What's on the Horizon for Space Physics in the Laboratory?

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University of Iowa

Bringing Space Down to Earth Workshop
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NASA and White House Office of Science and Technology Policy (PECASE)
National Science Foundation CAREER Award
National Science Foundation XSEDE Program
NSF/DOE Partnership in Plasma Physics

Outline

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- Introduction
  - Major Questions in Heliophysics
  - Why Study Space Physics in the Laboratory?
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  - Astrophysical Plasma Turbulence: Alfven Wave Collisions
  - Auroral Electron Acceleration
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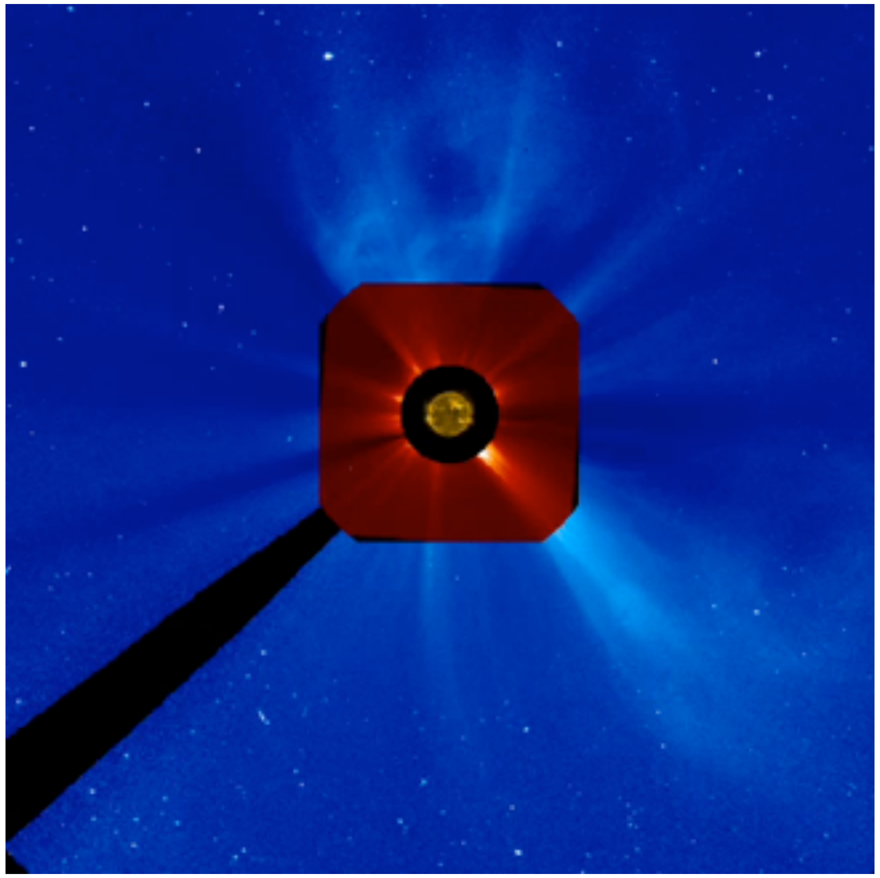
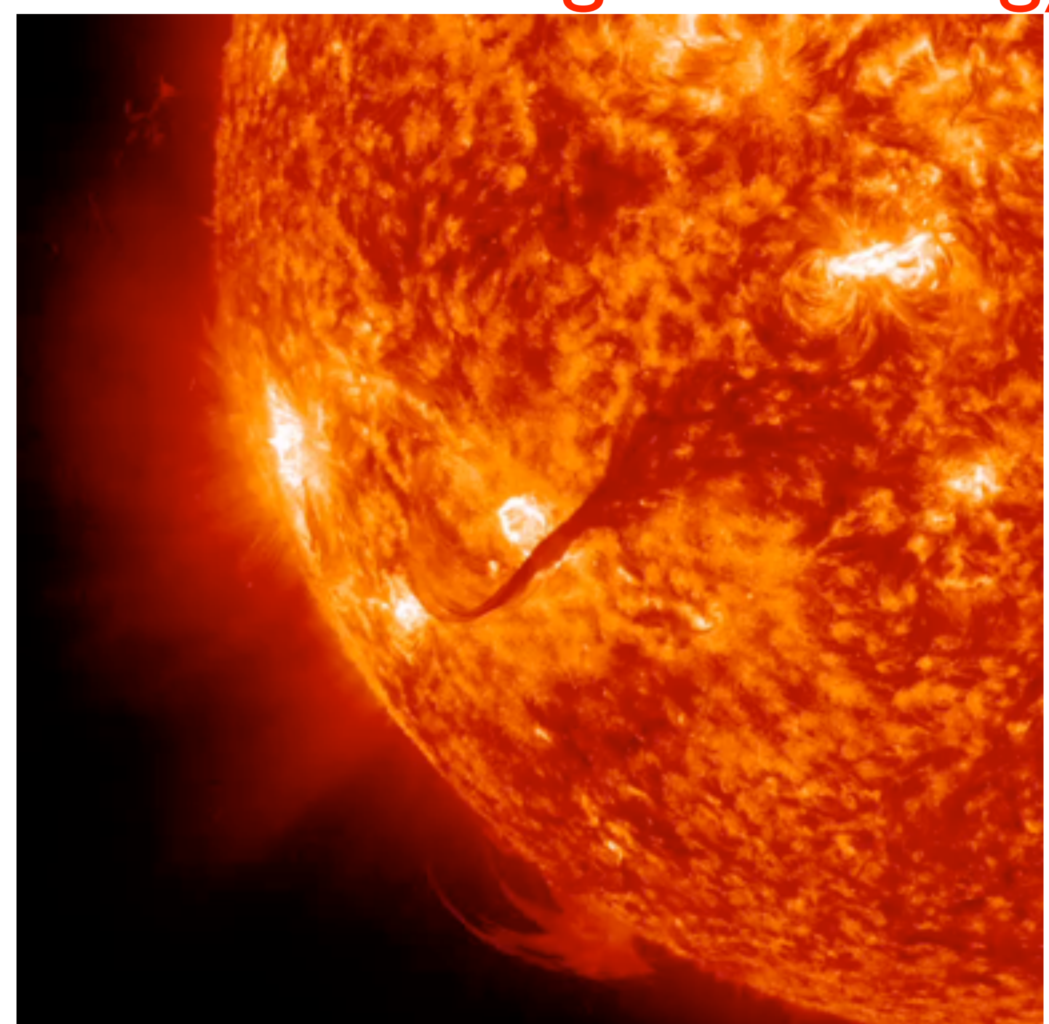
Major Heliophysics Science Questions

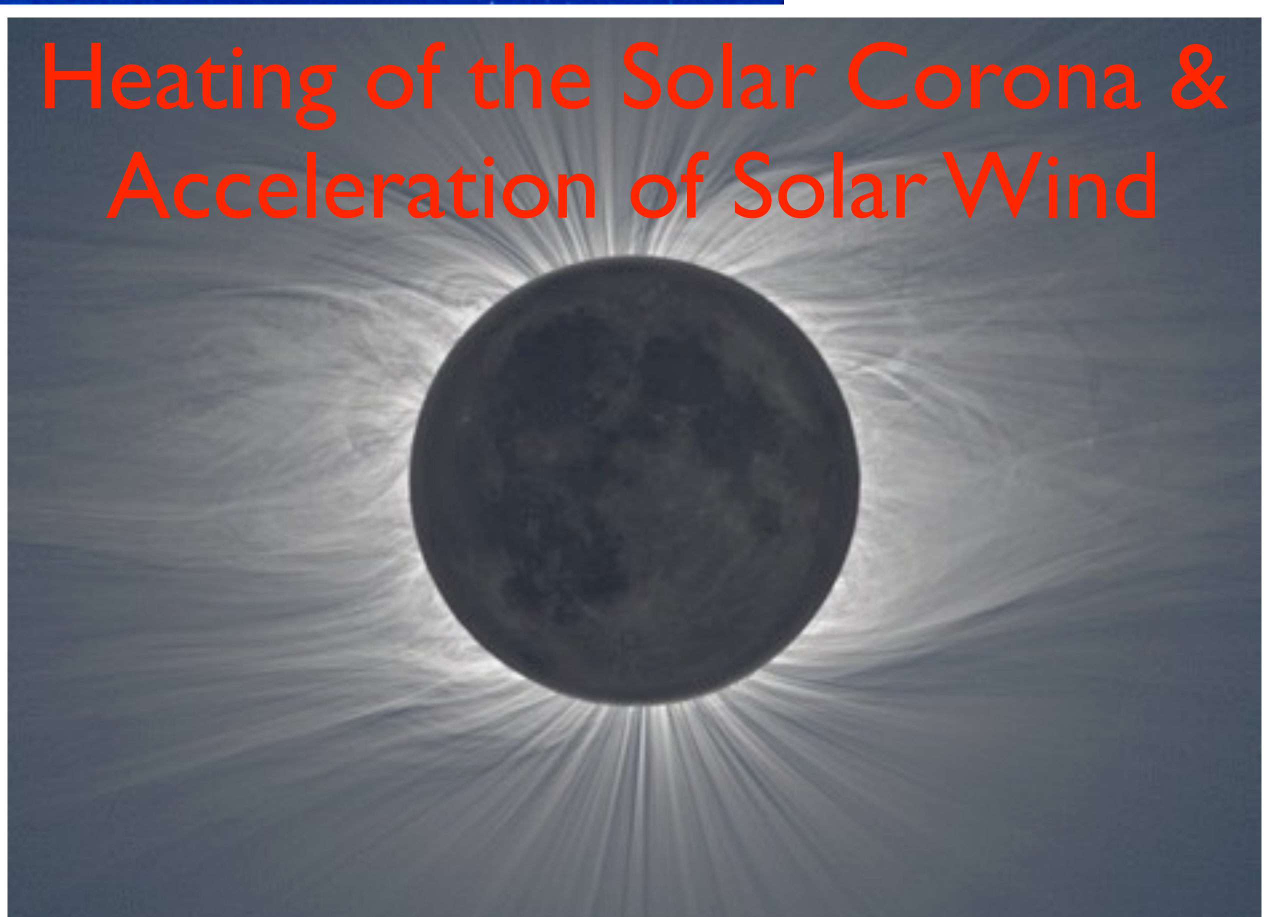


Propagation of Coronal Mass Ejections (CMEs) through the Heliosphere

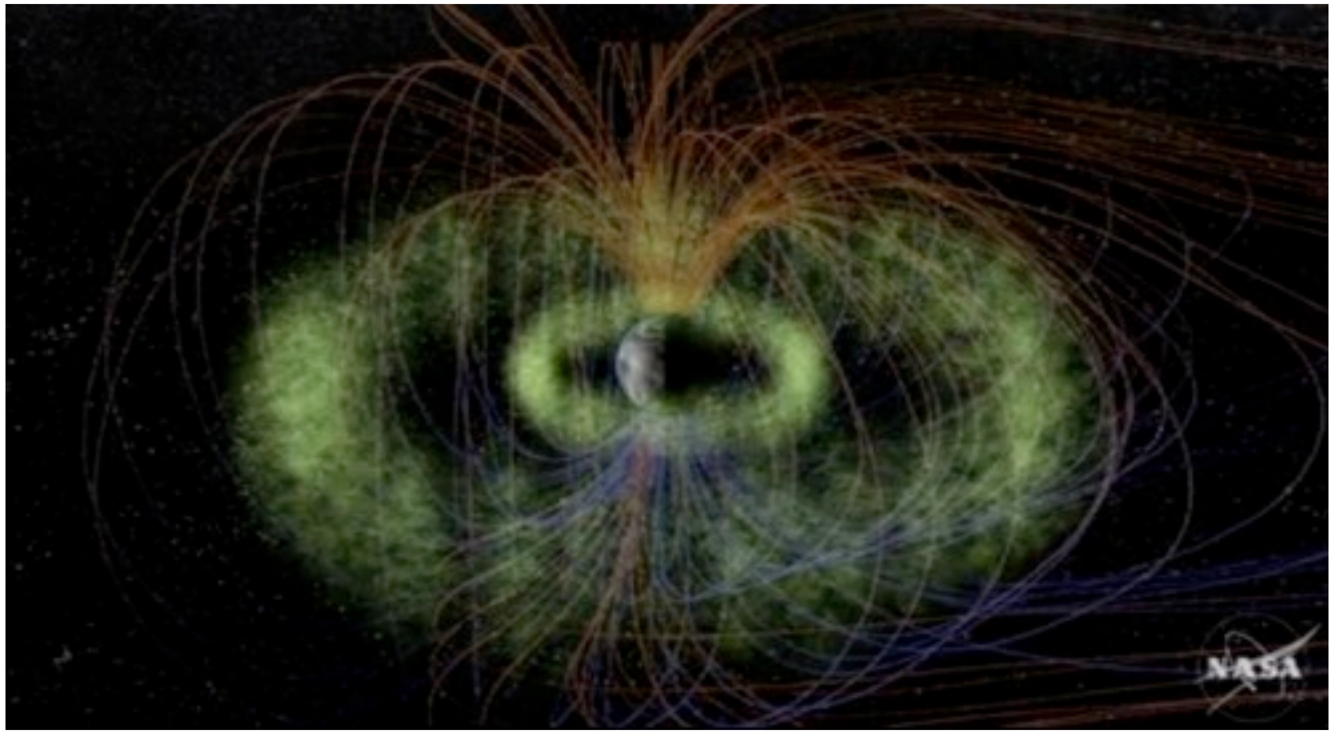
Storage and Explosive Release of Magnetic Energy



