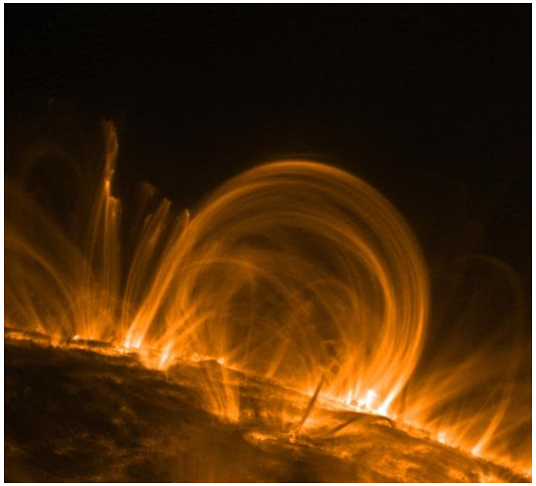


Heliophysics Summer School

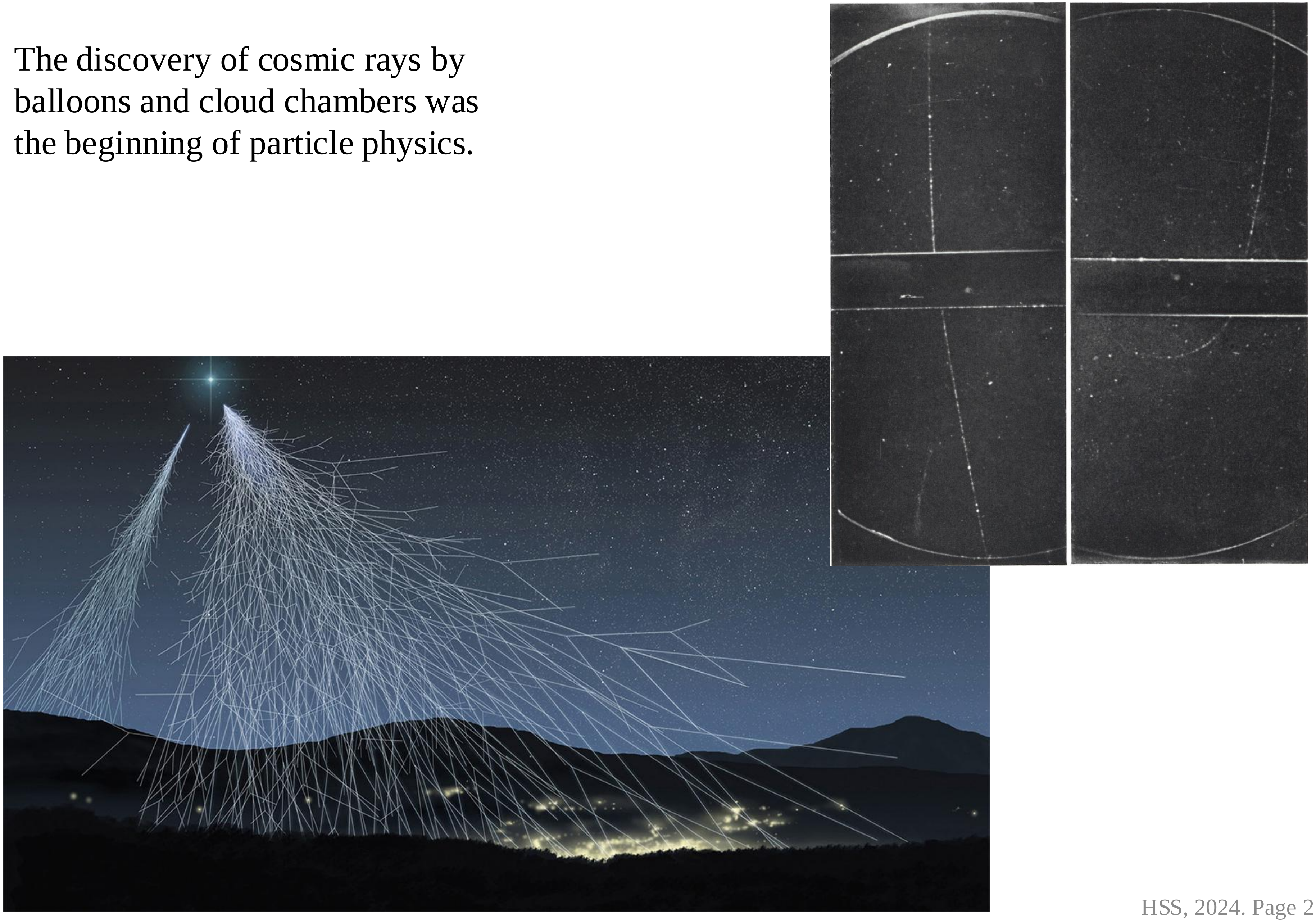
Part 2

- **Particle Acceleration Basics.**
- Magnetotail Reconnection
- Turbulent acceleration; electrons.
- Turbulent acceleration; ions.

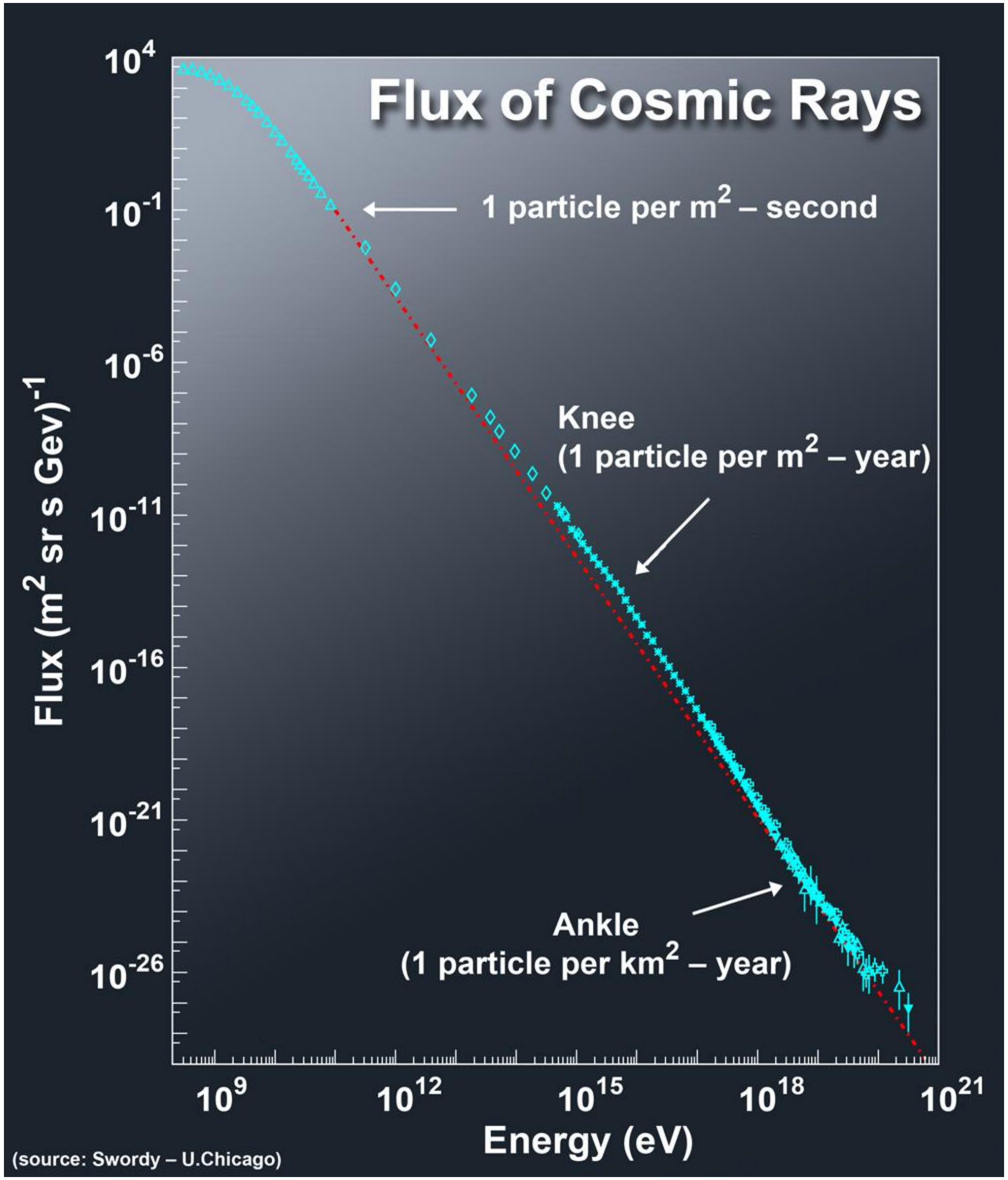
Prof. Robert Ergun
Email: ree@lasp.colorado.edu

Cosmic Rays

The discovery of cosmic rays by balloons and cloud chambers was the beginning of particle physics.



