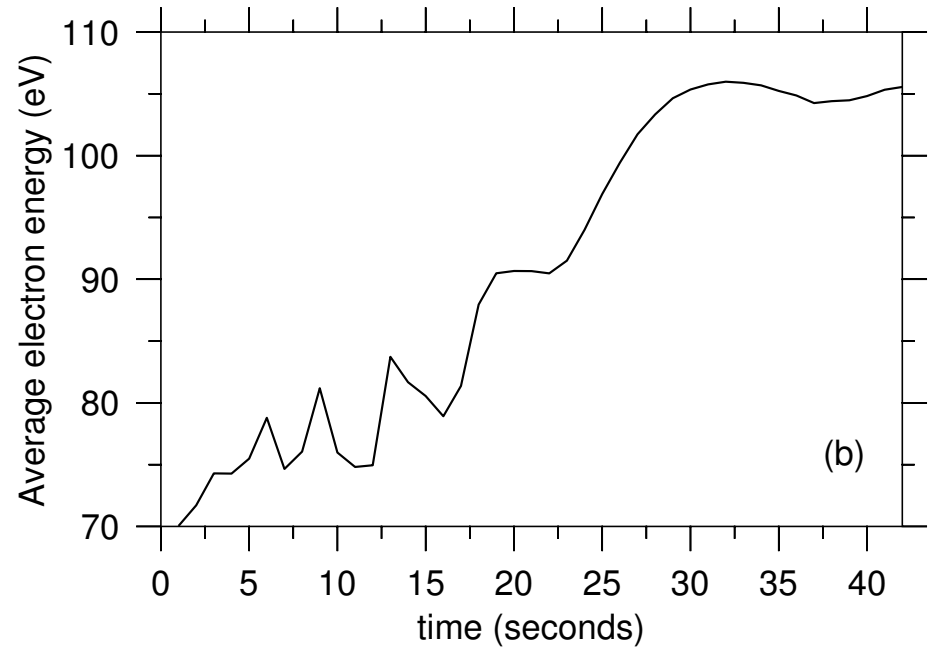
In the context of reconnection potentials - e.g. *Le et al.,* 2009.

Active injection experiments in ionosphere (Porcupine) - *Haeusler et al., 1986; Bohm et al., 1992.*

(Damiano et al., JGR, 2016)