Heating of the Solar Corona & Acceleration of Solar Wind

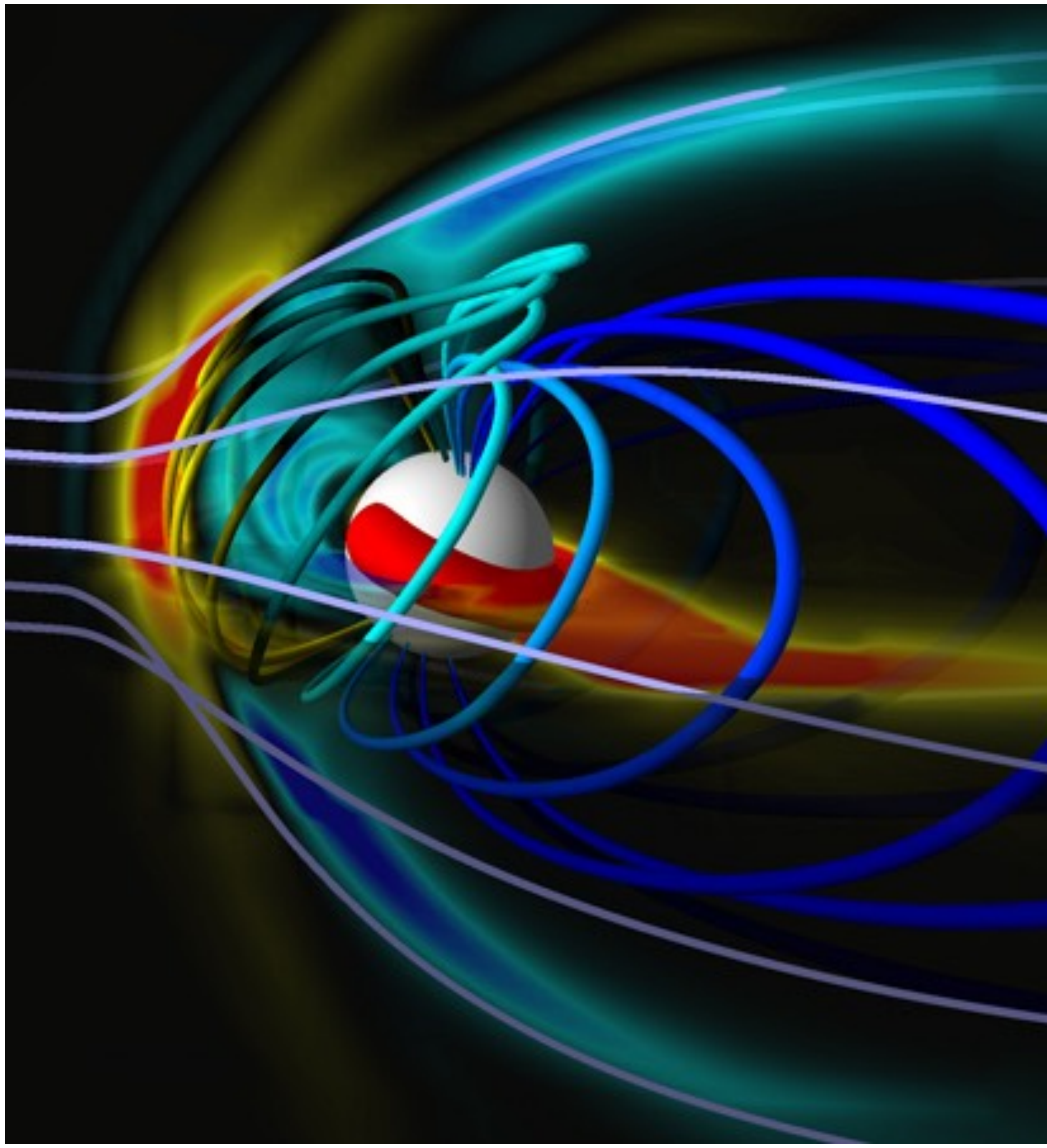


Major Heliophysics Science Questions



Energization and loss of energetic particles in Earth's magnetosphere

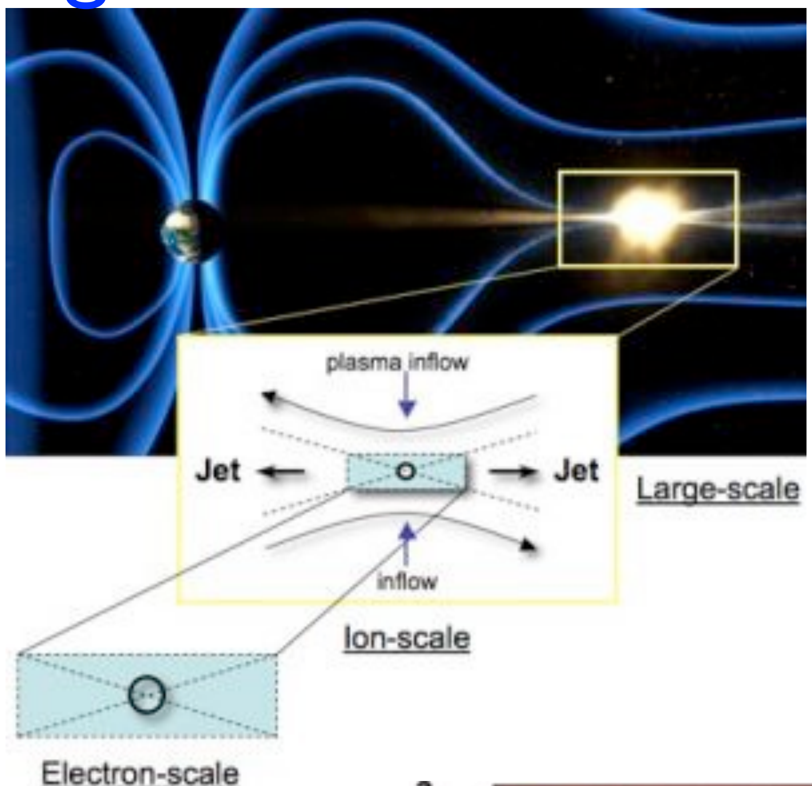
Effect of variable solar wind on Earth's coupled magnetosphere-ionosphere-thermosphere system



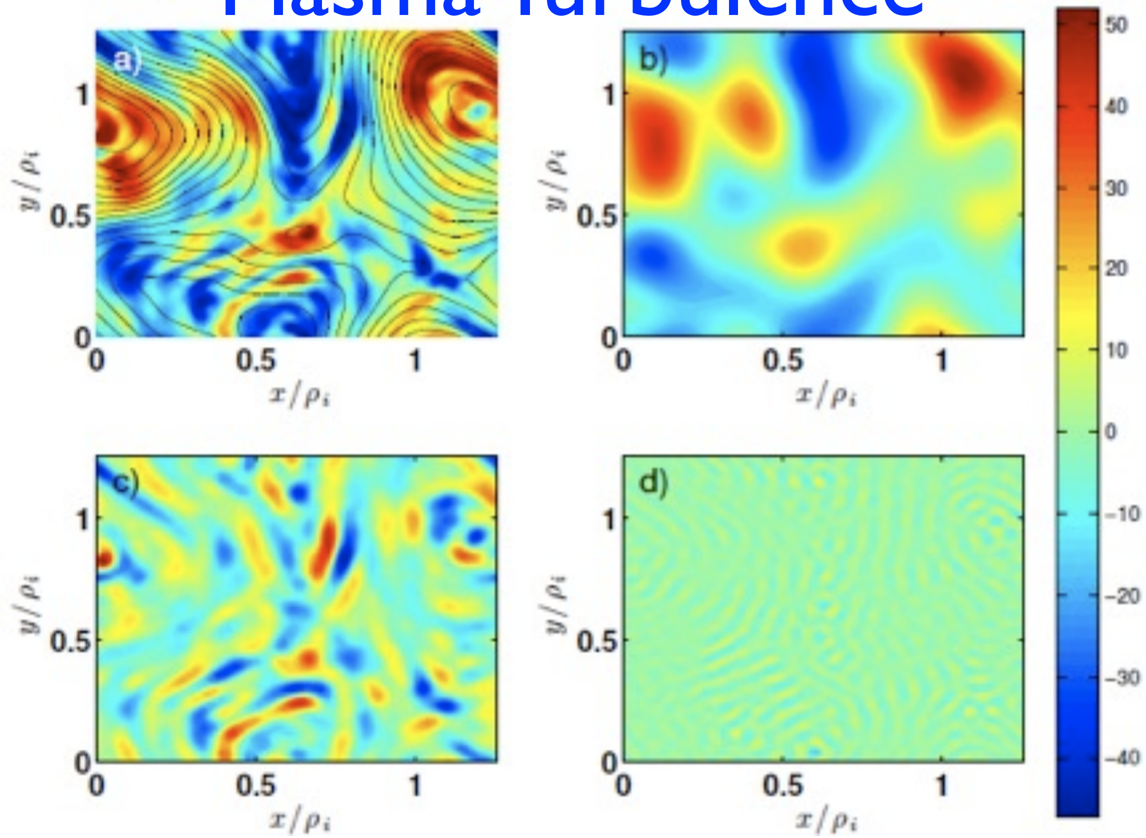
These are the science questions at the frontier of heliophysics to be tackled over the next decade and beyond!

Fundamental Plasma Physics Processes

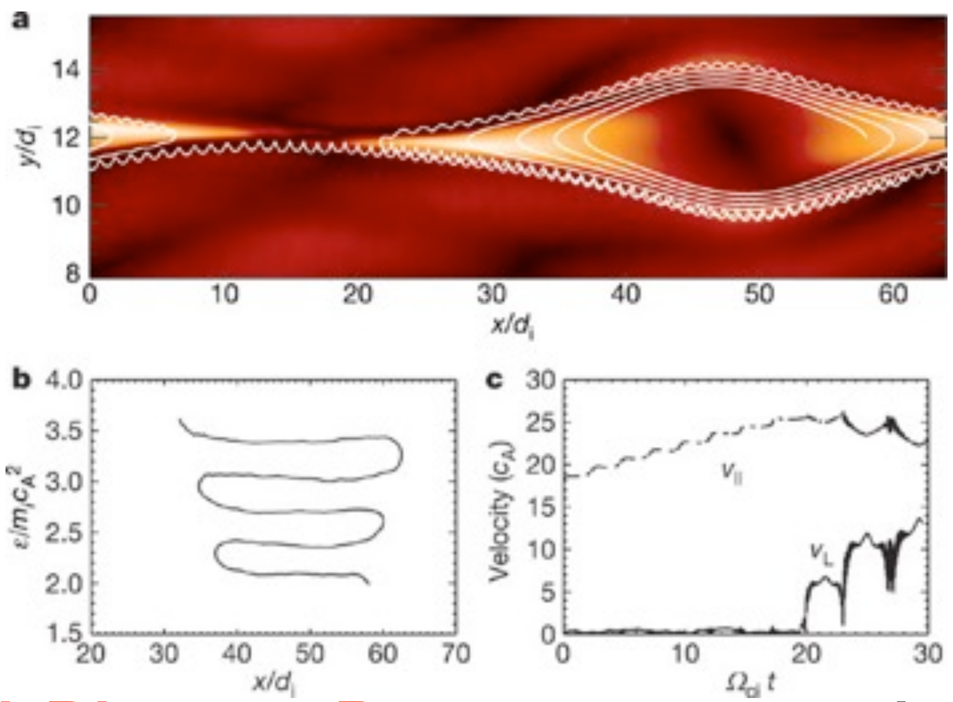
Magnetic Reconnection



Plasma Turbulence



(Howes & TenBarge, 2013)



Energetic Particle Acceleration

(Drake et al. 2006)

Fundamental Plasma Processes are key to progress in Heliophysics

Laboratory Experiments can complement study of these processes

Why Study Space Physics in the Laboratory?

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• Laboratory experiments explore the fundamental physics of space plasmas without limitations inherent to spacecraft measurements

Example: Single-point measurements

- Spacecraft missions are typically limited to one (or a few) points of measurement
- Laboratory measurements do not suffer from this limitation

• Other Advantages of Laboratory measurements

- Greater control of plasma conditions and applied perturbations
- Reproducibility
- Orders of magnitude less expensive than launching spacecraft

Why Study Space Physics in the Laboratory?

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Spacecraft Observations and Laboratory Experiments
probe the physics of real plasmas

complementary to other approaches

Analytical Theory and Numerical Simulation
enable a deeper understanding of the plasma physics,
but under more idealized conditions

Ultimately, a synergistic approach
using theory, simulation, observation, and experiment
will enable us to definitively identify and characterize
the fundamental physics governing the space environment

Questions to Stir Discussion

For a particular space physics problem,
what are the key quantities one needs to measure?

How can we make those measurements . . .
in space?
or in the laboratory?

How can laboratory experiments fill in the gaps
of what we cannot measure with spacecraft missions?

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Alfven Wave Collisions

The University of Iowa

Incompressible MHD Equations in symmetric Elsasser form:

Linear Term →

$\mathbf{z}^+$	travels down $\mathbf{B}_0$ field
$\mathbf{z}^-$	travels up $\mathbf{B}_0$ field

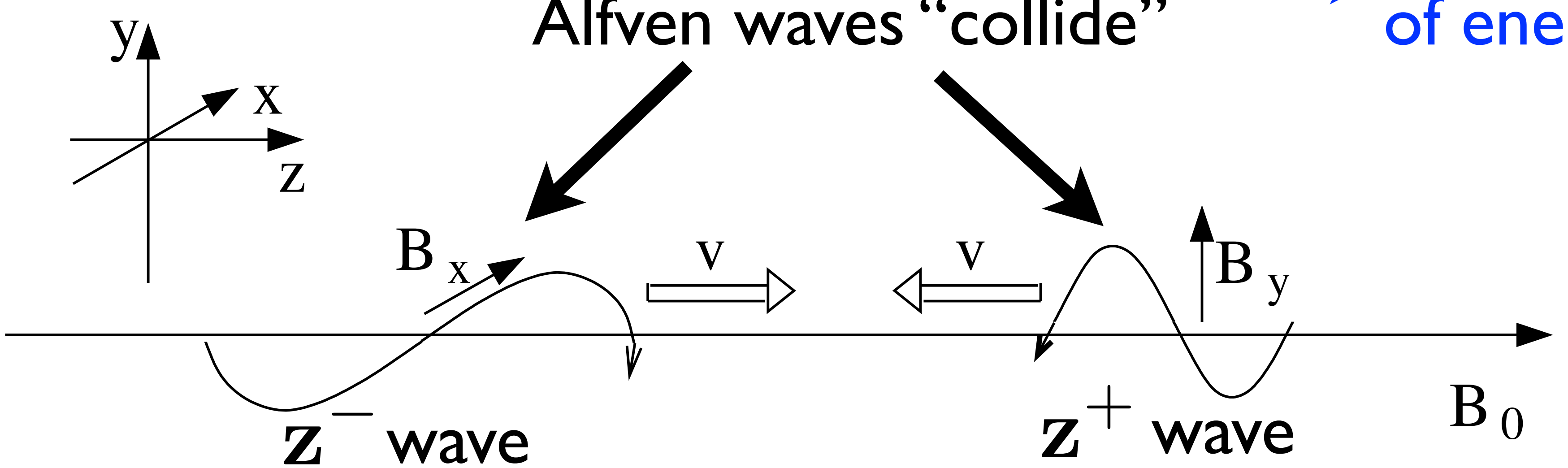
$$\frac{\partial \mathbf{z}^\pm}{\partial t} \mp \mathbf{v}_A \cdot \nabla \mathbf{z}^\pm + \mathbf{z}^\mp \cdot \nabla \mathbf{z}^\pm = -\nabla p$$

Nonlinear Term →

Responsible for "collisions" between oppositely propagating Alfven waves

$$\mathbf{z}^\pm = \mathbf{u} \pm \delta \mathbf{B} / \sqrt{4\pi\rho}$$

Counterpropagating Alfven waves "collide" → Nonlinear term leads to transfer of energy to higher wavenumber