Cosmic Rays


Flux of Cosmic Rays
1 particle per m² – second
Knee
(1 particle per m² – year)
Ankle
(1 particle per km² – year)
Flux (m² sr s Gev)⁻¹
10⁴
10⁻¹
10⁻⁶
10⁻¹¹
10⁻¹⁶
10⁻²¹
10⁻²⁶
10⁹
10¹²
10¹⁵
10¹⁸
10²¹
Energy (eV)
(source: Swordy – U.Chicago)

Collisional Versus Collisionless Plasmas

Collisional

(1) The interior of the Sun and planetary ionospheres examples of collisional plasmas; they have high densities

(2) Momentum and energy exchange between ions and electrons (and/or neutral particles) can be dominated by collisions.

(3) The force equation must include viscosity and collision terms related to momentum exchange.

(4) Collisions often lead to a Gaussian distribution as per the central limit theorem.

Collisionless

(1) The solar corona, solar wind, Earth's magnetosphere, and many astrophysical plasmas can be treated as "collisionless".

(2) Momentum and energy exchange between ions and electrons is dominated by ***B*** and ***E***.

(3) Due to low damping, collisionless plasmas are often turbulent.

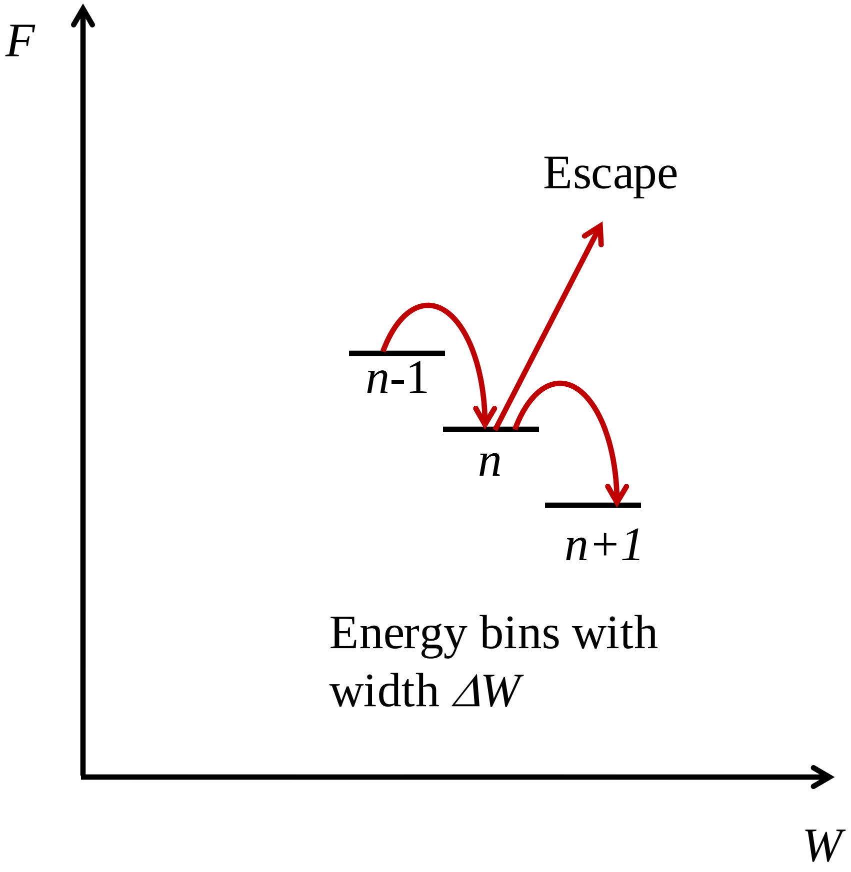
(4) Collisionless plasmas often do not have Gaussian distributions and may have energetic tails.

Fermi's Ideas: Power-Law Tail

The basic idea is to take a large volume of space and define the number of particles in that volume per unit energy as $F(W)$. Allow for a heating rate $W(\dot{W})$ and an escape rate $P_E(W)$. Separate F into bins with width ΔW. The heating causes bin n to gain particles from bin n-1:

$$Gain = F(W_{n-1})\frac{\dot{W}_{n-1}}{\Delta W}\delta t$$

$$Loss = F(W_n)\frac{\dot{W}_n}{\Delta W}\delta t + F(W_n)P_E(W_n)\delta t$$



Energy bins with width ΔW

P_E is the probability of escape.
In steady state, *Gain* = *Loss*, so:

$$F(W_{n-1})\frac{\dot{W}_{n-1}}{\Delta W} = F(W_n)\frac{\dot{W}_n}{\Delta W} + F(W_n)P_E(W_n)$$

Fermi's Ideas: Power-Law Tail

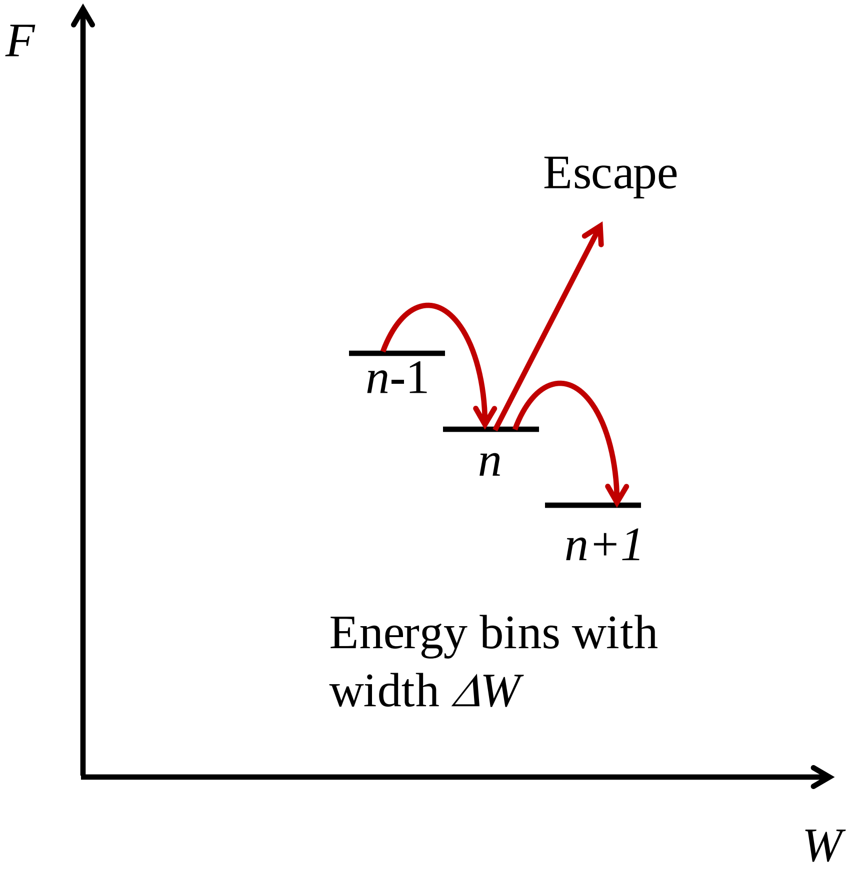
$$F(W_{n-1})\frac{\dot{W}_{n-1}}{\Delta W} = F(W_n)\frac{\dot{W}_n}{\Delta W} + F(W_n)P_E(W_n)$$

The above formula becomes a differential equation:

$$F(W_n)\frac{\dot{W}_n}{\Delta W} - F(W_{n-1})\frac{\dot{W}_{n-1}}{\Delta W} = -F(W_n)P_E(W_n)$$

$$\frac{d(F\dot{W})}{dW} = -F(W_n)P_E(W_n)$$

Fermi assumed that $\dot{W} = W/t_{acl}$ and that $P_E(W_n) = 1/t_{esc}$, which gives the solution:



Energy bins with width *ΔW*

$$F \propto W^{-\alpha}$$

Power Law!

$$\alpha = 1 + t_{acl}/t_{esc}$$

Fermi Acceleration

Fermi acceleration. Energization often involving reflection that can lead to an energetic tail in a particle distribution.