Evolution of trapped electron population



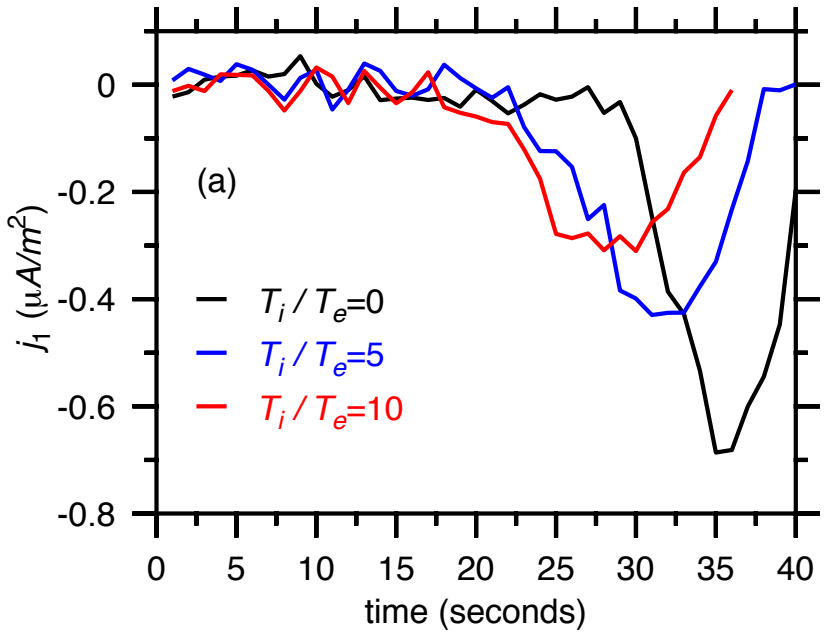


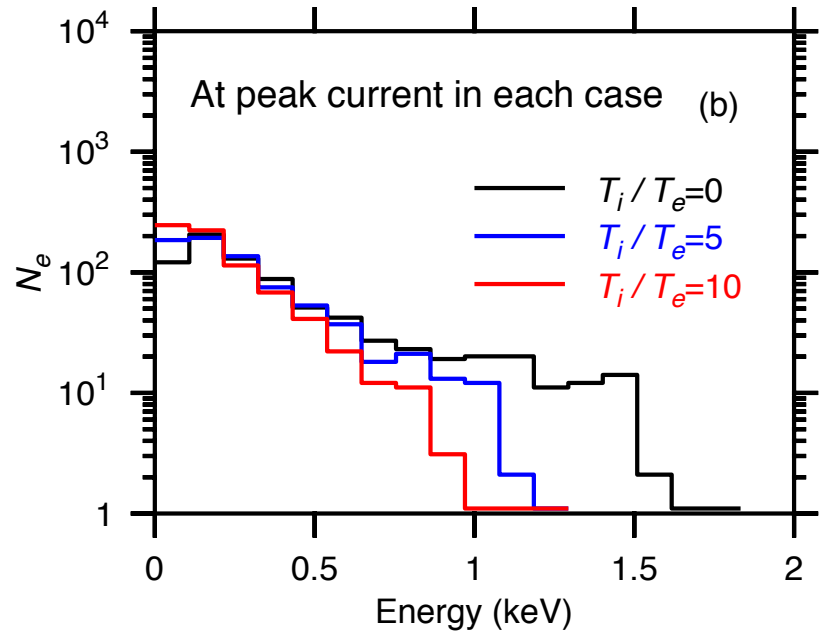
- Electrons trapped in potential well gain modest energy as wave speed is increased.
- Electrons become de-trapped after short time interval.
- De-trapping time grows shorter as ion temperature increases.

KAW not an efficient accelerator for considered scenario, but can still dictate the terms to the rest of the field line.

Ionospheric signatures

Initial wave perturbations at equator the same in each case.



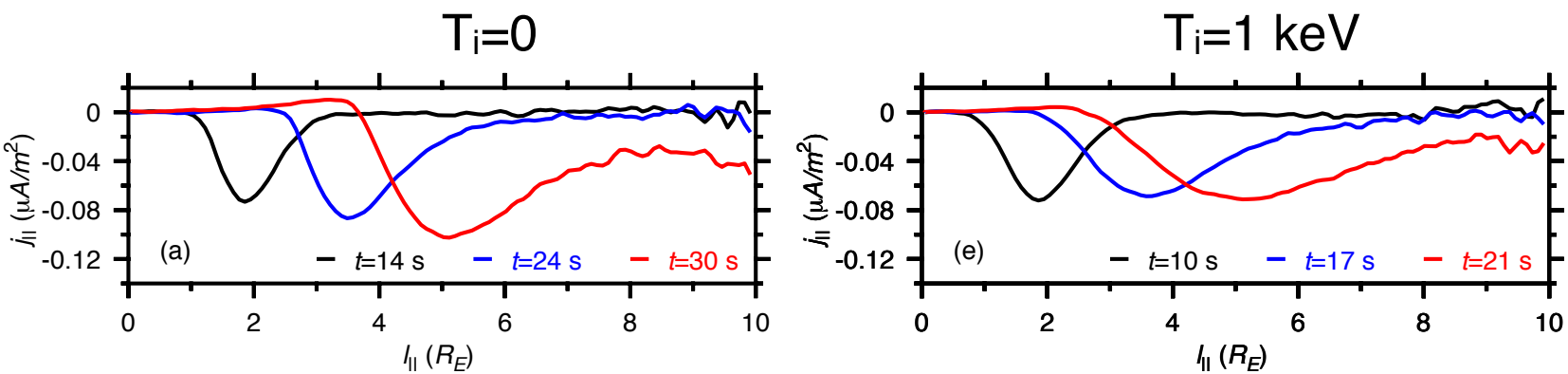


Arrival time of wave signature at ionosphere reduced as T_i/T_e increases.

$$\omega = k_{||} V_A \sqrt{1 + k_\perp^2 \rho_s^2 (1 + \frac{T_i}{T_e})}$$

Ion temperature may act as a regulator of broadband auroral precipitation!