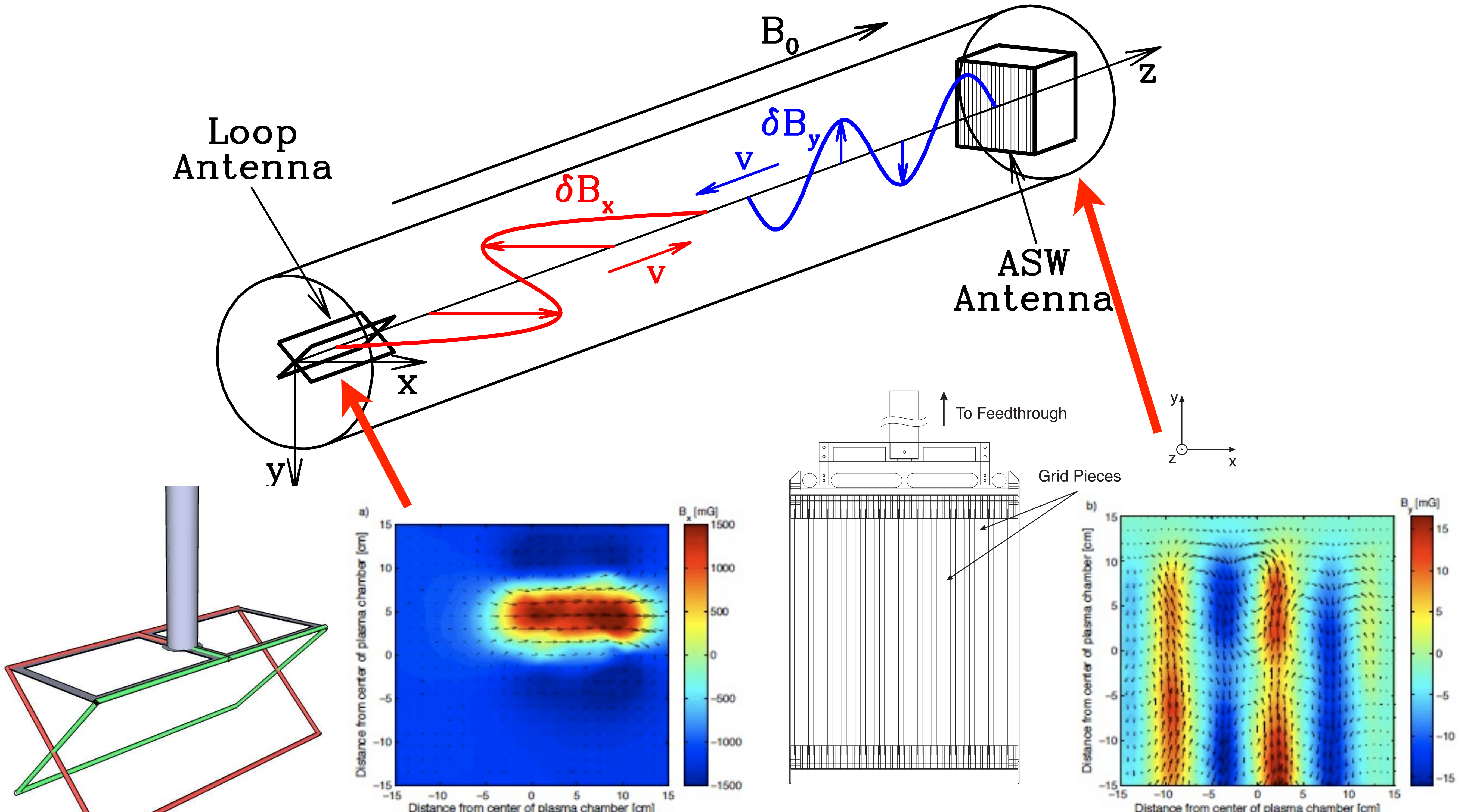


Alfven wave collisions are the fundamental building block of plasma turbulence!

(Kraichnan, 1965)

Experimental Verification of Alfven Wave Collisions

Basic Experiment of Alfven Wave Collisions on the LAPD



Loop Antenna

(Carter, UCLA)

ASW Antenna

(Kletzing & Skiff, Univ. Iowa)

Q1: Experimental Verification of Alfven Wave Collisions

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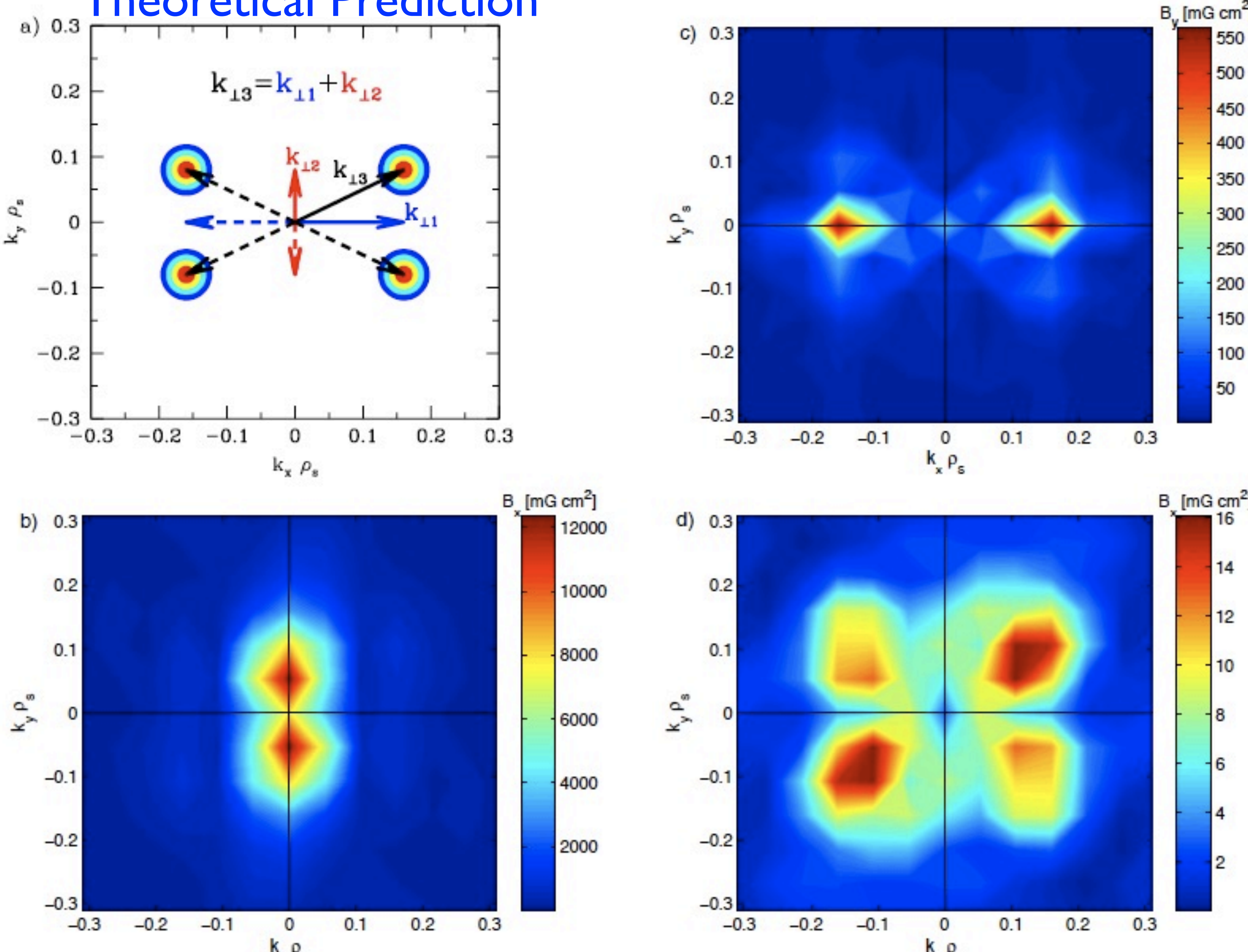
Theoretical Prediction



ASW Antenna Alfven Wave

Nonlinearly produced daughter Alfven wave

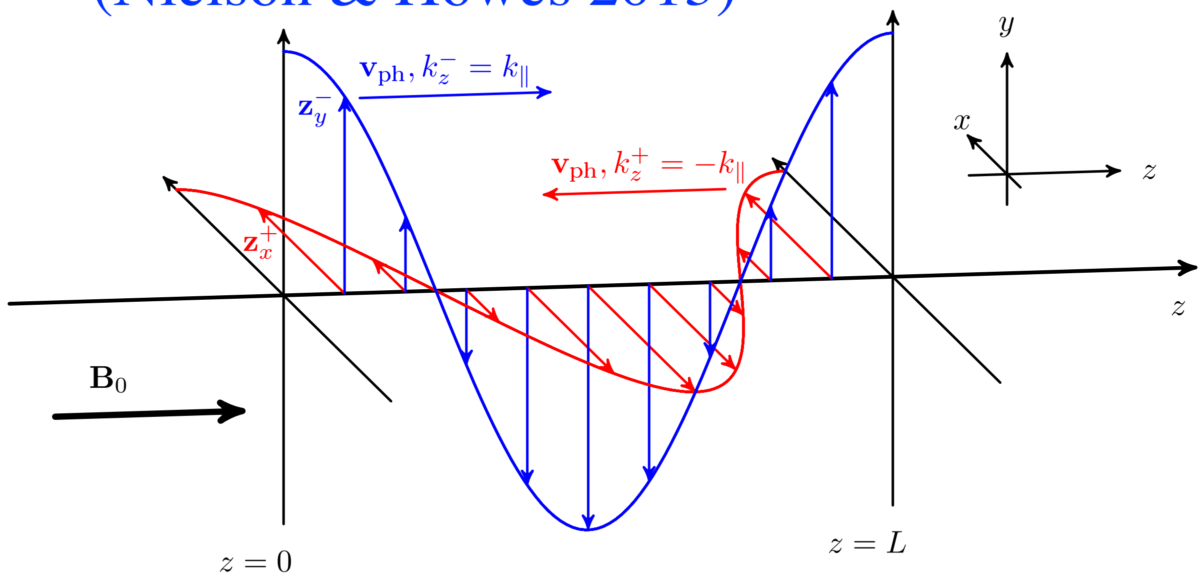
Loop Antenna Alfven Wave

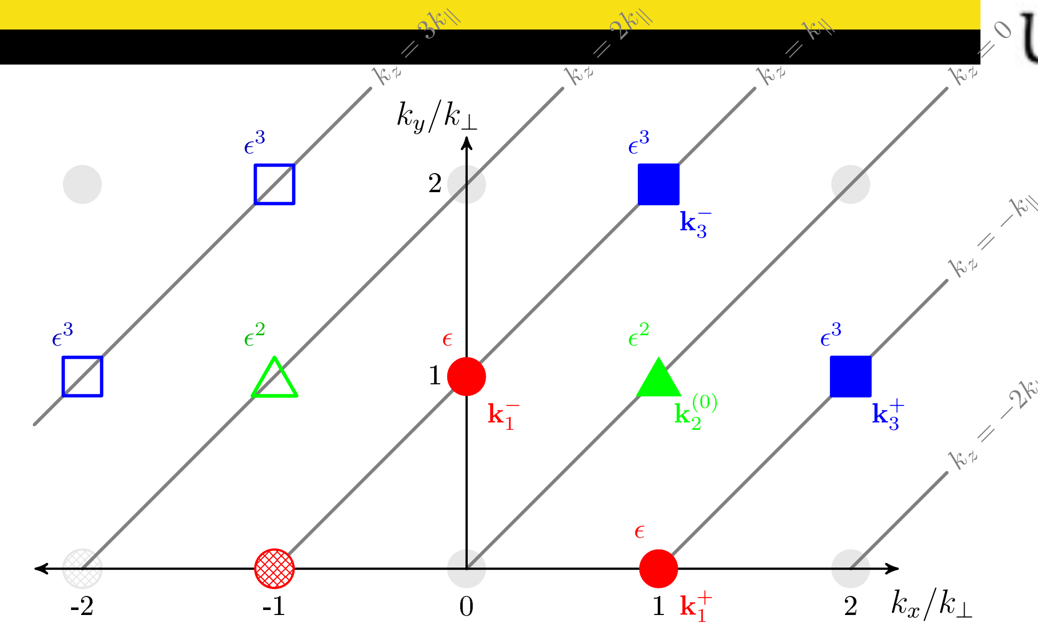
(Howes, Drake, Nielson, Skiff, Kletzing, & Carter 2012, Phys. Rev. Lett.)

Verification of the Physics of Alfven Wave Collisions

- Analytical Calculation

(Nielson & Howes 2013)

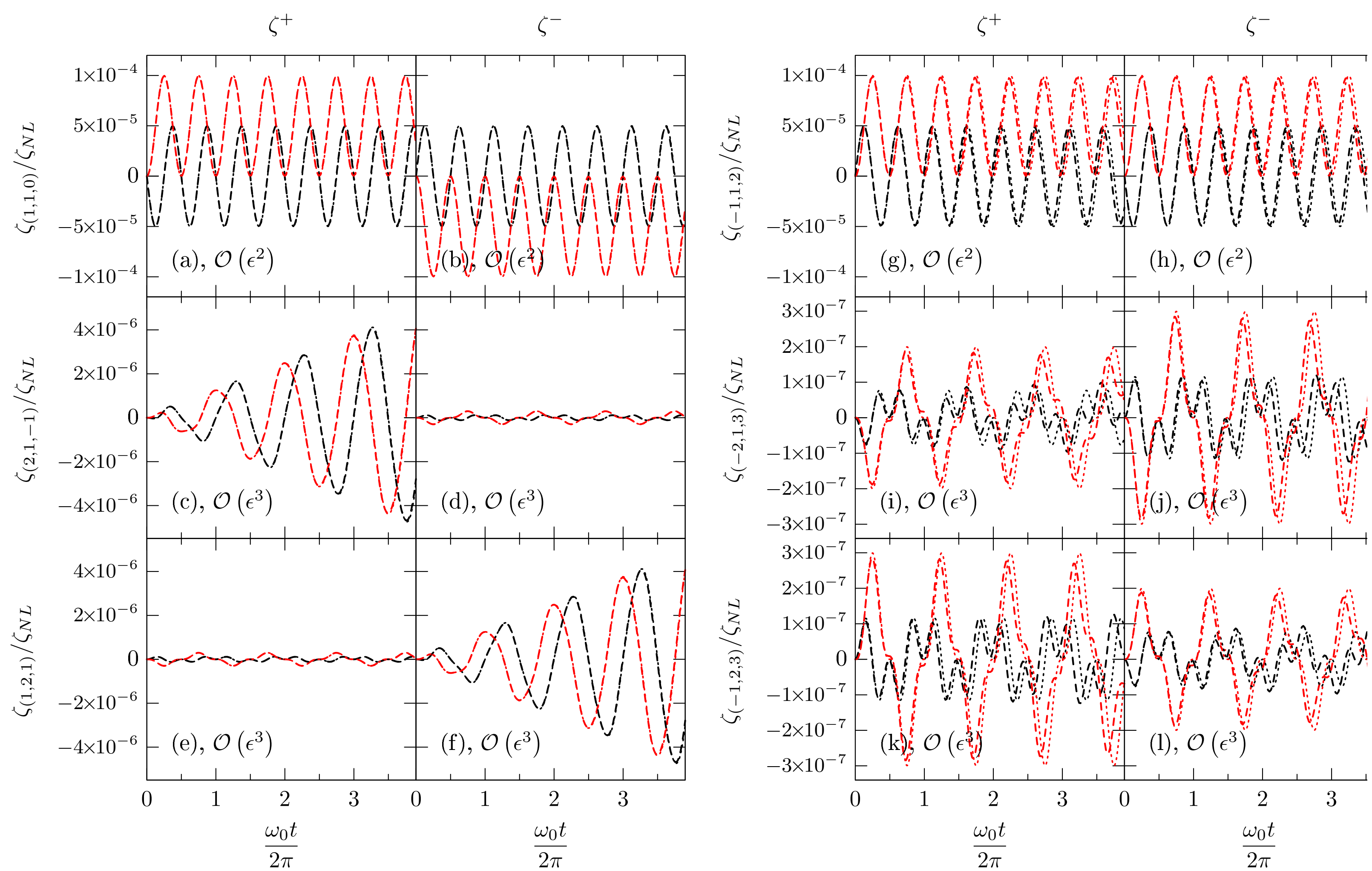




$$\mathbf{k}_1^+ + \mathbf{k}_1^- = \mathbf{k}_2^{(0)} \qquad \mathbf{k}_1^\pm + \mathbf{k}_2^{(0)} = \mathbf{k}_3^\pm$$

- Numerical Validation using gyrokinetic simulations

(Nielson, Howes, & Dorland 2013, Phys. Plasmas **20**:072303)