A common use of *Fermi acceleration* refers to the curvature drift (or reflection), which allows a particle to gain energy from an electric field normal to the curvature.

A reflection leads to electron velocity gain of V_{Alfven} so this process is weak in the magnetosphere.

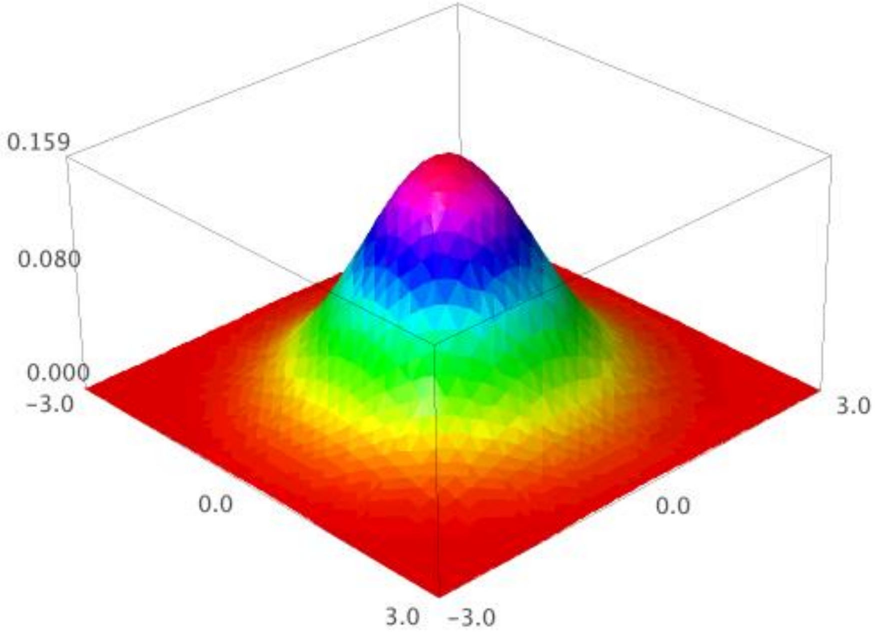
However, multiple reflections in a collapsing island could lead to significant energization.
Nice example: Drake, Shay, & Swisdak, 2008

Requirements for Power Law Tail

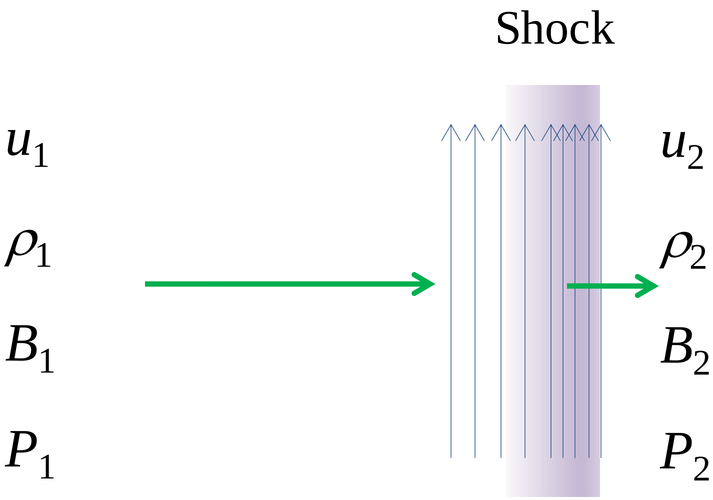
(1) Collisionless

(2) An energization mechanism that favors energetic particles.

Collisions often lead to a Gaussian (central limit theorem).



Diffusive Shock Acceleration



Shock

u_1

ρ_1

B_1

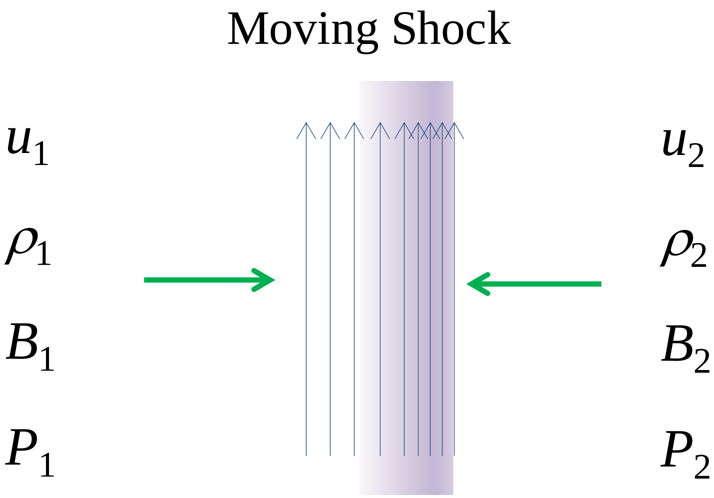
P_1

u_2

ρ_2

B_2

P_2



Moving Shock

u_1

ρ_1

B_1

P_1

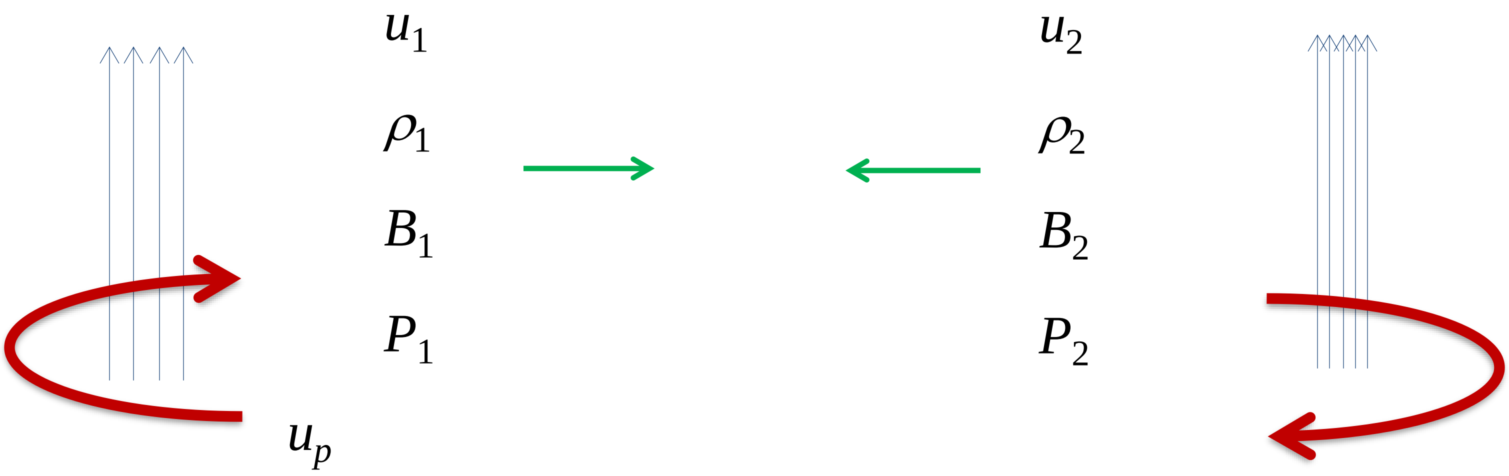
u_2

ρ_2

B_2

P_2

Diffusive Shock Acceleration



u_1

ρ_1

B_1

P_1

u_p

u_2

ρ_2

B_2

P_2

Because of the motion, each time the particle reflects it gains energy:

$u_p \rightarrow -(u_p + 2u_1)$

Because of the motion, each time the particle reflects it gains energy:

$u_p \rightarrow -(u_p + 2u_2)$

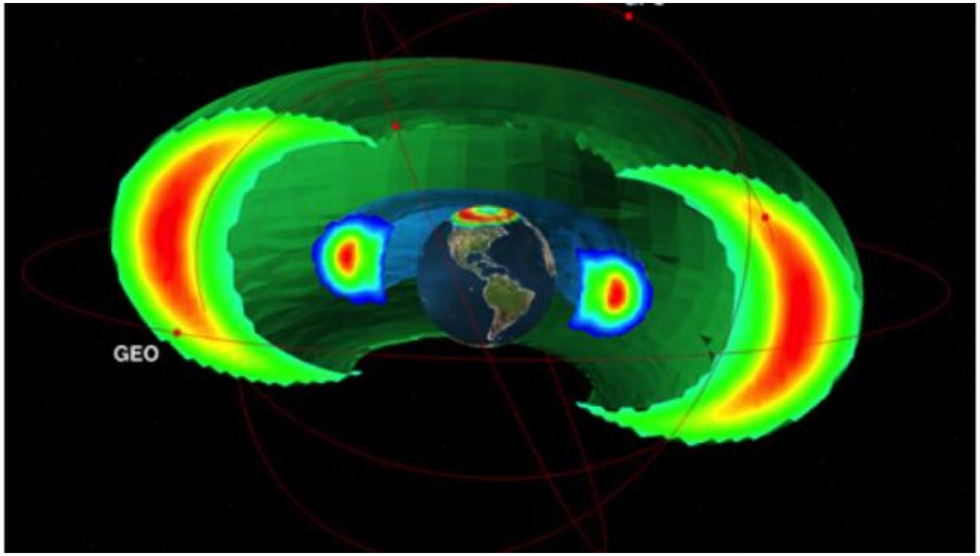
Energetic particles gain more energy (relativistic).