Parallel current evolution along field line

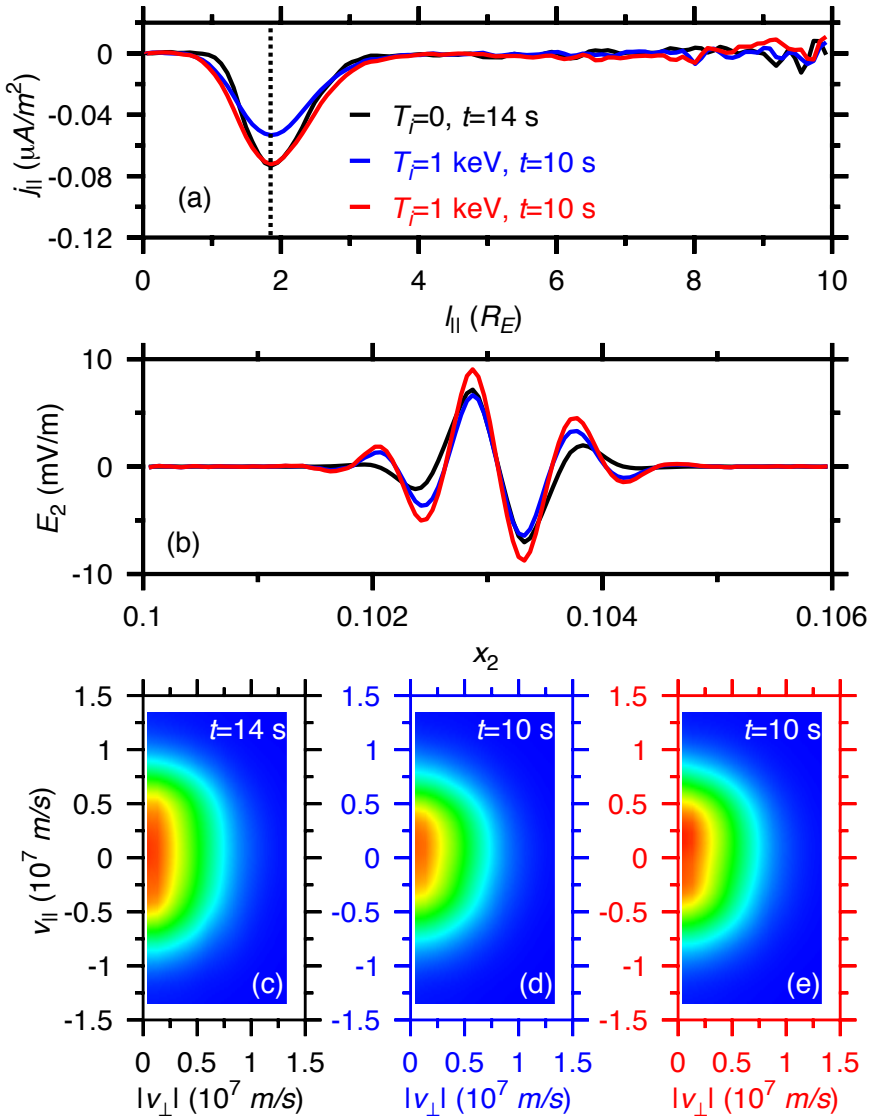


$$\omega = k_{||} V_A \sqrt{1 + k_\perp^2 \rho_s^2 (1 + \frac{T_i}{T_e})}$$

More wave energy dispersion in T_i=1 keV case -> reduces $j_{||}$ and $E_{||}$.

(Damiano et al., JGR, 2016)