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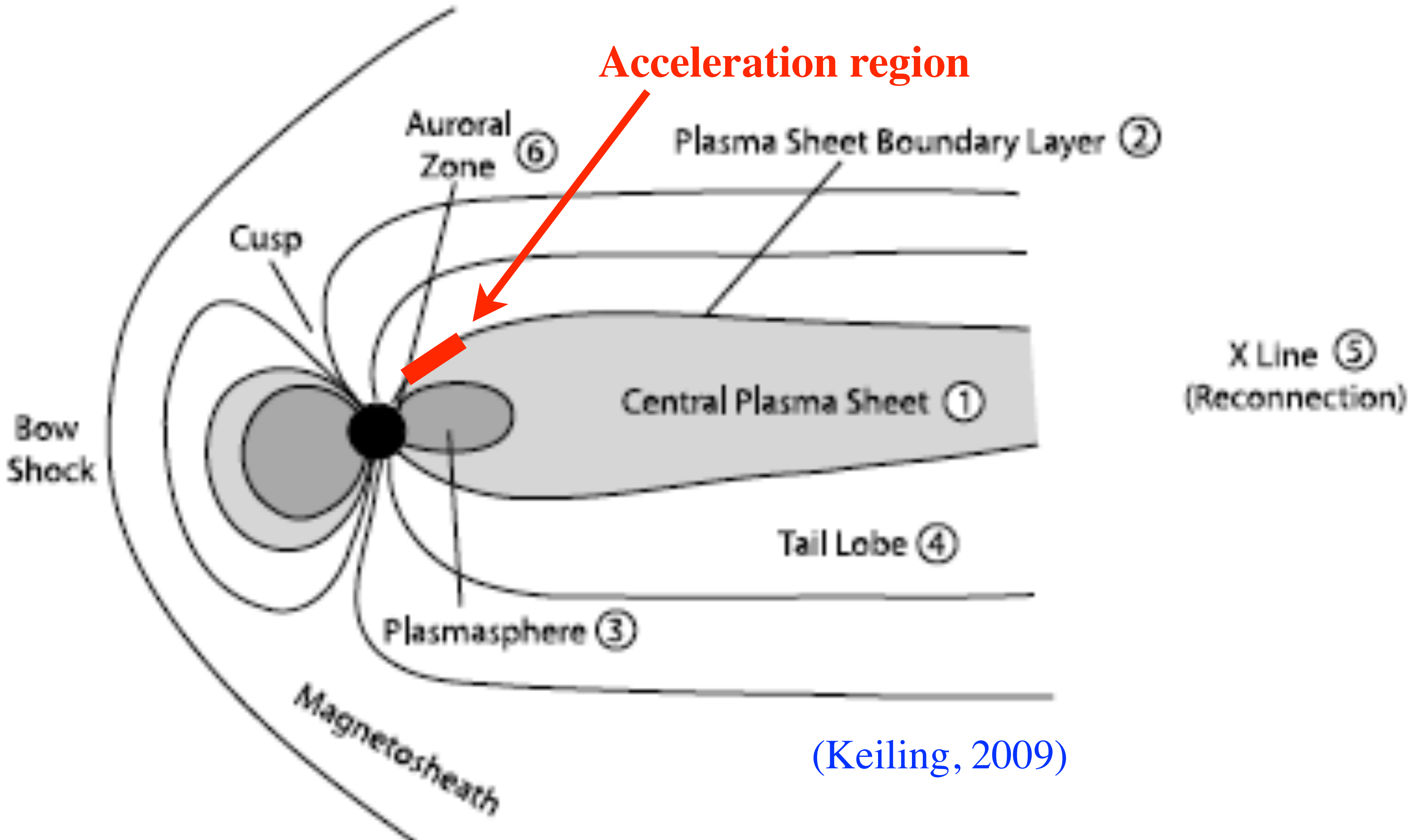
Auroral Electron Acceleration

The University of Iowa

The physical mechanism leading to the glowing aurora is one of the oldest problems in space physics

Electron Acceleration by Alfven Waves



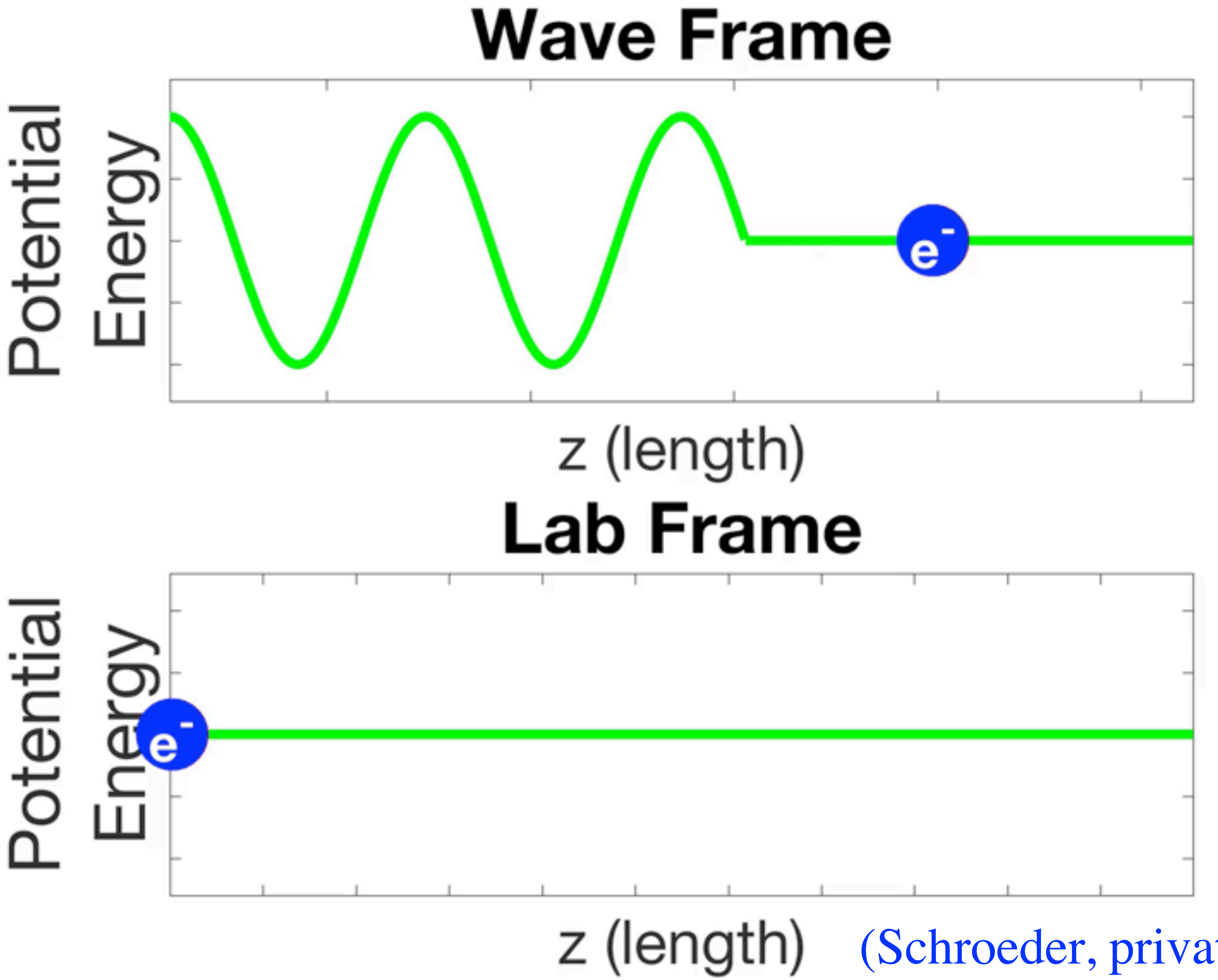
(Keiling, 2009)

- Shifts in the magnetic field (due to reconnection) in the magnetotail are transmitted to Earth along field lines as Alfven waves

- At about $2R_E \lesssim r \lesssim 3R_E$, electrons can be accelerated by the parallel electric field of Alfven waves in the inertial regime

Single-Bounce Fermi Acceleration

- Single-bounce Fermi acceleration by parallel electric field



(Schroeder, private comm.)

Measuring Electron Velocity Distribution

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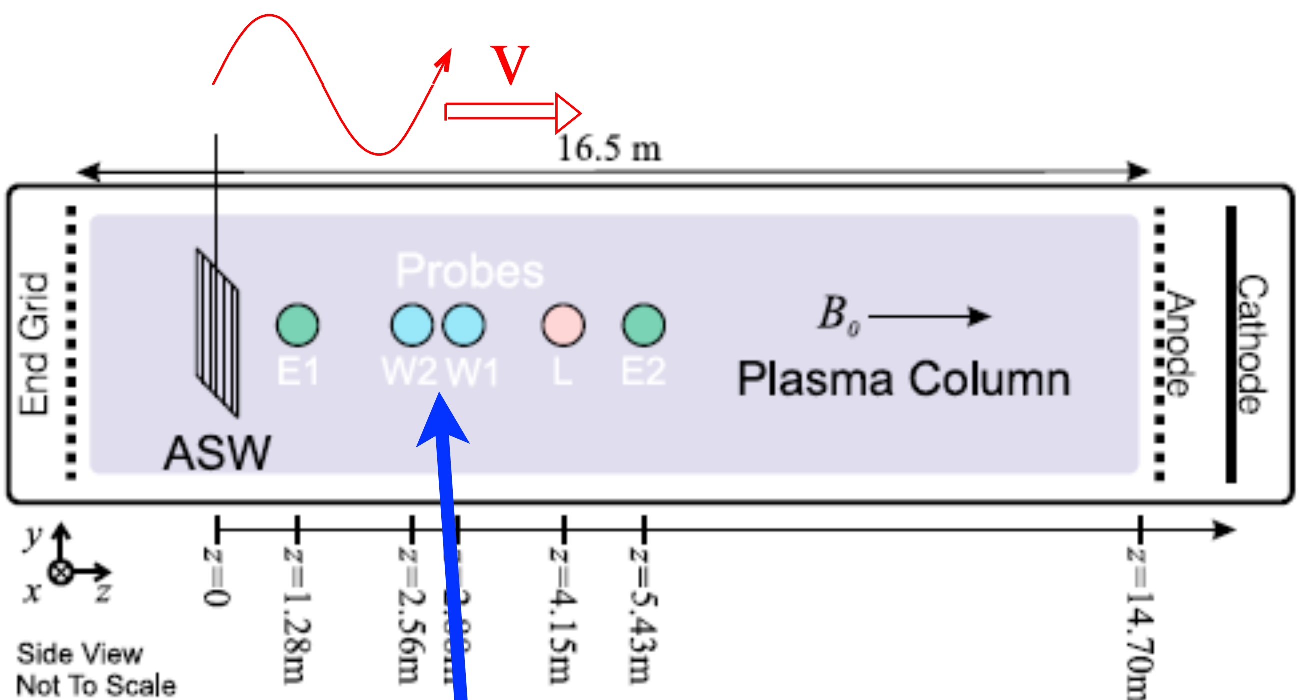
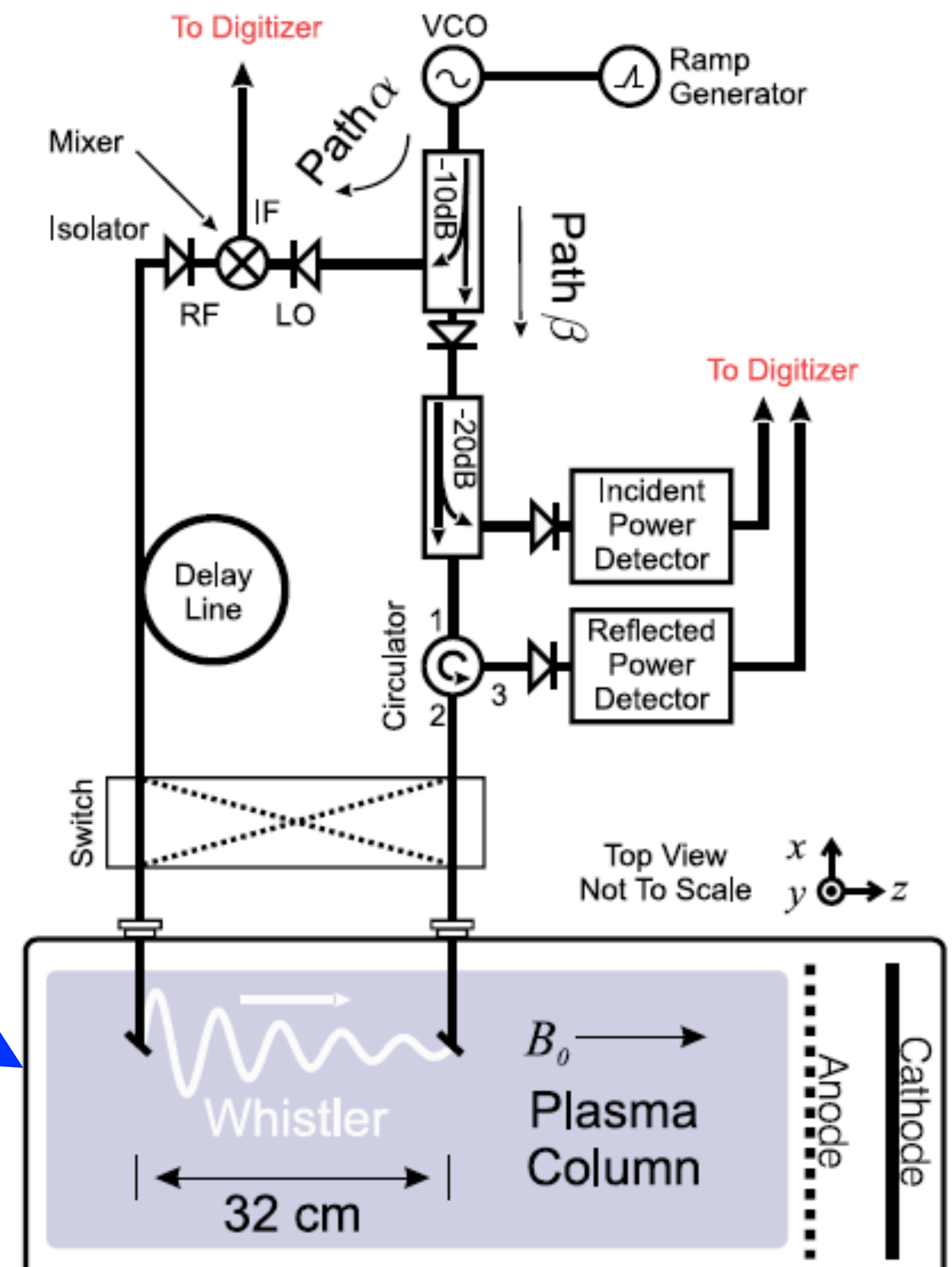
- Launch an inertial Alfven wave ($v_{te} < v_A$) in LAPD Plasma



- Measure the electron distribution function using the absorption of whistler waves