Betatron Acceleration

Suppose a particle with perpendicular energy of 10 keV is in a uniform 20 nT magnetic field. What will its perpendicular energy be if *B* is increases in time to 2000 nT? What happens to the parallel energy?

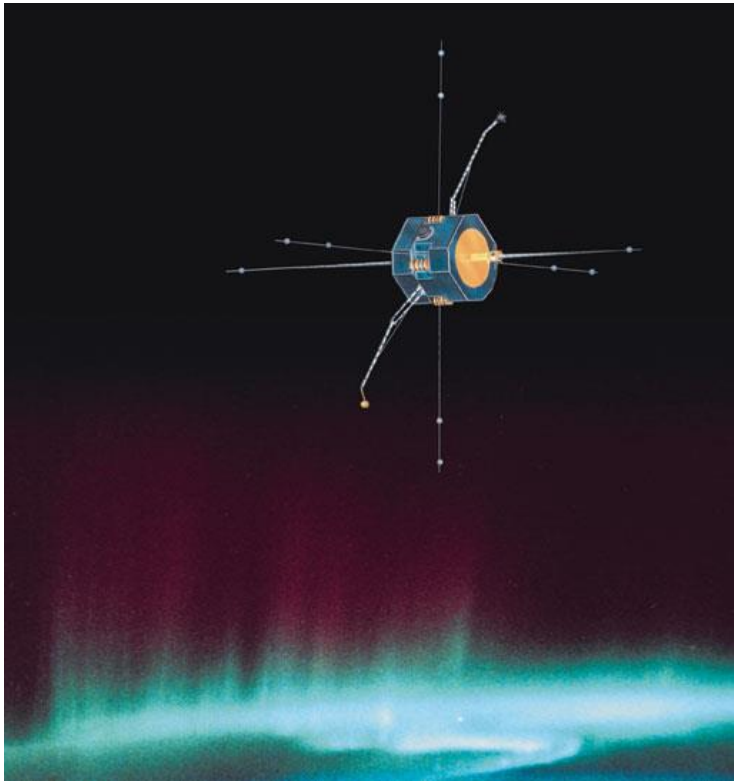
$$\mu \equiv \frac{W_\perp}{B}$$

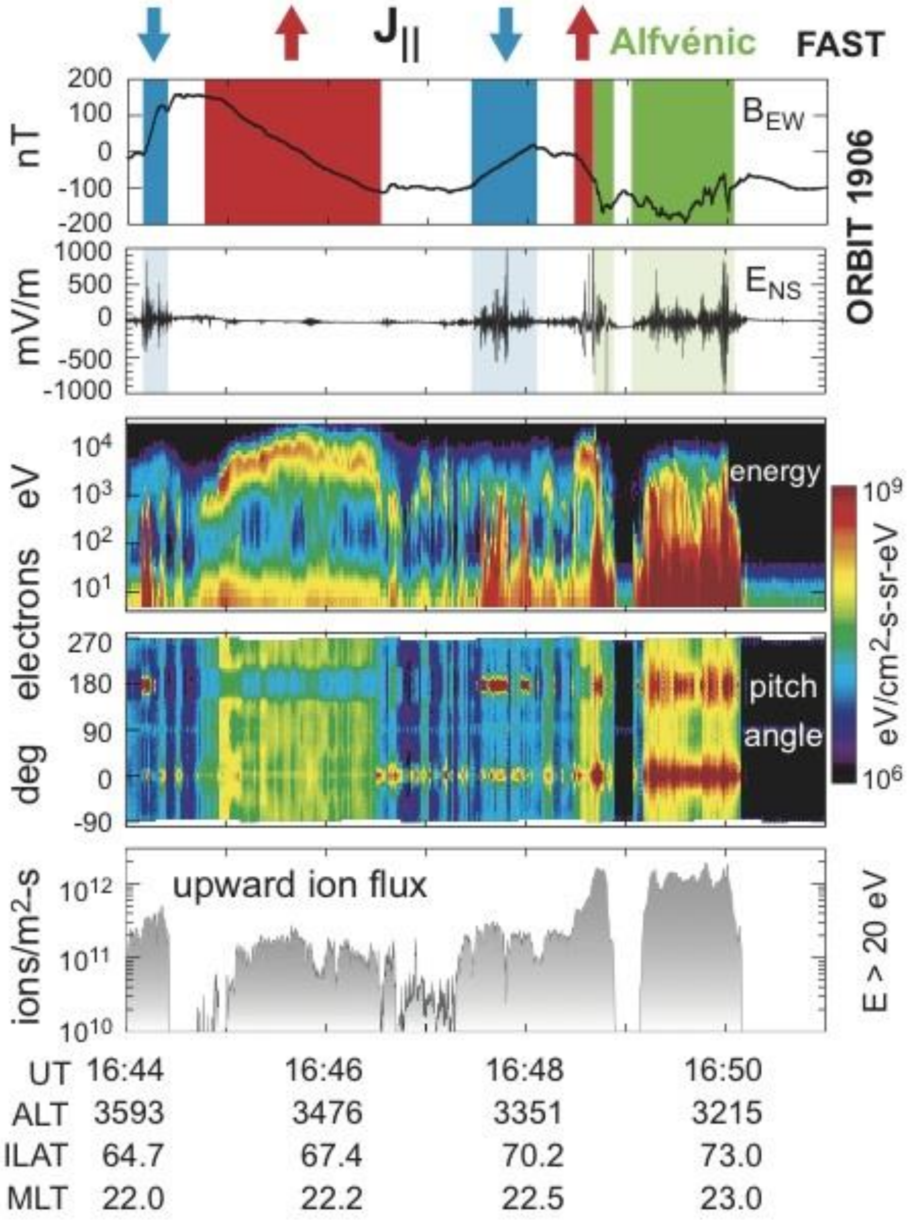
Since μ is conserved, $W_\perp$ increased to 1 MeV. Quite a bit of heating!
The parallel energy is unchanged.



Aurora and Particle Acceleration

Later Discovery: Three Particle Acceleration Processes





Stochastic Energization

To start, we assume that the $\boldsymbol{E}$ has a well-defined correlation time. An individual particle undergoes a series of uncorrelated impulses

$$\delta \boldsymbol{v} = \frac{e}{m}\boldsymbol{E}t_{corr}$$

that result in a "random walk" in v. During an impulse, the energy change is:

$$\delta \mathrm{W} = \frac{1}{2}m(\boldsymbol{v}_o + \delta\boldsymbol{v})^2 - \frac{1}{2}mv_o^2 = \frac{1}{2}m\left(\boldsymbol{v}_o \cdot \delta\boldsymbol{v} + \delta\boldsymbol{v}^{\mathbf{2}}\right)2$$

where $\boldsymbol{v}_o$ is the momentum prior to an impulse. In 1st order heating, $\boldsymbol{v}_o$ and $\delta\boldsymbol{v}$ may have a correlation. In other words, $\langle \boldsymbol{v}_o \cdot \delta\boldsymbol{v} \rangle \neq 0$.