Perpendicular dispersion of wave energy

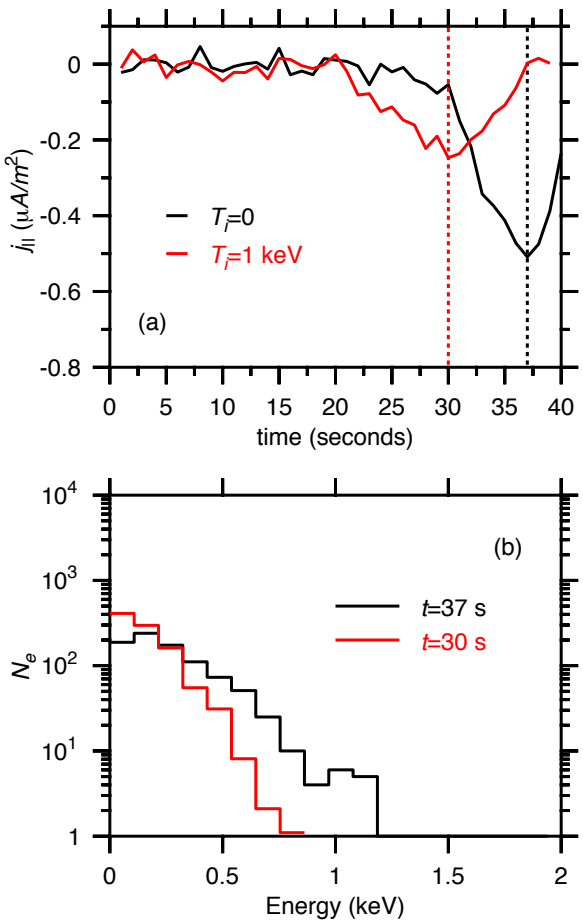


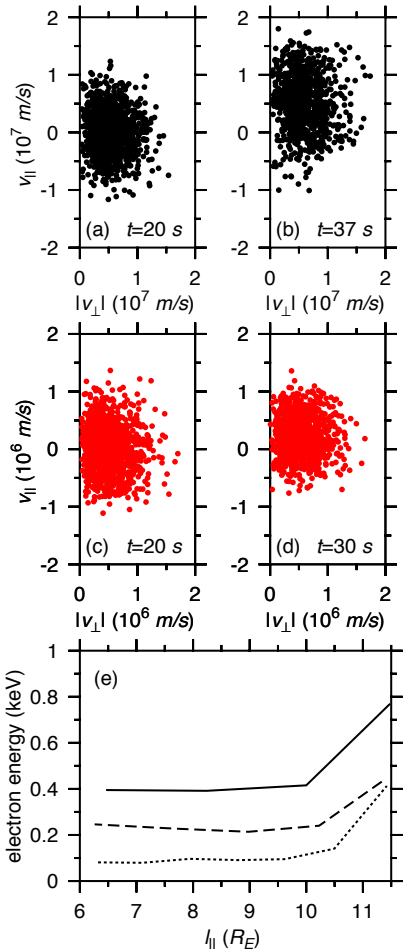
Note more perpendicular dispersion in T_i=1 keV cases

(Damiano et al., JGR, 2016)

Primary acceleration co-incident with arrival of wave at ionosphere

(Damiano et al., JGR, 2015)





Acceleration of bulk, back to sloshing...

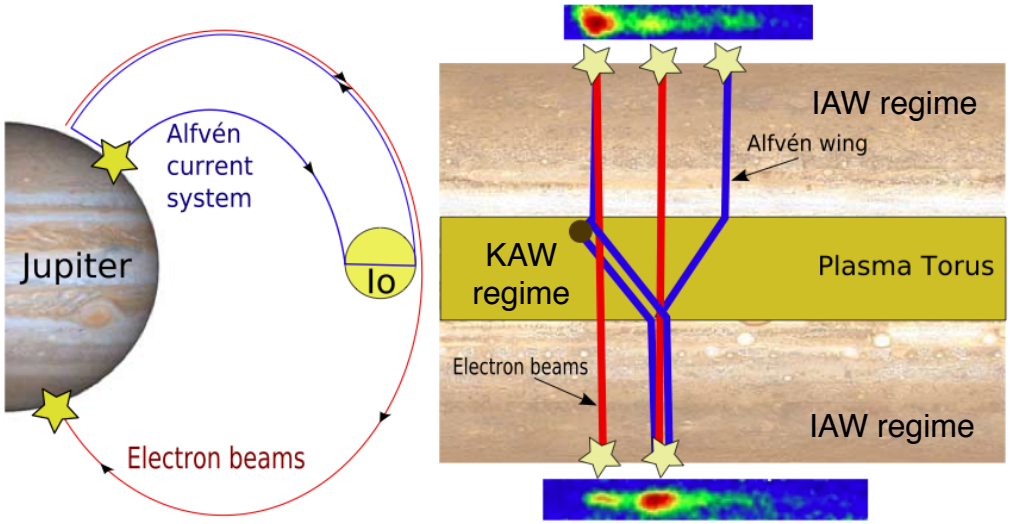
Summary

- Observations link broadband electron precipitation with Alfvenic Poynting flux.
- Qualitative features of electron energization by dispersive scale Alfven waves are consistent between observations and simulations.
- Laboratory experiments are beginning to reproduce features of electron acceleration expected from inertial scale Alfven waves.
- Global flux tube simulations illustrate how ion temperature effects can act to regulate broadband auroral precipitation.
- <u>For considered scenario</u>, most of the electron energization is the result of non-resonant interaction with IAWs.
- *Must consider range of parameters ($k_\perp$, $k_{/\!/}$, $E_\perp$, T_i, T_e) and perturbations.*
- *Comparative magnetosphere's (e.g. Jupiter).*

PPPL

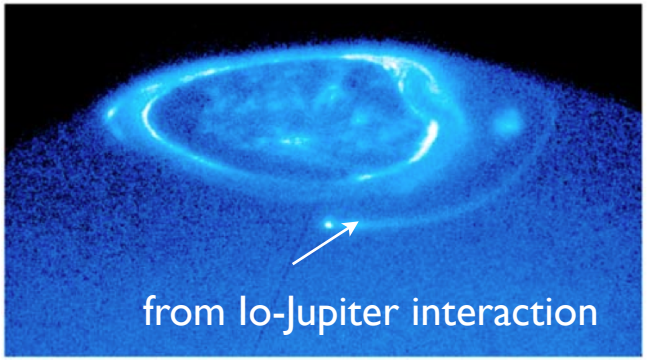
Alfvenic Aurora at Jupiter

Volcanic activity leads to high density plasma torus - Io's motion through the torus leads to generation of Alfven waves.



(Bonfond et al., 2008)

UV Aurora at Jupiter



HST observation