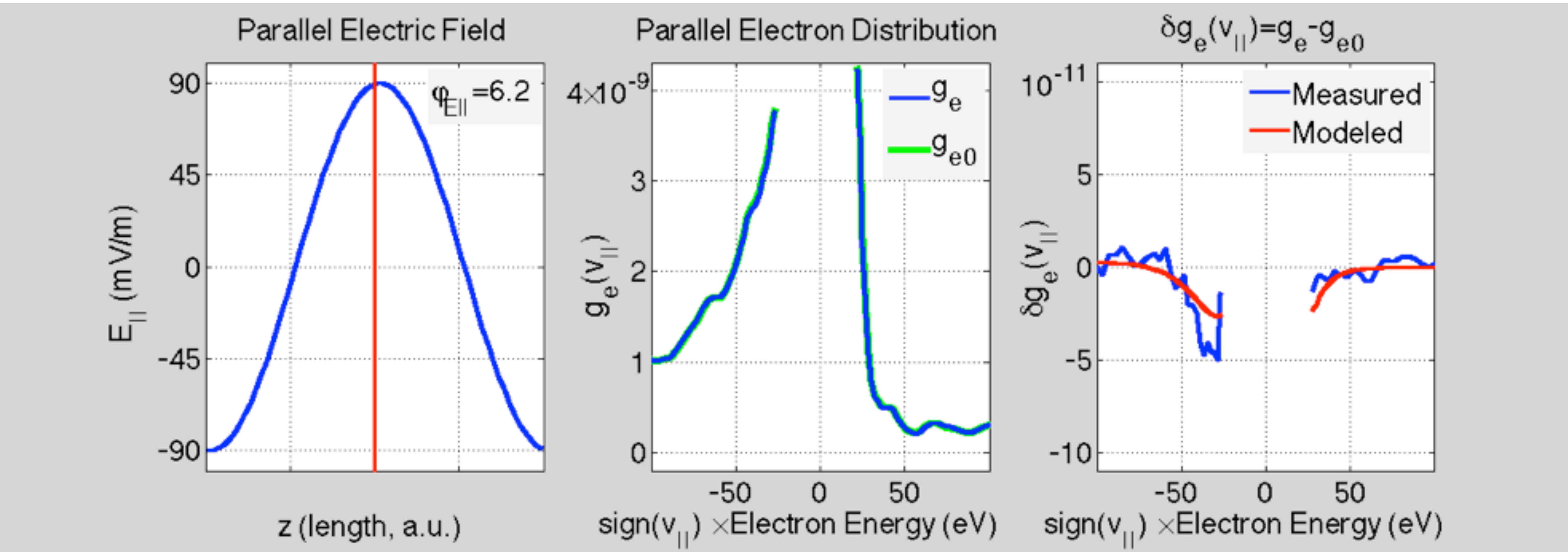


Whistler Wave Absorption Diagnostic

(Thuecks, Skiff, & Kletzing, 2012)

Electron Perturbation due to Alfven Wave

- Good agreement between analytically modeled and experimentally measured perturbed electron velocity distribution



(Schroeder et al., 2016, 2017)

- This is the linear effect of the Alfven wave on the electrons
- Currently, we are attempting to measure the nonlinear effect of accelerated electrons here on the Large Plasma Device (LAPD)

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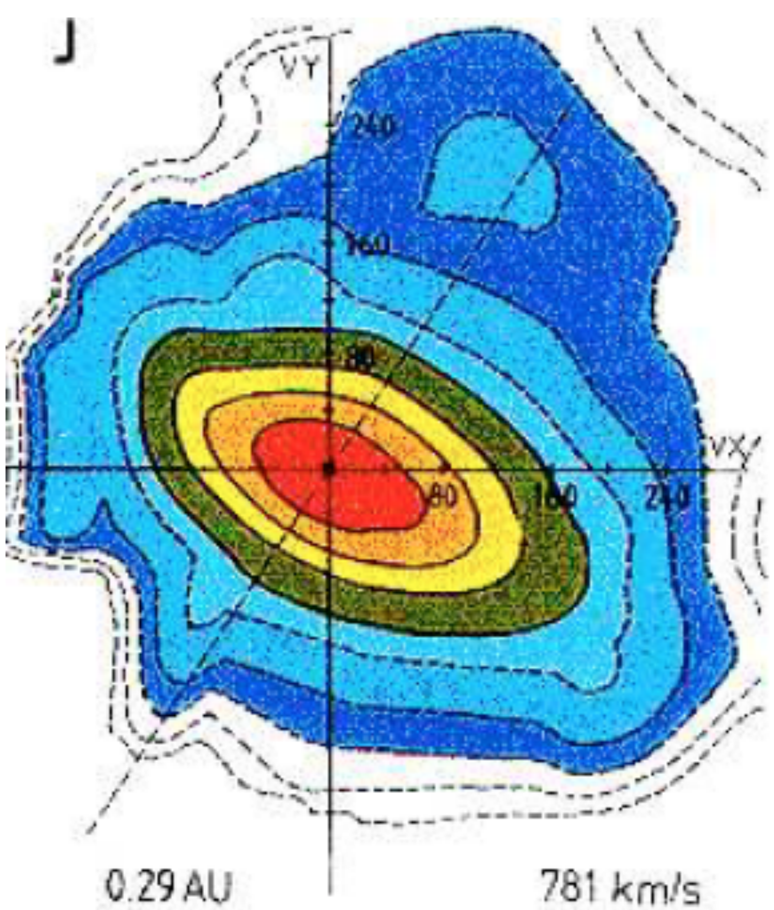
Velocity Space is the New Frontier

• In space & astrophysical plasmas, velocity space contains a vastly underutilized store of information about the plasma dynamics

Helios spacecraft



(Marsch *et al*., 1982)

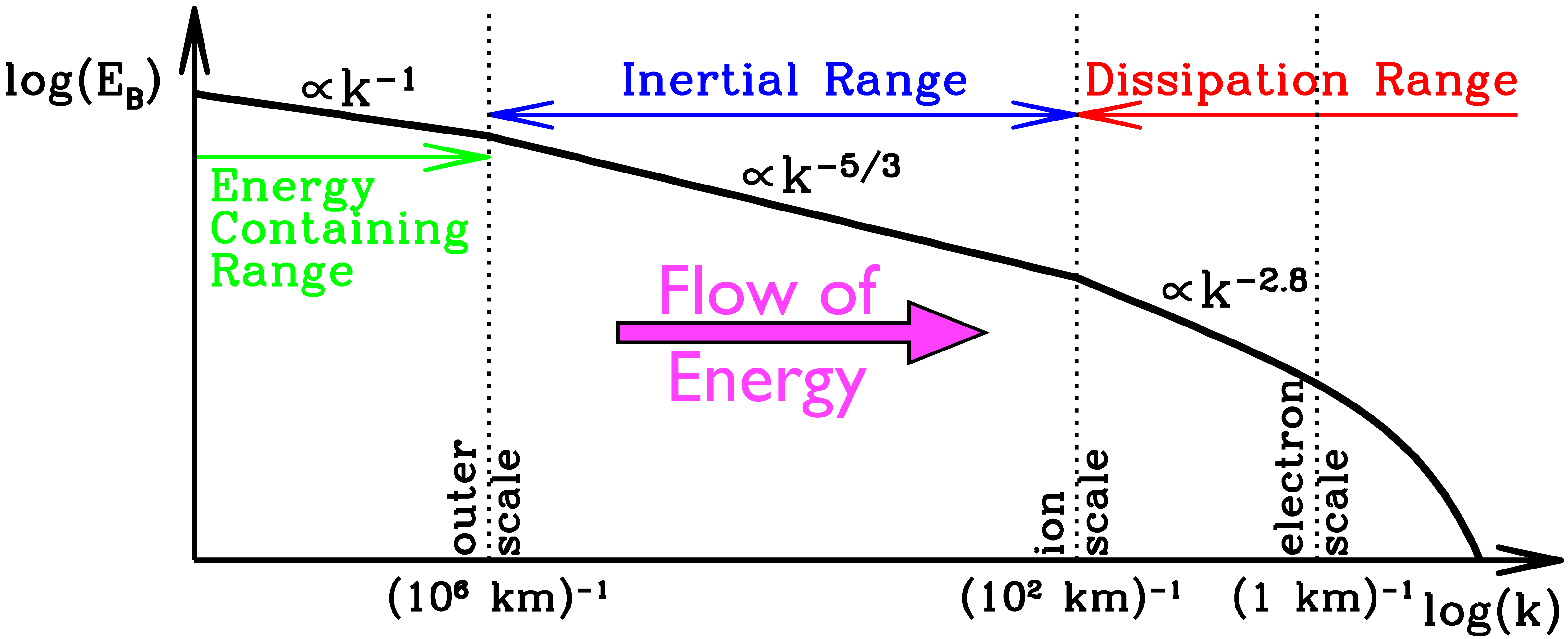
• 3D velocity distribution functions have been measured in space for decades

• Rarely used for more than computing moments:
density, bulk flow, anisotropic temperatures

• But velocity space contains a vast store of information about the dynamics & energetics

Velocity space is the most important new frontier in space physics!

Kinetic Turbulence in the Solar Wind

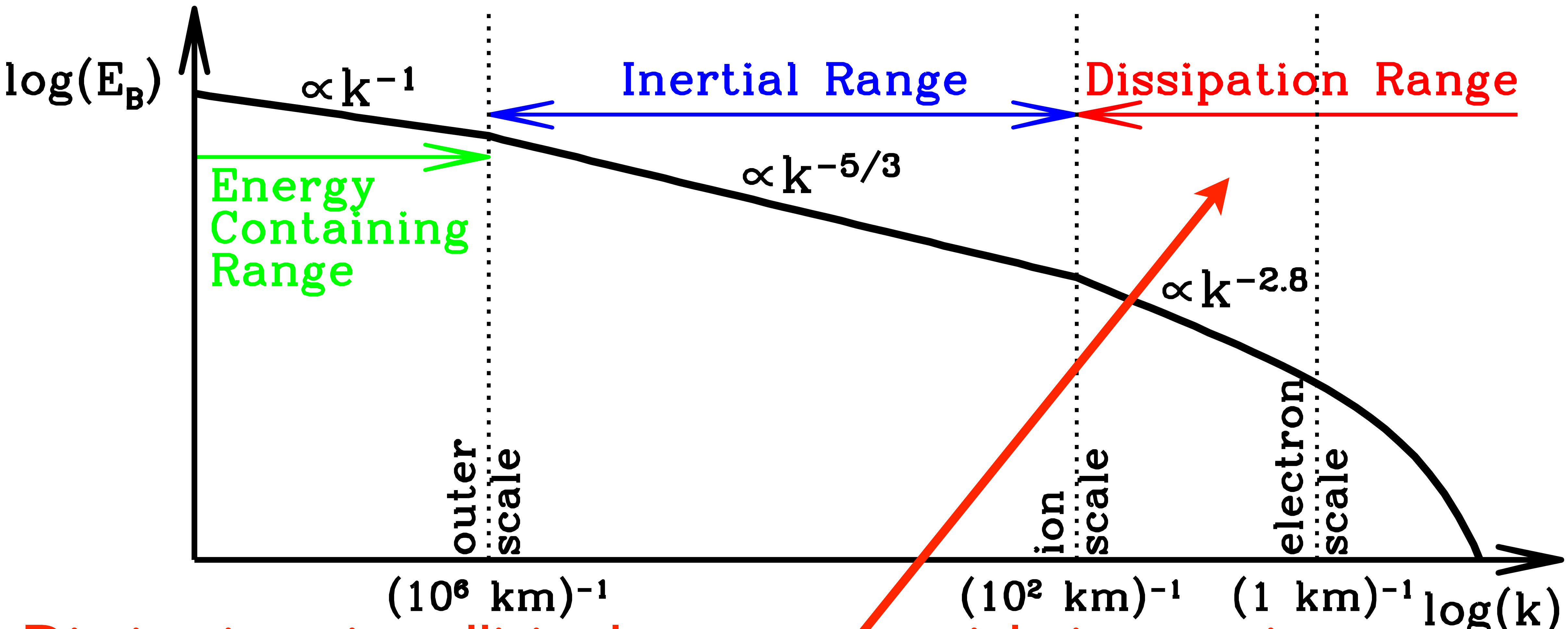


Ultimate Goal:

To understand the dynamics and energetics of the entire cascade

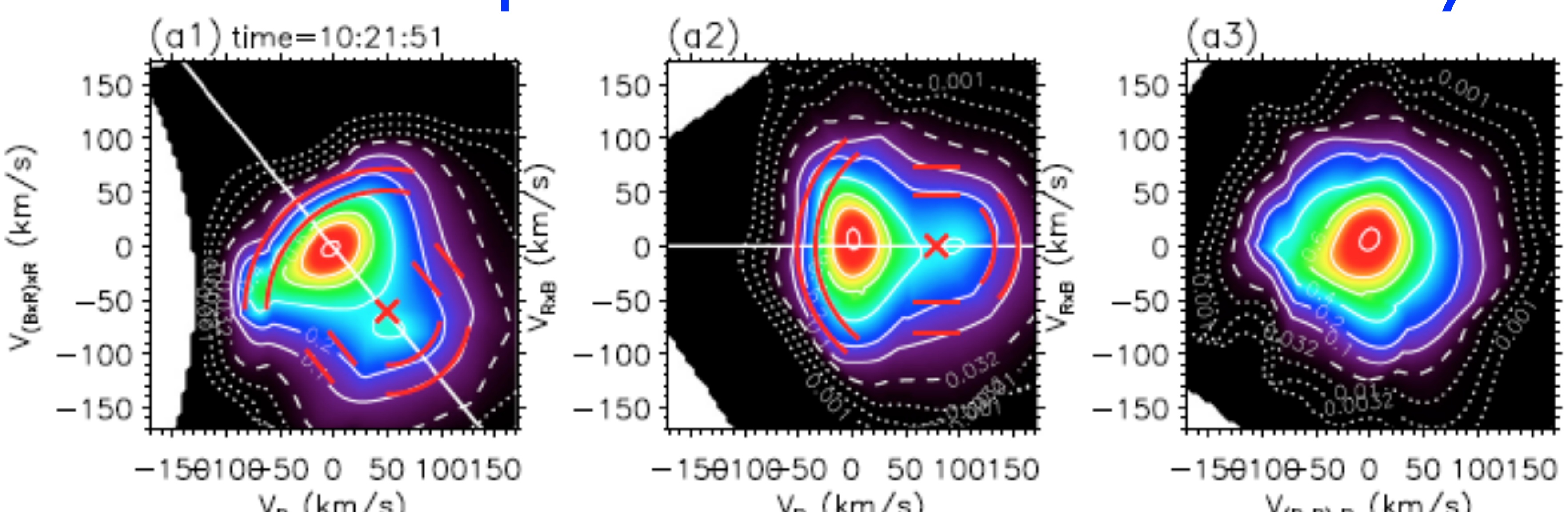
Flow of energy from large scale turbulent motions to plasma heat