Stochastic Energization

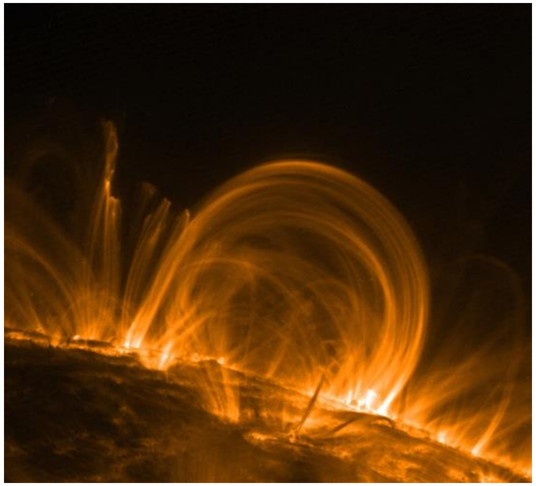
Here, we look at random turbulence mainly perpendicular to $\boldsymbol{B}$, so we assume $\langle \boldsymbol{v}_o \cdot \delta \boldsymbol{v} \rangle = 0$. In 2nd order heating, the impulse has a random direction and sign compared to the initial velocity, so the net energy change after N impulses is:

$$\sum_N \delta \mathrm{W} \approx \frac{1}{2} m \delta \boldsymbol{v}^{\mathbf{2}} = \frac{e^2 t_{corr}^2 N \langle |\boldsymbol{E}^2| \rangle}{\mathbf{2} m}$$

Assuming $\delta \boldsymbol{v} \ll \boldsymbol{v}_o$, the resulting heating rate after a time period of $N\, t_{corr}$ and is then:

$$\frac{\delta \mathrm{W}}{\Delta t} \approx \frac{e^2 t_{corr}^2 N \langle |\boldsymbol{E}^2| \rangle}{\mathbf{2} m N t_{corr}}$$

$$\dot{\mathrm{W}} \approx \frac{e^2 t_{corr} \langle |\boldsymbol{E}^2| \rangle}{\mathbf{2} m}$$



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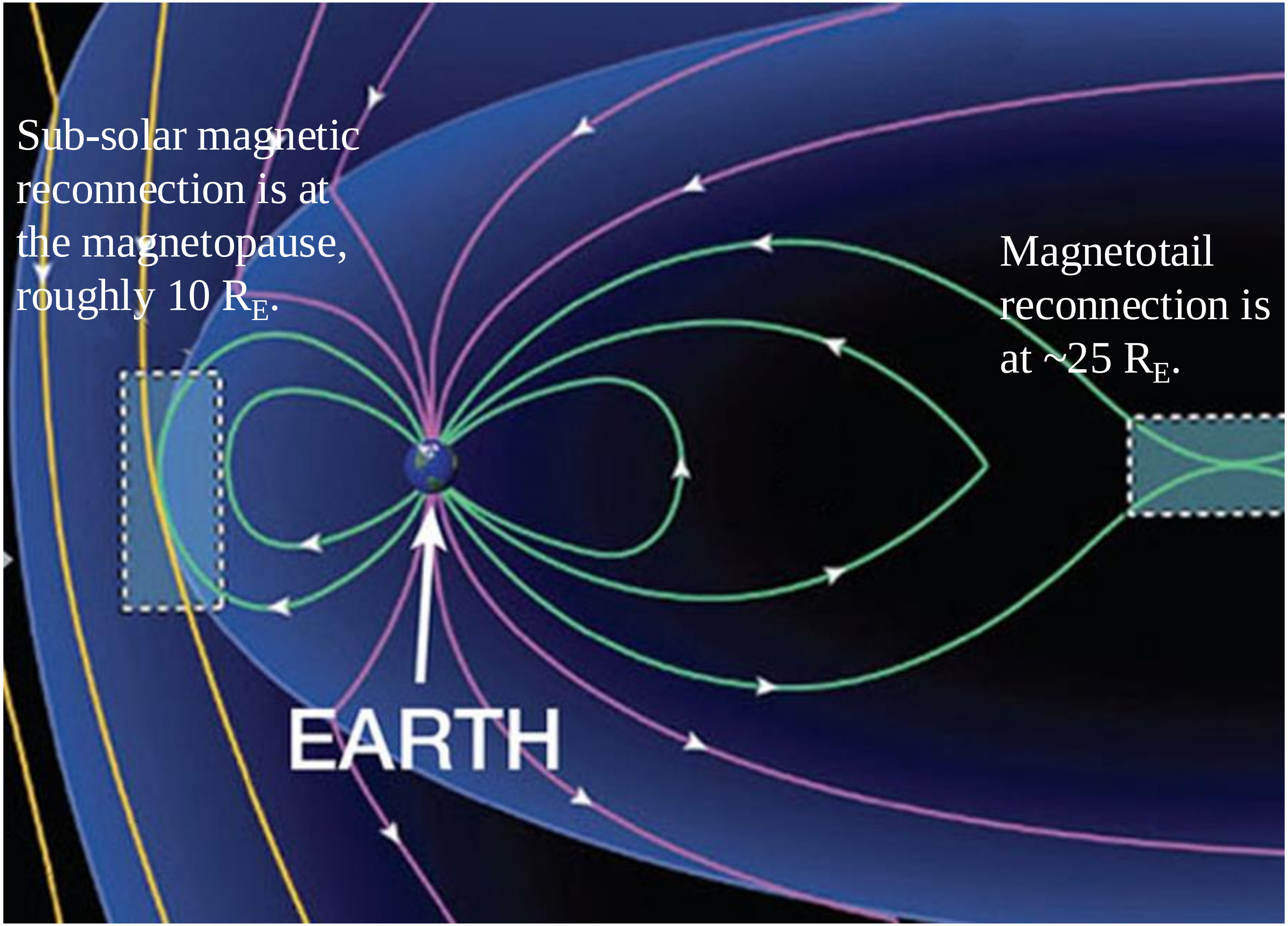
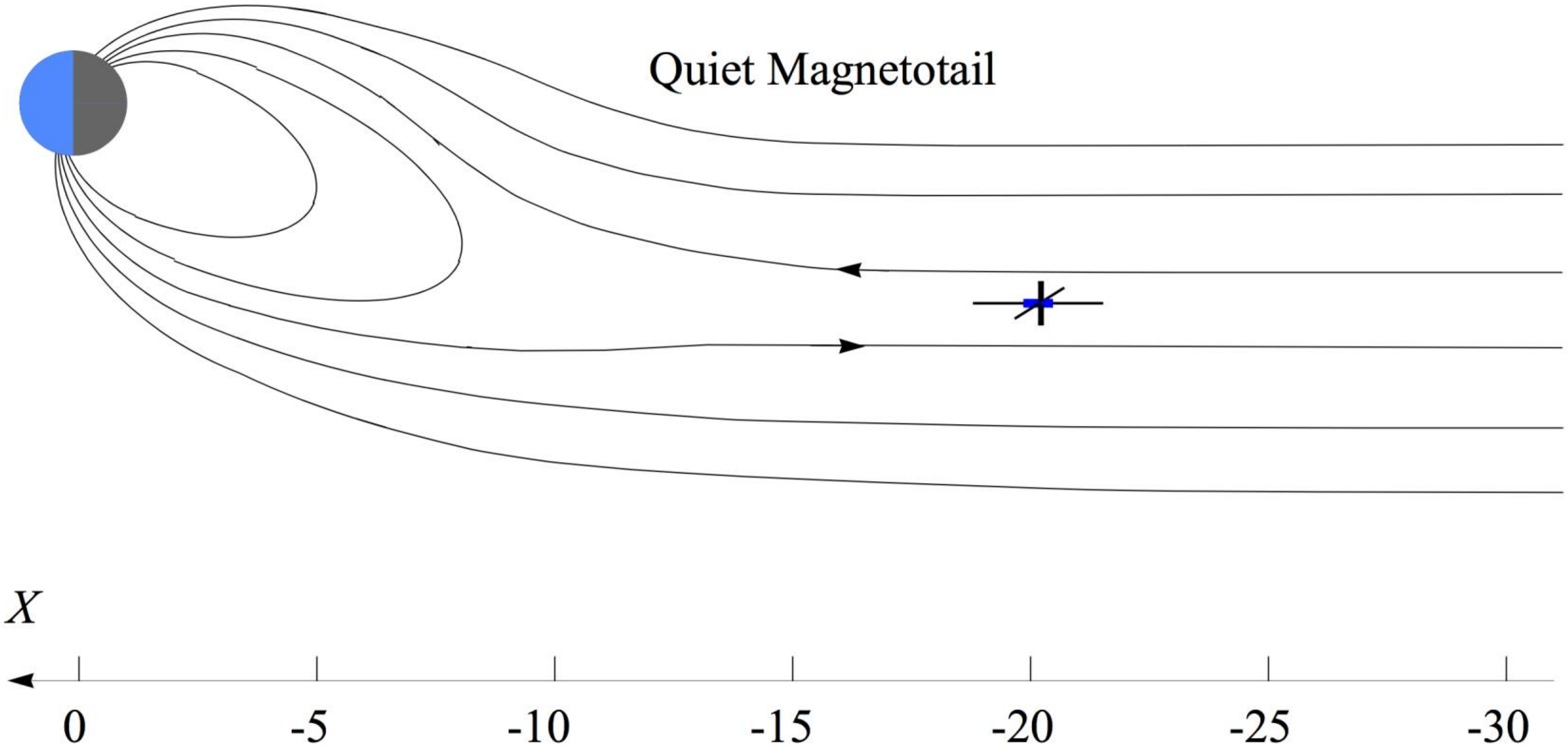
Magnetotail Reconnection



Sub-solar magnetic reconnection is at the magnetopause, roughly 10 R_E.