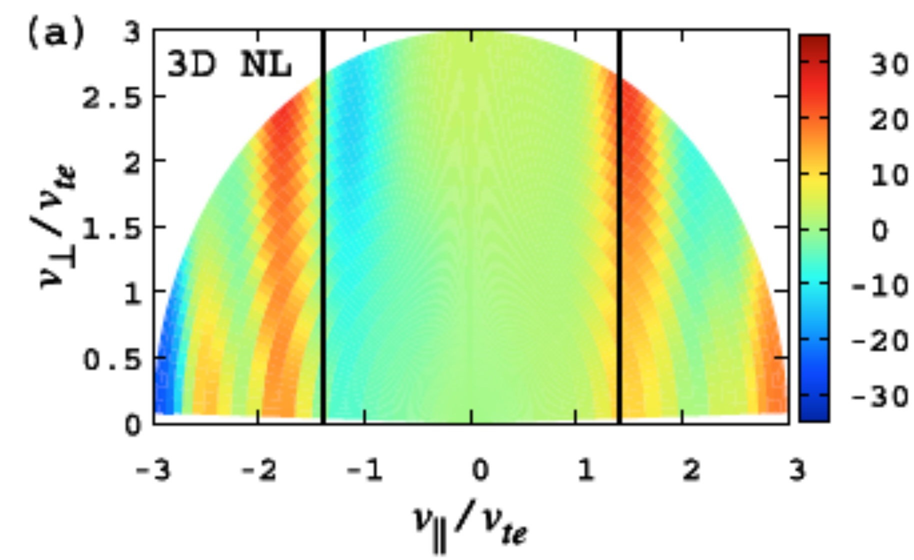
Kinetic Turbulence in the Solar Wind



Dissipation via collisionless wave-particle interactions

Leads to perturbations in the velocity distribution function



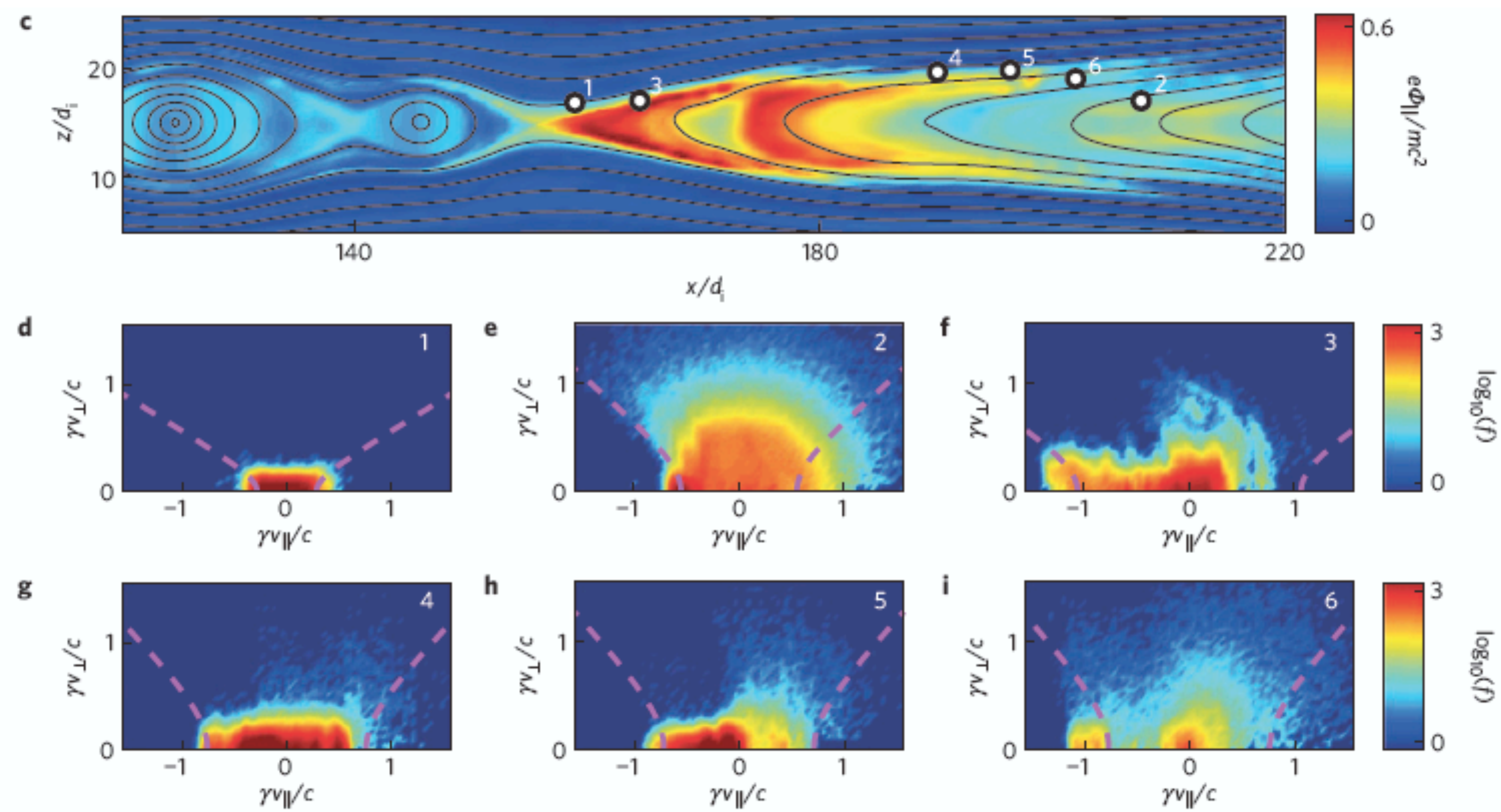


(He, Wang, Tu, Marsch, & Zong, 2015)

(Li, Howes, Klein, & TenBarge, 2016)

Velocity Space is the New Frontier

In collisionless magnetic reconnection, velocity space contains vital information about the energization of particles



(Egedal, Daughton, & Le, 2012)

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What’s on the Horizon?

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• Innovative diagnostics and analysis methods enable a wide range of new investigations

<u>Workshop Goal</u>:

What new investigations are made possible by advances in diagnostic capabilities and sophisticated new analysis techniques?

- Wave absorption diagnostics enable sensitive measurements of particle velocity distributions

- The field-particle correlation technique directly probes the particle energization in space or laboratory plasmas

Wave Absorption Diagnostics

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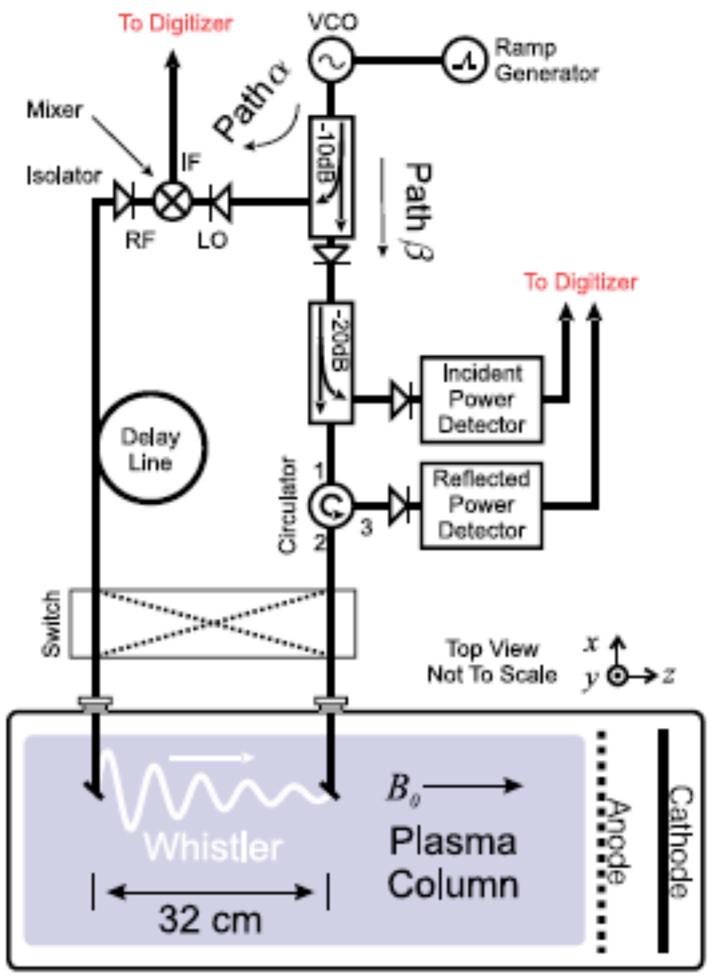
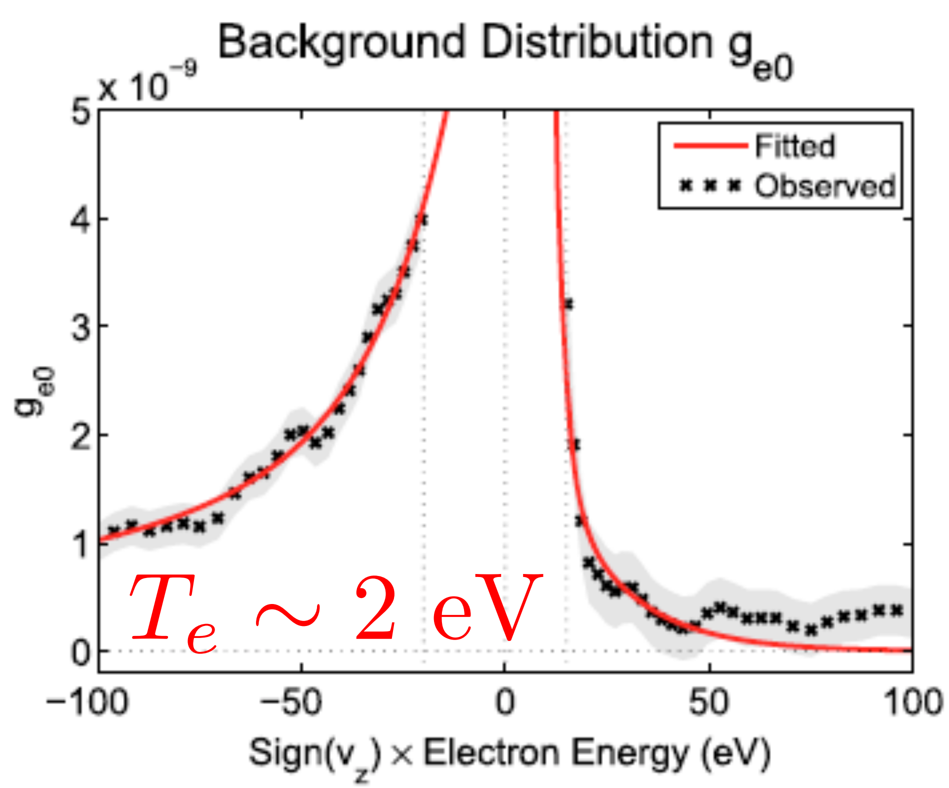
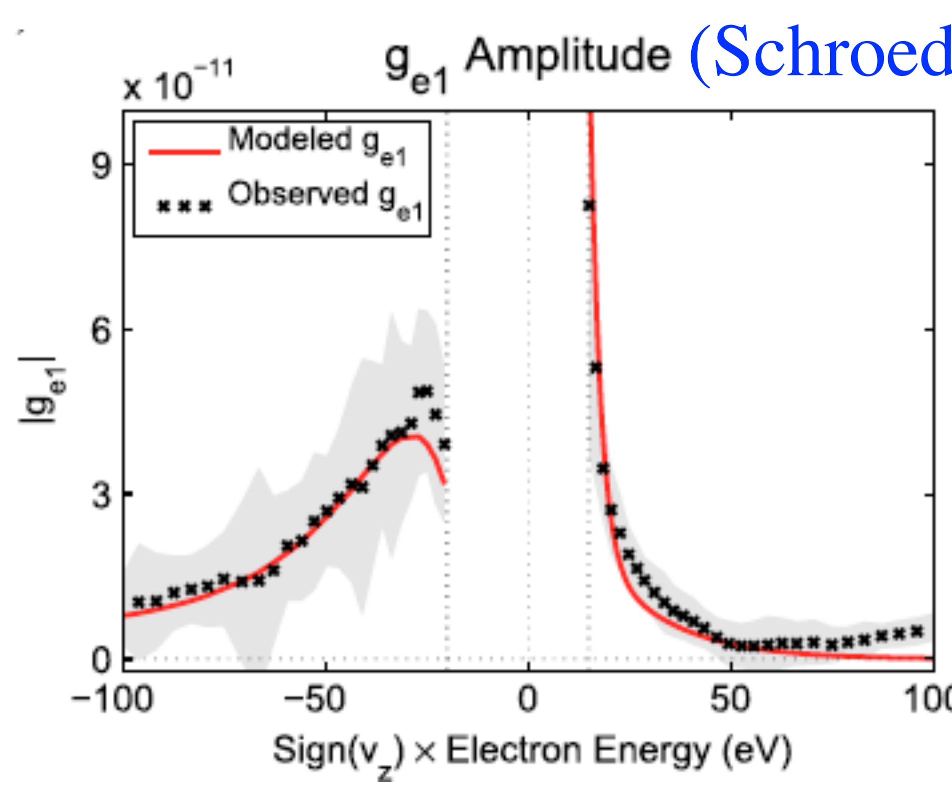


Example: Whistler Wave Absorption Diagnostic

(Thuecks, Skiff, & Kletzing, 2012; Schroeder *et al*. 2017)

- Enables sensitive measurements in the suprathermal tail of the electron velocity distribution





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Maxwell-Boltzmann Equations of Kinetic Plasma Theory

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Boltzmann Equation

$$\frac{\partial f_s}{\partial t} + \mathbf{v} \cdot \nabla f_s + \frac{q_s}{m_s} \left[\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c} \right] \cdot \frac{\partial f_s}{\partial \mathbf{v}} = \left(\frac{\partial f_s}{\partial t} \right)_{\text{coll}}$$

0

Lorentz Term responsible for interactions between fields and particles

Maxwell's Equations

$$\nabla \times \mathbf{E} = \frac{1}{c} \frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \cdot \mathbf{E} = 4\pi \rho_q$$

$$\nabla \times \mathbf{B} = \frac{4\pi}{c} \mathbf{j} + \frac{1}{c} \frac{\partial \mathbf{E}}{\partial t}$$

$$\nabla \cdot \mathbf{B} = 0$$

Particle Energization

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Conserved Vlasov-Maxwell Energy

$$W = \int d^3\mathbf{r} \left[\frac{|\mathbf{E}|^2 + |\mathbf{B}|^2}{8\pi} + \sum_s \int d^3\mathbf{v} \frac{1}{2} m_s v^2 f_s(\mathbf{r}, \mathbf{v}, t) \right]$$

Particle Energy $W_s \equiv \int d^3\mathbf{r} d^3\mathbf{v} \; \frac{1}{2} m_s v^2 f_s(\mathbf{r}, \mathbf{v}, t)$

Particles gain energy lost by the electromagnetic fields

$$\sum_s \frac{dW_s}{dt} = -\frac{d}{dt} \int d^3\mathbf{r} \left[\frac{|\mathbf{E}|^2 + |\mathbf{B}|^2}{8\pi} \right]$$

Particle Energization

Particles gain energy lost by the electromagnetic fields

$$\sum_s \frac{dW_s}{dt} = -\frac{d}{dt}\int d^3\mathbf{r}\left[\frac{|\mathbf{E}|^2 + |\mathbf{B}|^2}{8\pi}\right]$$

where the change in particle microscopic kinetic energy is

$$\frac{\partial W_s}{\partial t} = \int dx \int dv\ \frac{1}{2} m_s v^2 \frac{\partial f_s}{\partial t}$$

We want to measure the change in particle energy . . .

. . . using measurements of the change in the distribution function.

Vlasov equation $$\frac{\partial f_s}{\partial t} = -\mathbf{v}\cdot\nabla f_s - \frac{q_s}{m_s}\left[\mathbf{E} + \frac{\mathbf{v}\times\mathbf{B}}{c}\right]\cdot\frac{\partial f_s}{\partial \mathbf{v}}$$

But single-point spacecraft measurements preclude volume integral!