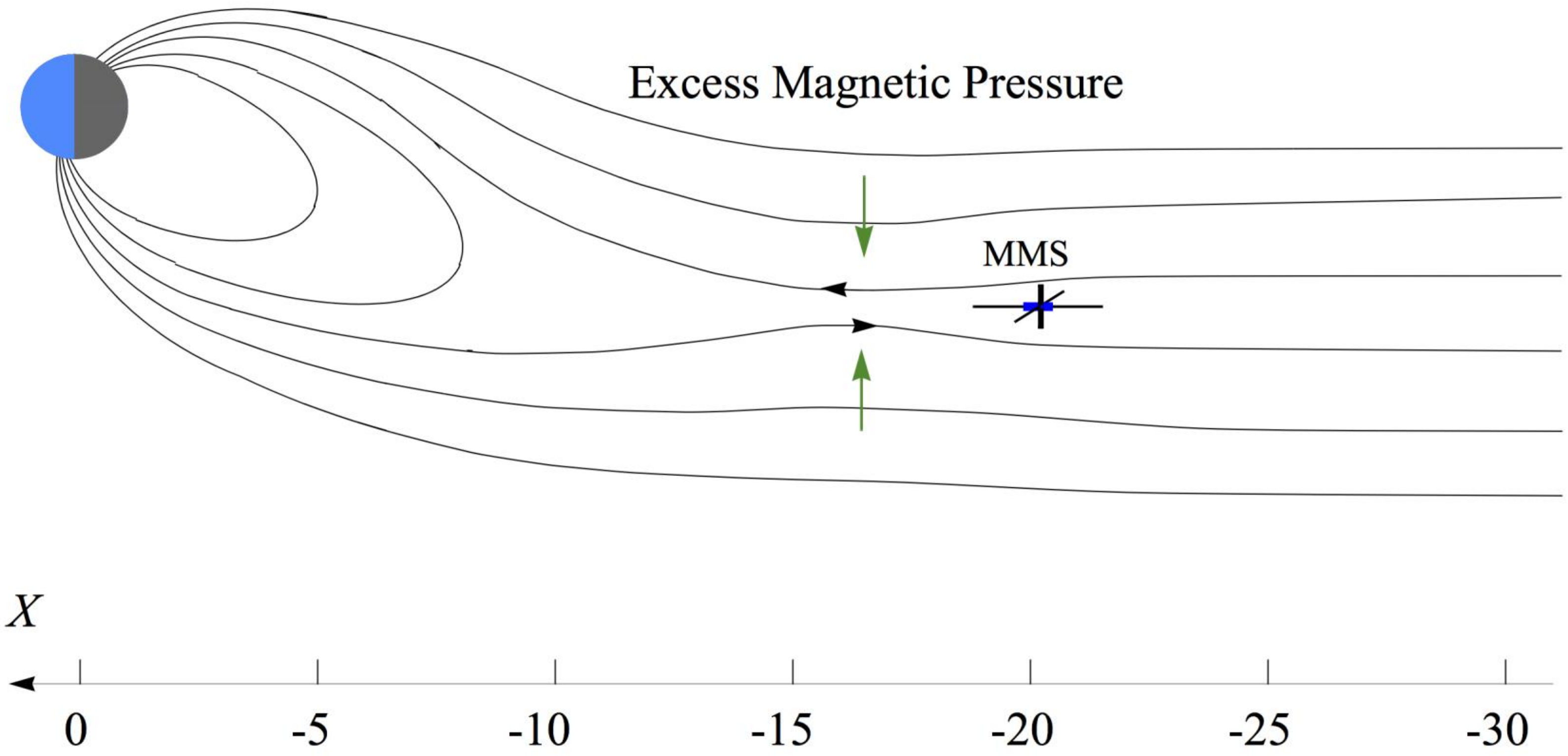
Magnetotail reconnection is at ~25 R_E.

Magnetotail Reconnection



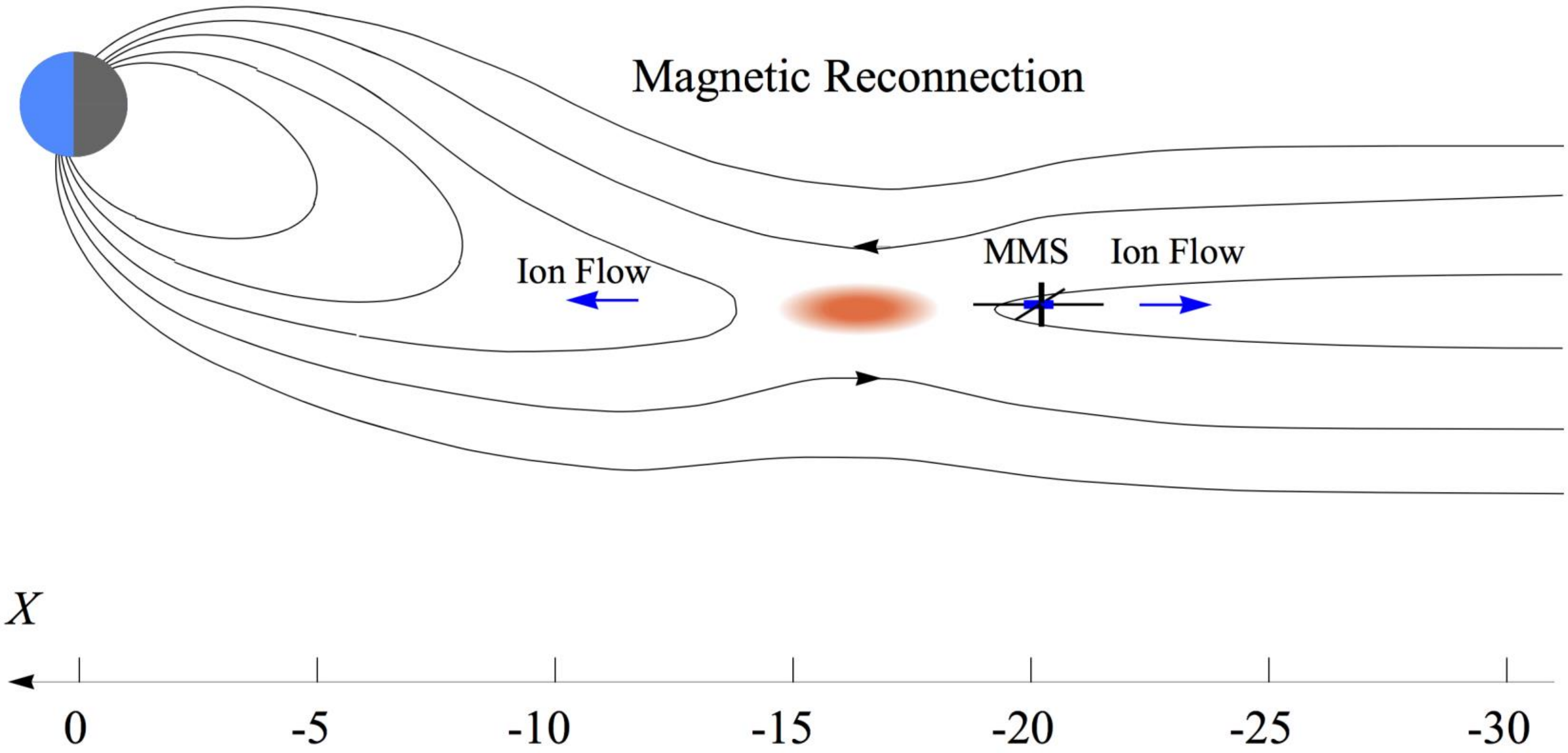
MMS is at -20 R_E.

Magnetotail Reconnection



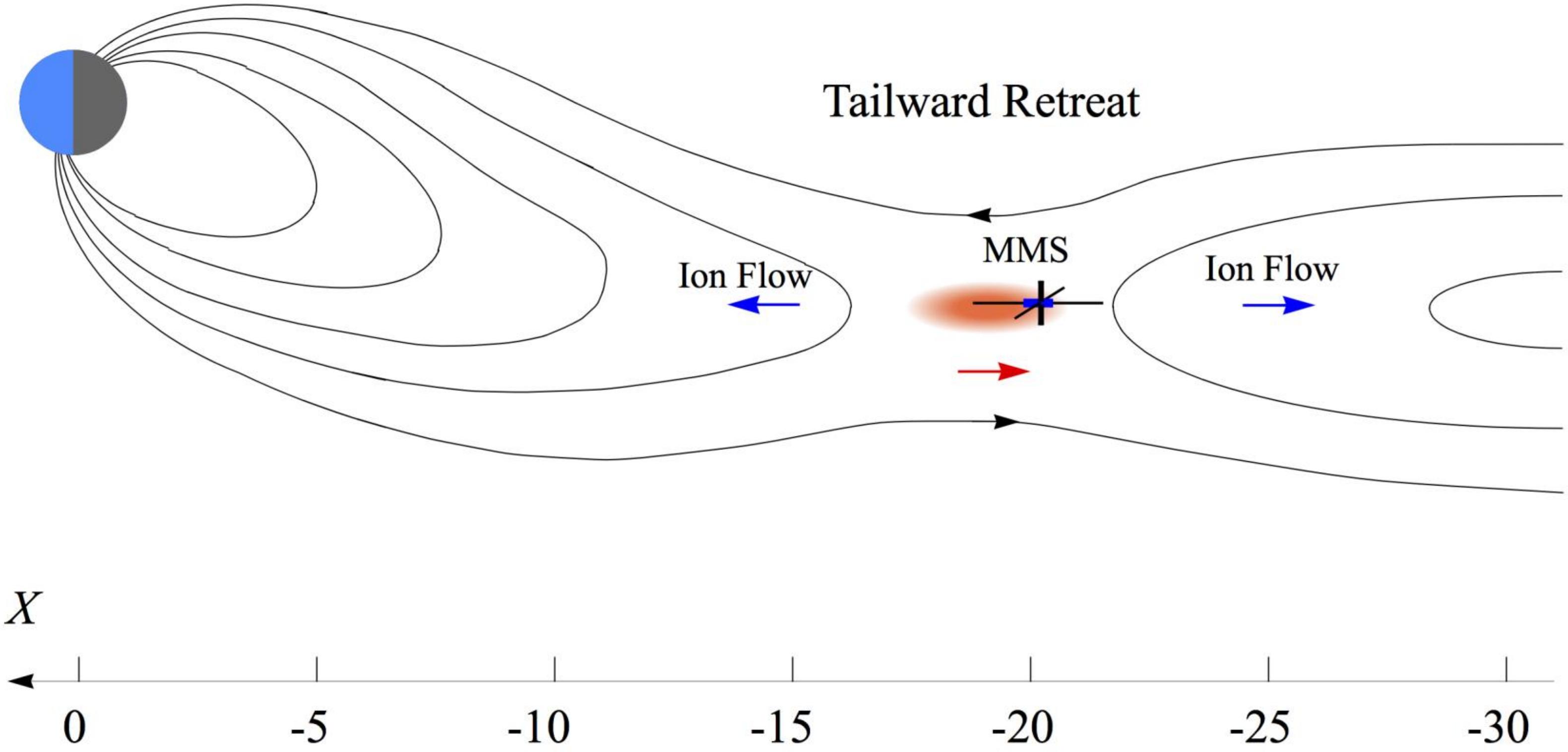
Excess magnetic pressure can cause the current sheet to thin.

Magnetotail Reconnection



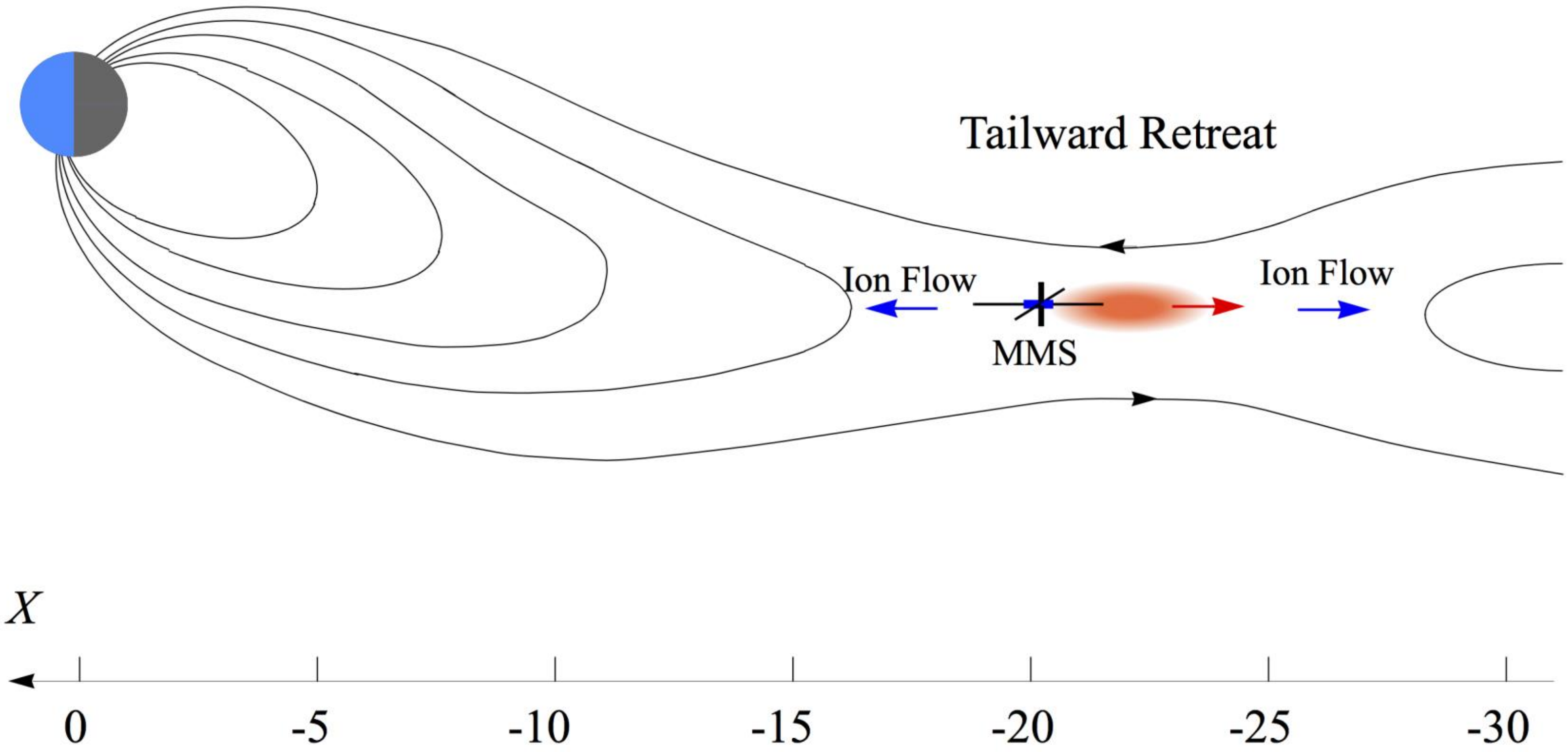
Magnetic reconnection can initiate at ~ -15 R_E.
MMS observes a tailward flow typically several 100’s of km/s.

Magnetotail Reconnection

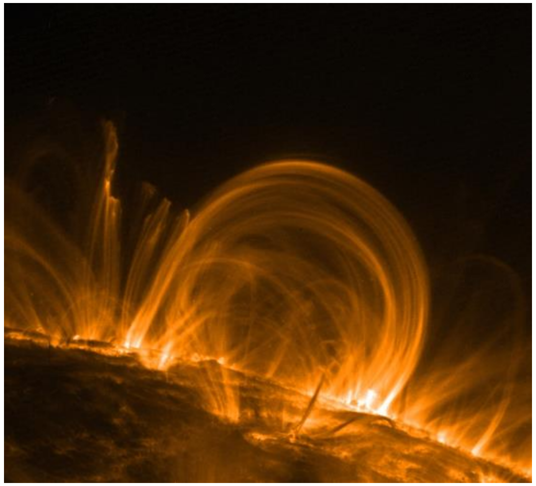


The magnetic reconnection region often retreats tailward. MMS can observe the magnetic reconnection.
(1) $\boldsymbol{B} = 0$. (2) V_x goes negative to positive. (3) B_z goes negative to positive.