Field-Particle Correlations

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Define:

Phase-space energy density $w_s(\mathbf{r},\mathbf{v},t) = \frac{m_s v^2}{2} f_s(\mathbf{r},\mathbf{v},t)$

$$\frac{\partial w_s(\mathbf{r},\mathbf{v},t)}{\partial t} = -\mathbf{v}\cdot\nabla w_s - q_s \frac{v^2}{2}\mathbf{E}\cdot\frac{\partial f_s}{\partial \mathbf{v}} - \frac{q_s}{c}\frac{v^2}{2}(\mathbf{v}\times\mathbf{B})\cdot\frac{\partial f_s}{\partial \mathbf{v}}$$

This term is responsible for particle energization

How do we isolate the physics responsible for the energy transfer?

Take correlation of field $E_\parallel$ and particle $f_s(\mathbf{v})$ measurements

$$C_{E_\parallel}(\mathbf{v},t,\tau) = C\left(-q_s \frac{v_\parallel^2}{2}\frac{\partial f_s(\mathbf{r}_0,\mathbf{v},t)}{\partial v_\parallel}, E_\parallel(\mathbf{r}_0,t)\right)$$

(Klein & Howes, 2016; Howes, Klein, & Li, 2017)

Field-Particle Correlations

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$$C_{E_\parallel}(\mathbf{v},t,\tau) = C\left(-q_s \frac{v_\parallel^2}{2}\frac{\partial f_s(\mathbf{r}_0,\mathbf{v},t)}{\partial v_\parallel}, E_\parallel(\mathbf{r}_0,t)\right)$$

Benefits of this novel field-particle correlation technique:

1) Energy Transfer Calculation:

- Unnormalized correlation directly calculates energy transfer
- Can be used with single-point measurements

2) Velocity dependence of particle energization:

- Will highlight the resonant nature of mechanism
- Each mechanism will have a distinct velocity-space signature
    - Landau Damping, Transit Time Damping, Cyclotron Damping
    - Stochastic Ion Heating
    - Collisionless Magnetic Reconnection
- Properties of velocity-space signature can distinguish mechanism

Field-Particle Correlation Results

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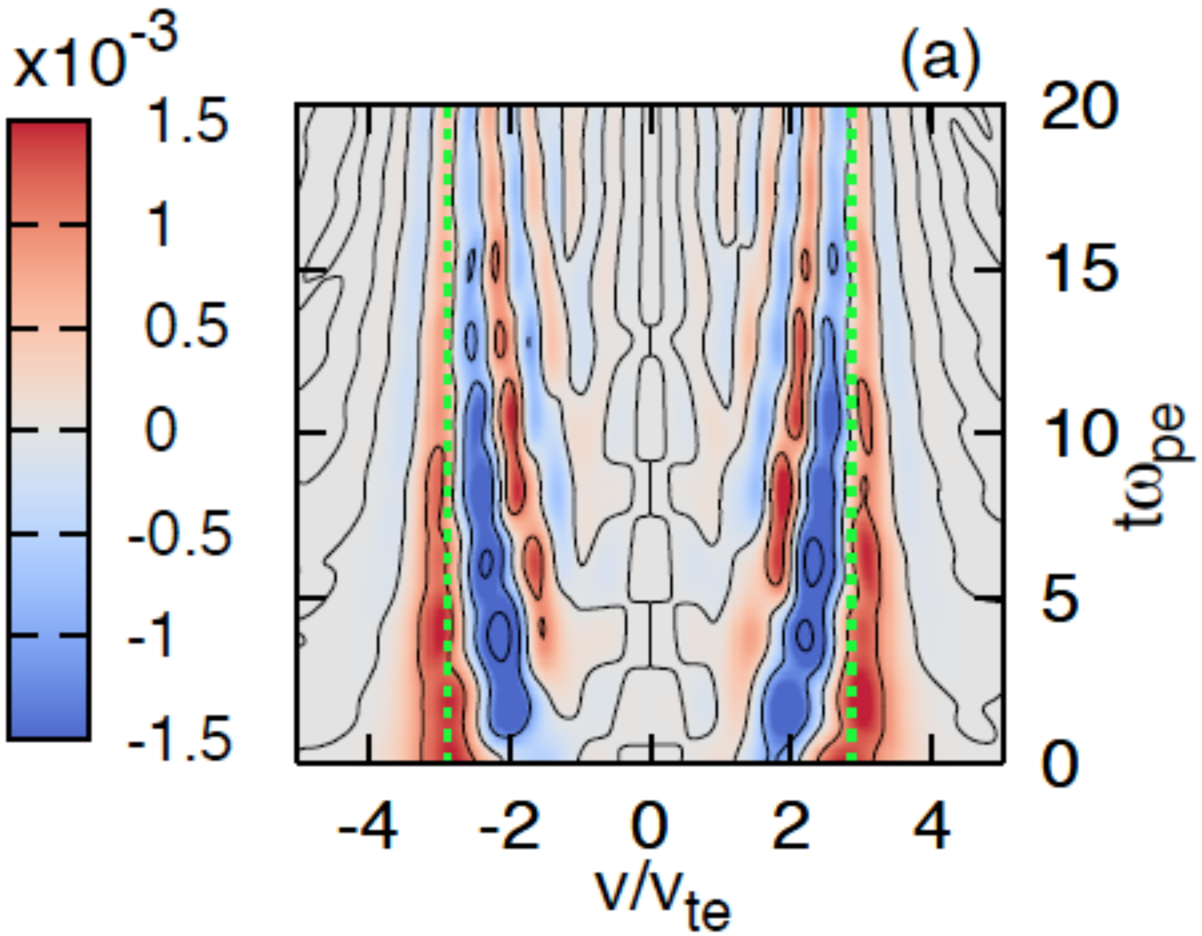
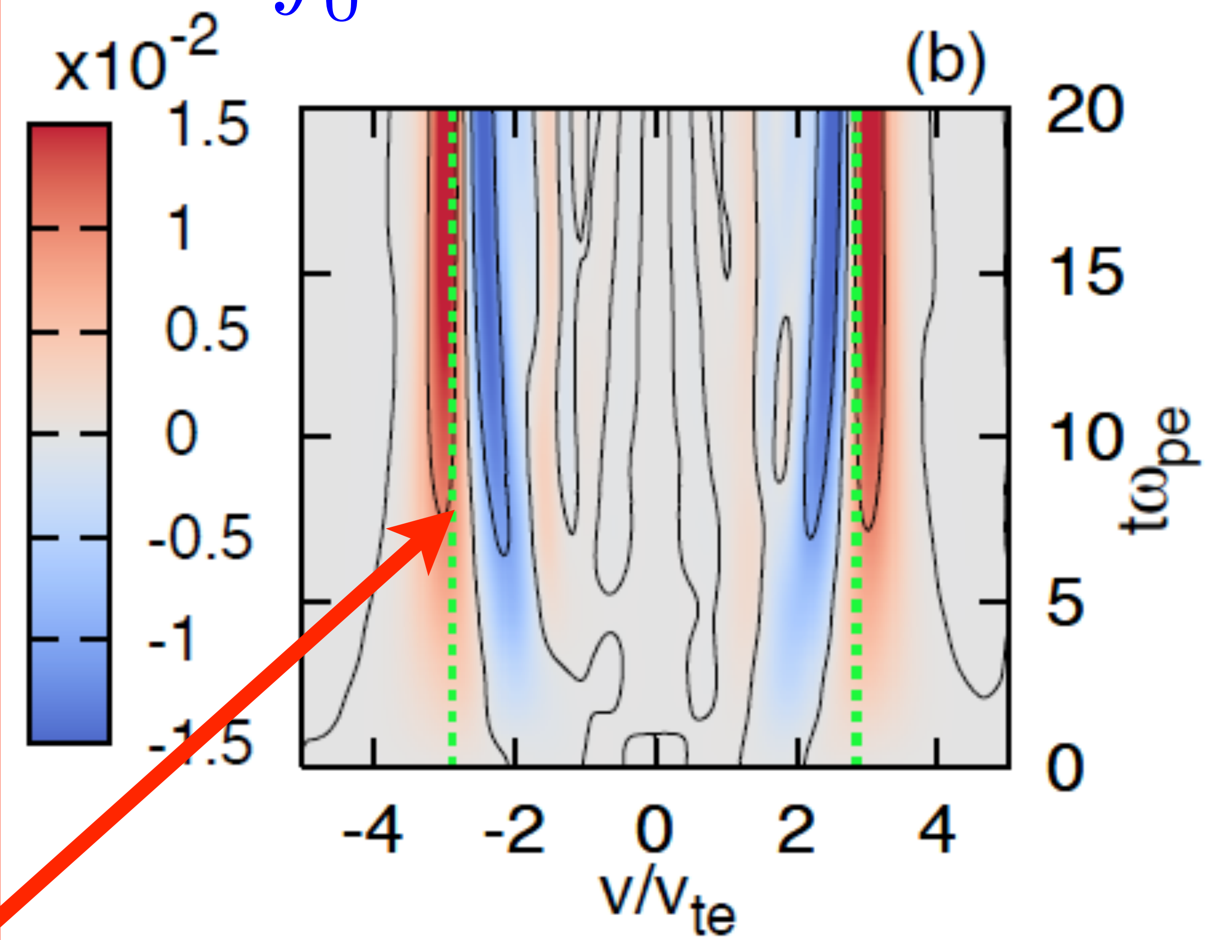
For a correlation time $\omega_{pe}\tau = 6.28$

$C_1(v,t,\tau)$



$\int_0^t dt' C_1(v,t',\tau)$



Key Property

Velocity-space signature of quasilinear flattening . . .

but from single-point measurements!

Questions for Field-Particle Correlations

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- What diagnostics are capable of measuring ion and electron velocity distribution functions?

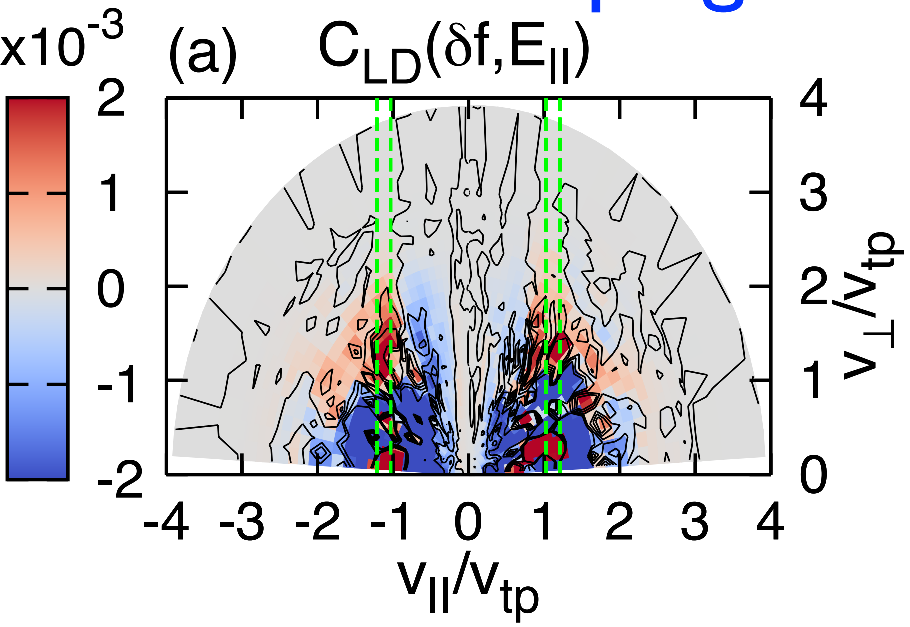
- What are the advantages and limitations of different velocity distribution measurement approaches?

- Can we use co-located field and particle velocity measurements in the laboratory to determine definitively the mechanisms of particle energization?

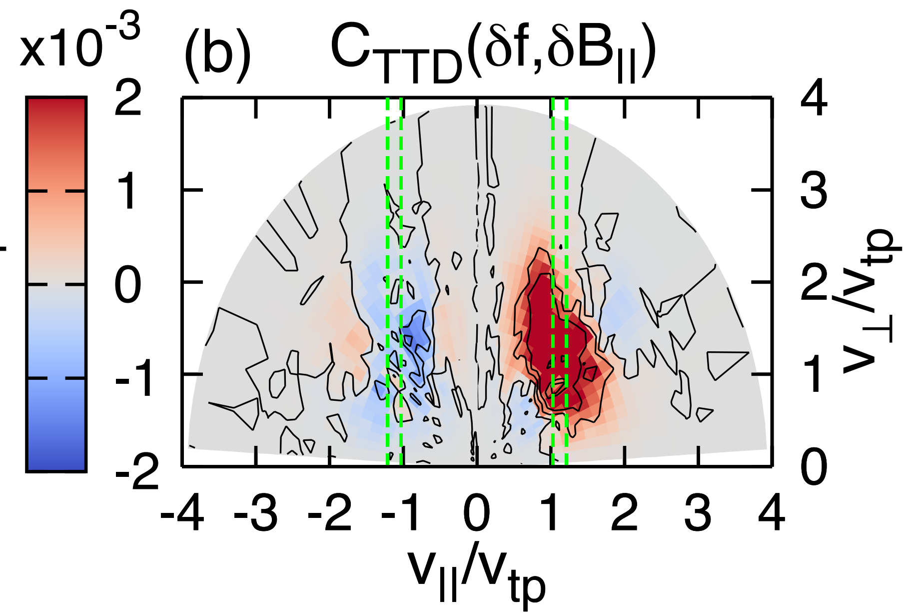
Applicability to Strongly Turbulent Systems

AstroGK Simulations

Landau Damping

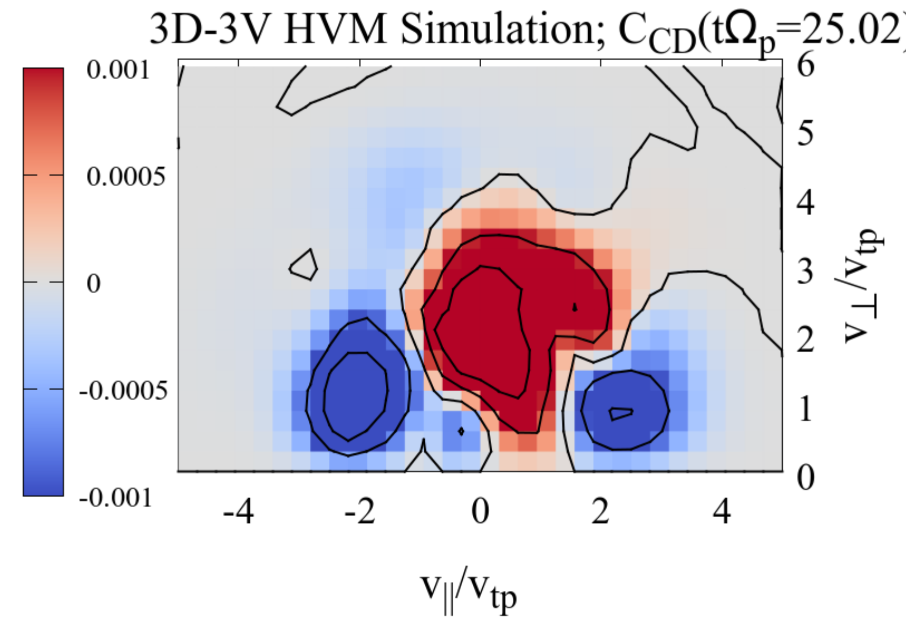


Transit Time Damping



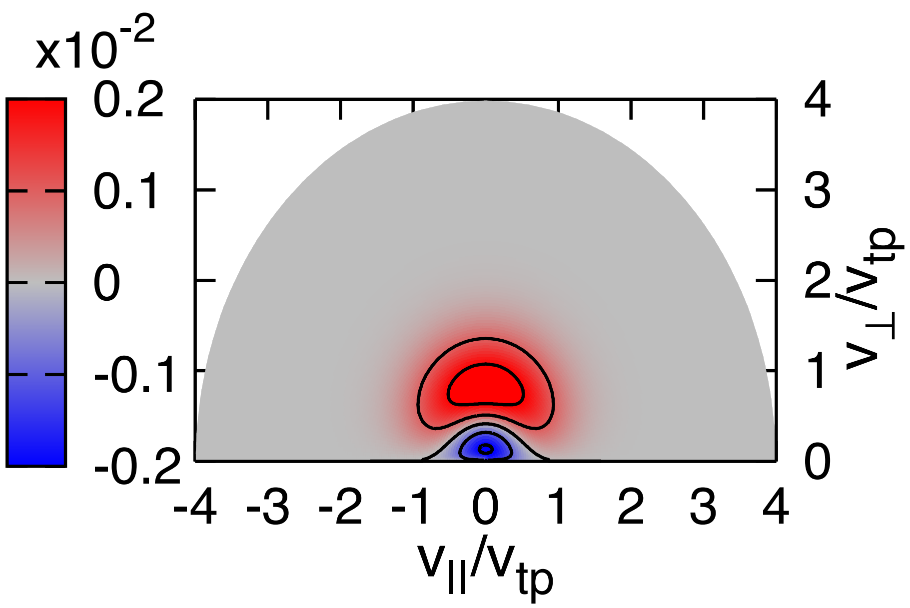
HVM Simulation

Cyclotron Damping



Theoretical Prediction

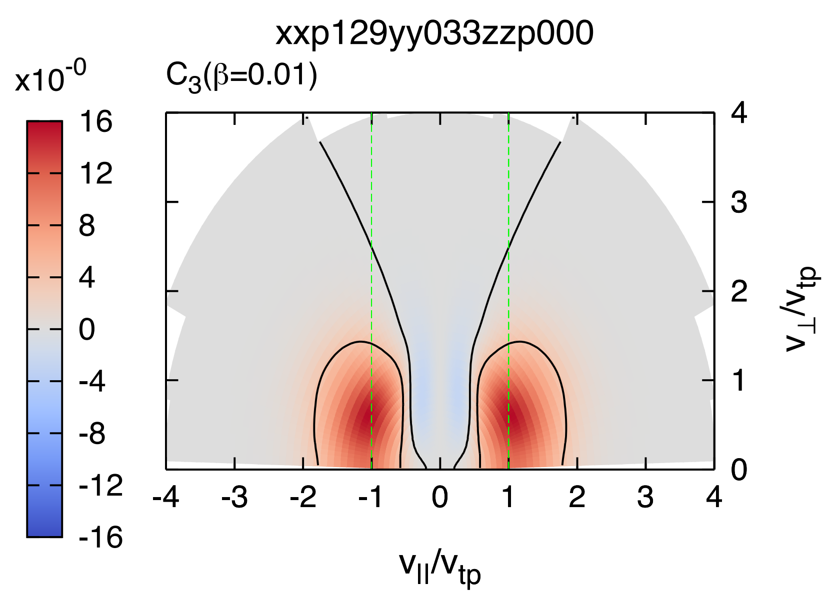
Stochastic Ion Heating



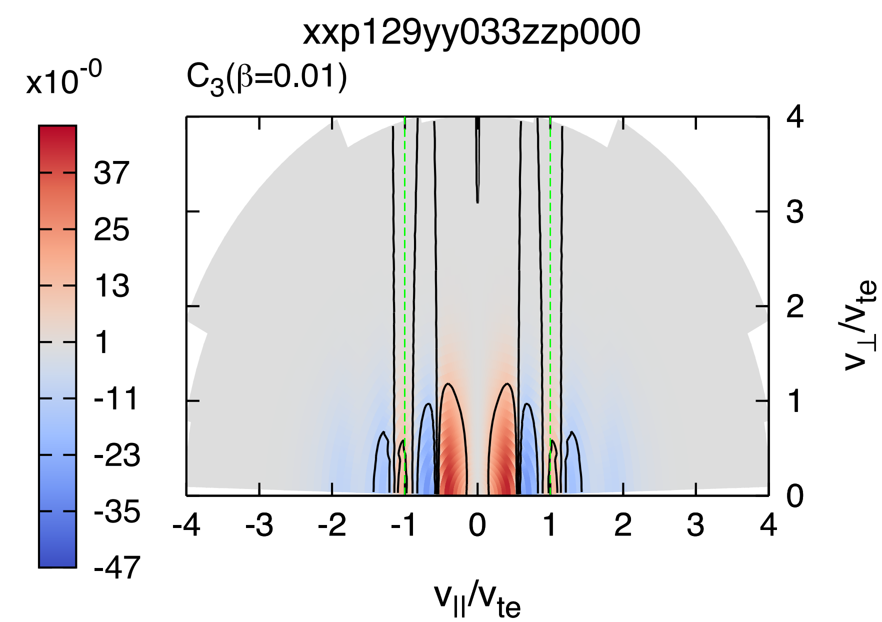
AstroGK Simulation

Magnetic Reconnection

Ions

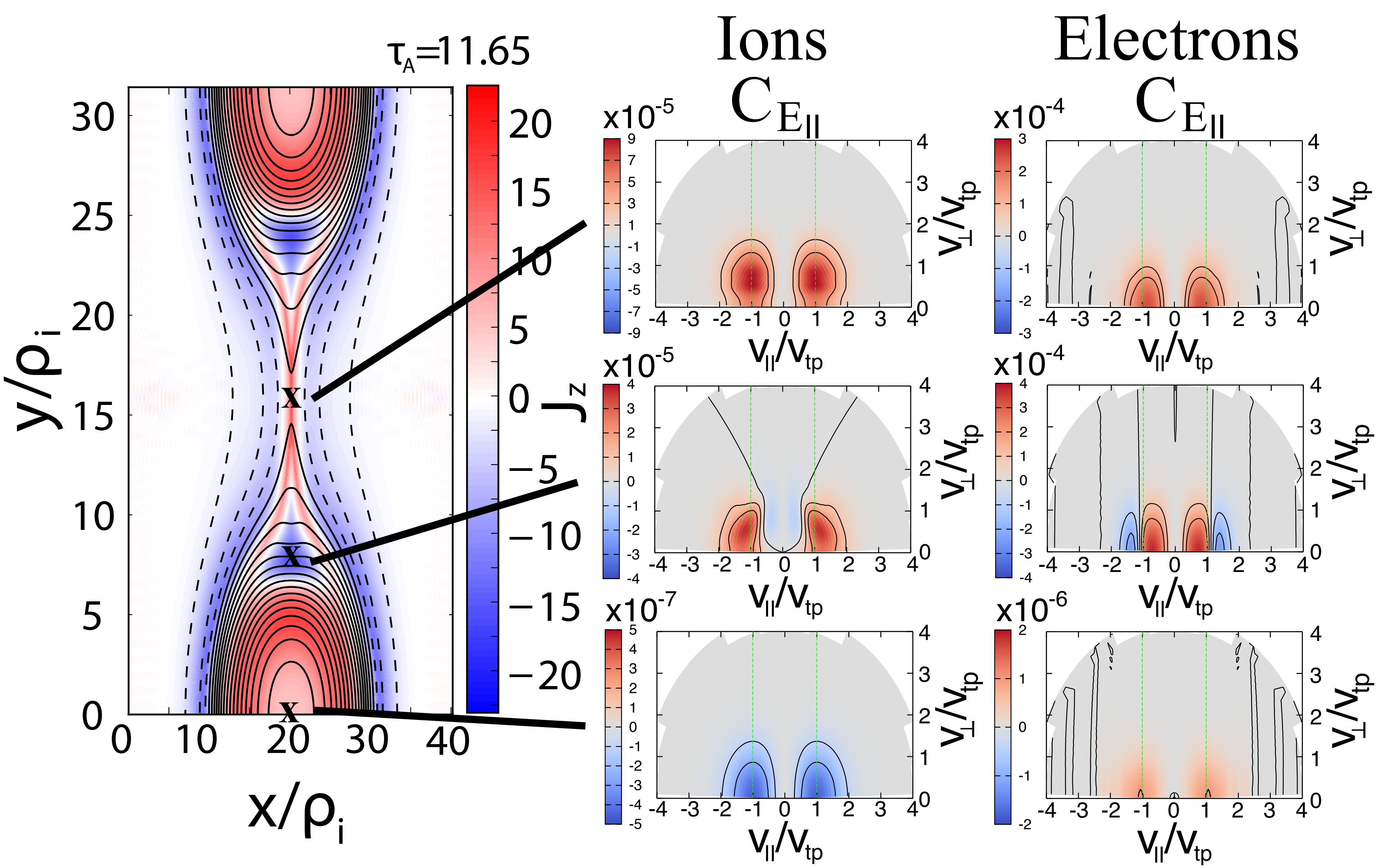


Electrons



Magnetic Reconnection

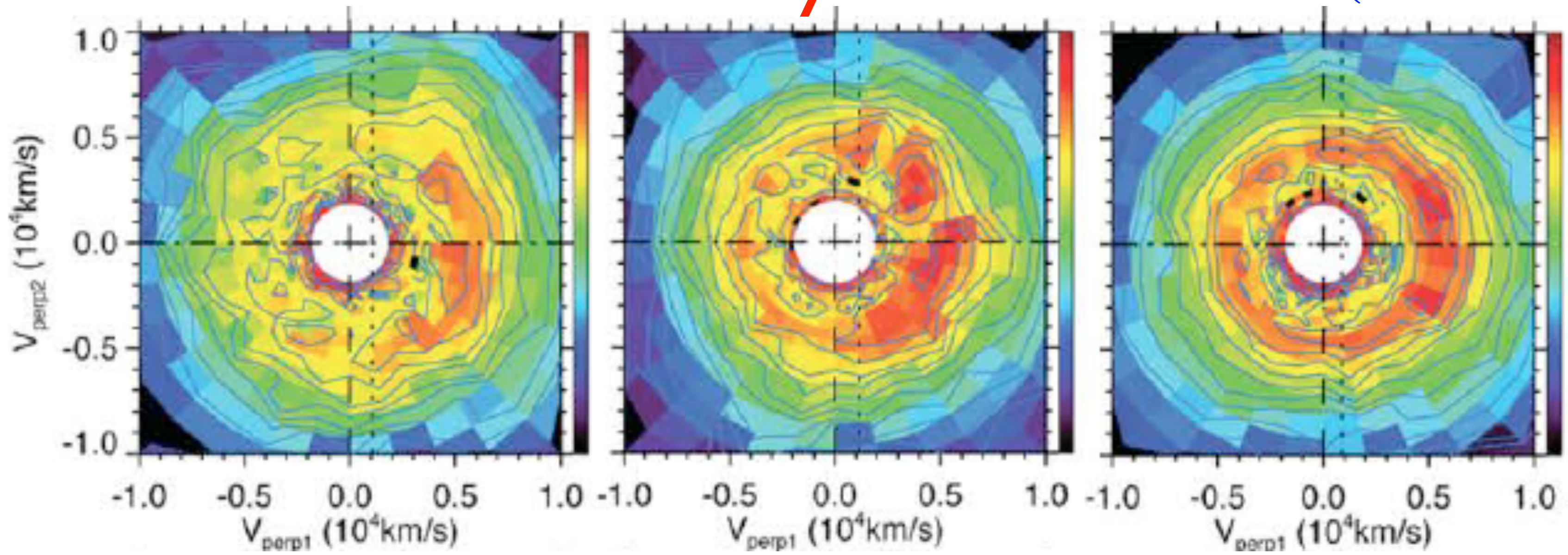
Particle energization varies by spatial position within the reconnection geometry



Numerical Simulations

- Spacecraft instruments and laboratory diagnostics can measure fluctuations in the particle velocity distribution functions

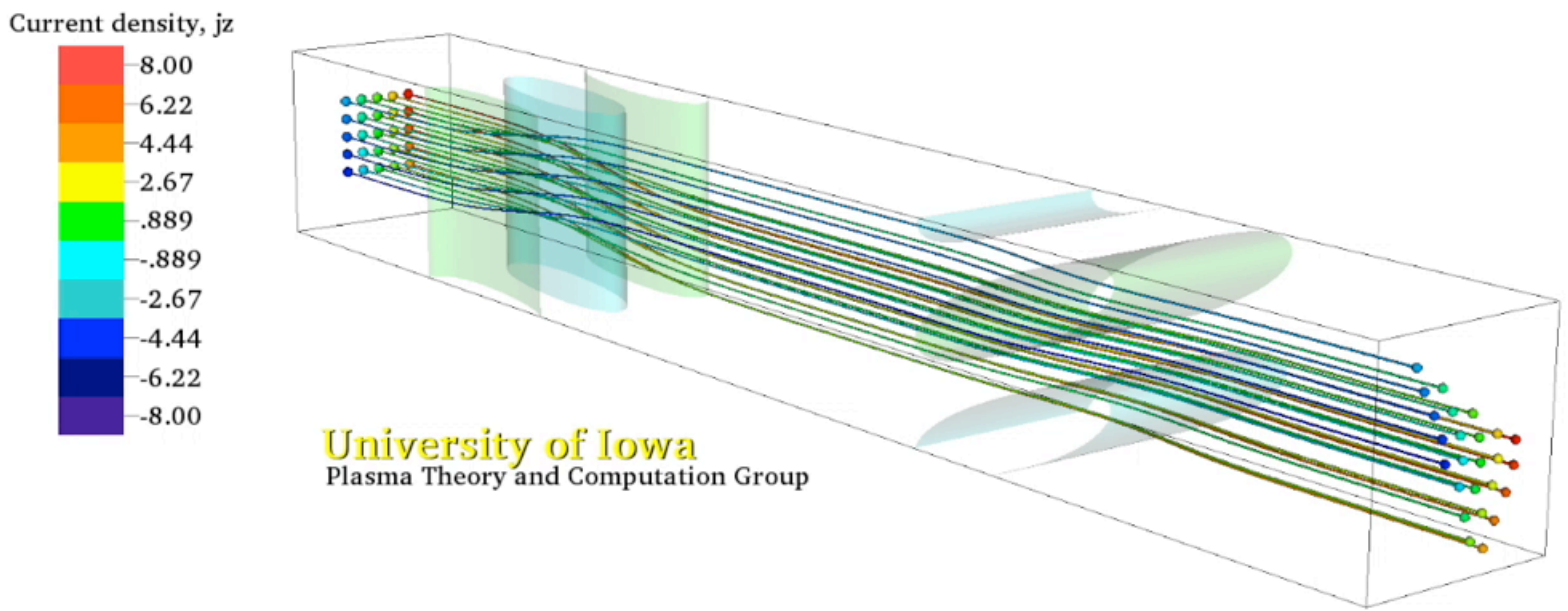
MMS electron velocity distributions (Burch *et al*., 2016)



- Kinetic numerical simulations play a critical role:
  - To interpret fluctuations in velocity space that arise through the weakly collisional plasma dynamics
  - To make connections between idealized theoertical models and the messy reality of spacecraft observations and laboratory measurements

Collisions Between Alfven Wavepackets

Localized Alfven Wave Collision simulations can be used to design and interpret experiments in the LAPD



Where do we go from here?

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- Measurements of velocity space will enable far greater understanding of particle energization in space plasmas

- Can we devise new experiments on the LAPD that use co-located field and particle velocity measurements to:

(i) Compute the energy transfer between fields and particles?

(ii) Identify the physical mechanism by its velocity-space signature?

END