Magnetotail Reconnection



After the magnetic reconnection region retreats, MMS observes a earthward flow and B_z positive. “Flow reversal” is an excellent indicator.



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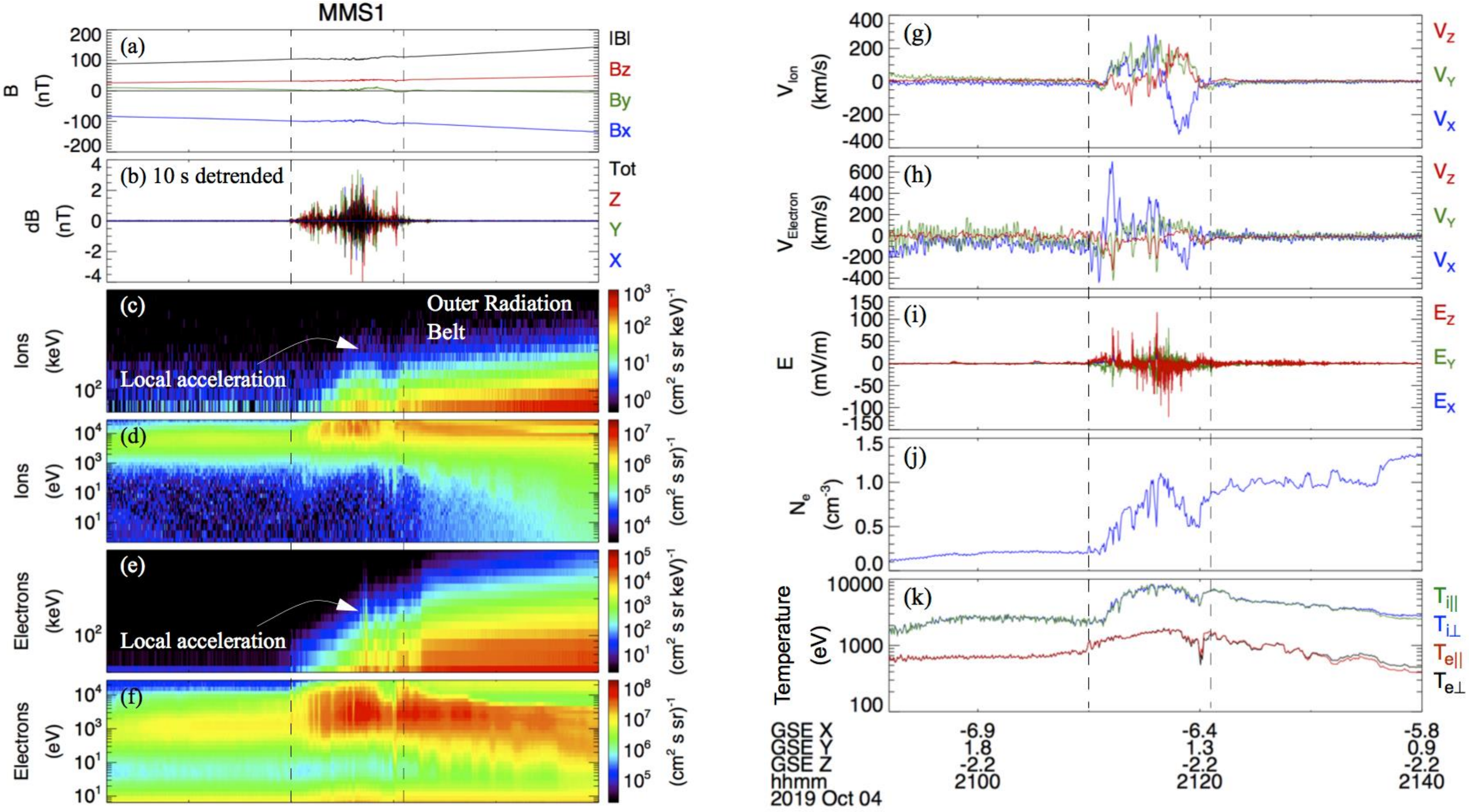
Magnetotail Reconnection

Electron Acceleration

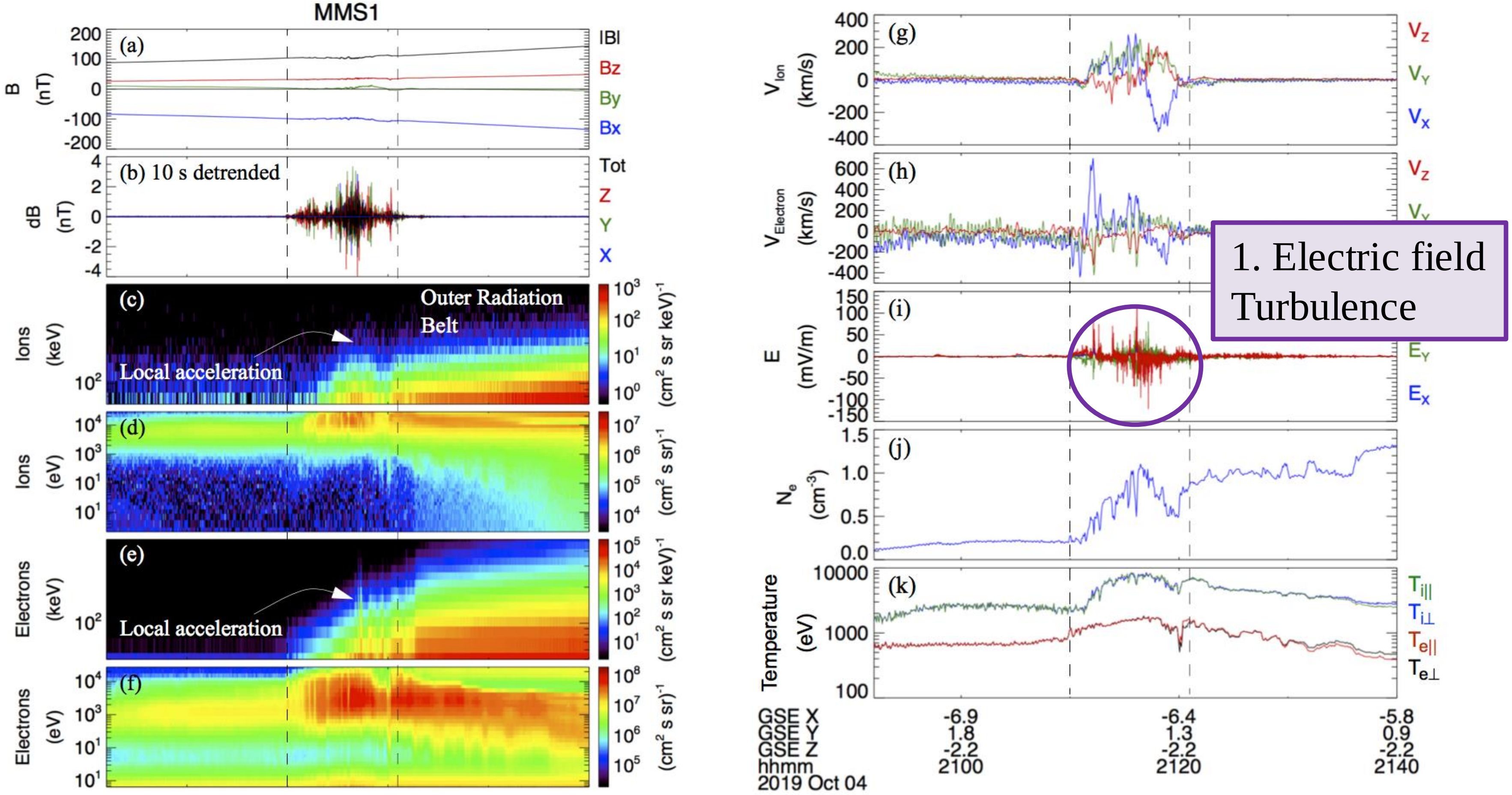
- Electron acceleration can be dominated by stochastic energization in strong turbulence, when present.
- Electron acceleration is a natural consequence of turbulence: higher-energy particles are first in line receiving dissipated energy.
- Electron acceleration in turbulence can be greatly amplified by trapping in a magnetic depletion.

Electron Acceleration: Near-Earth Event



Ergun, Usanova, et al., 2022; Usanova & Ergun, 2022

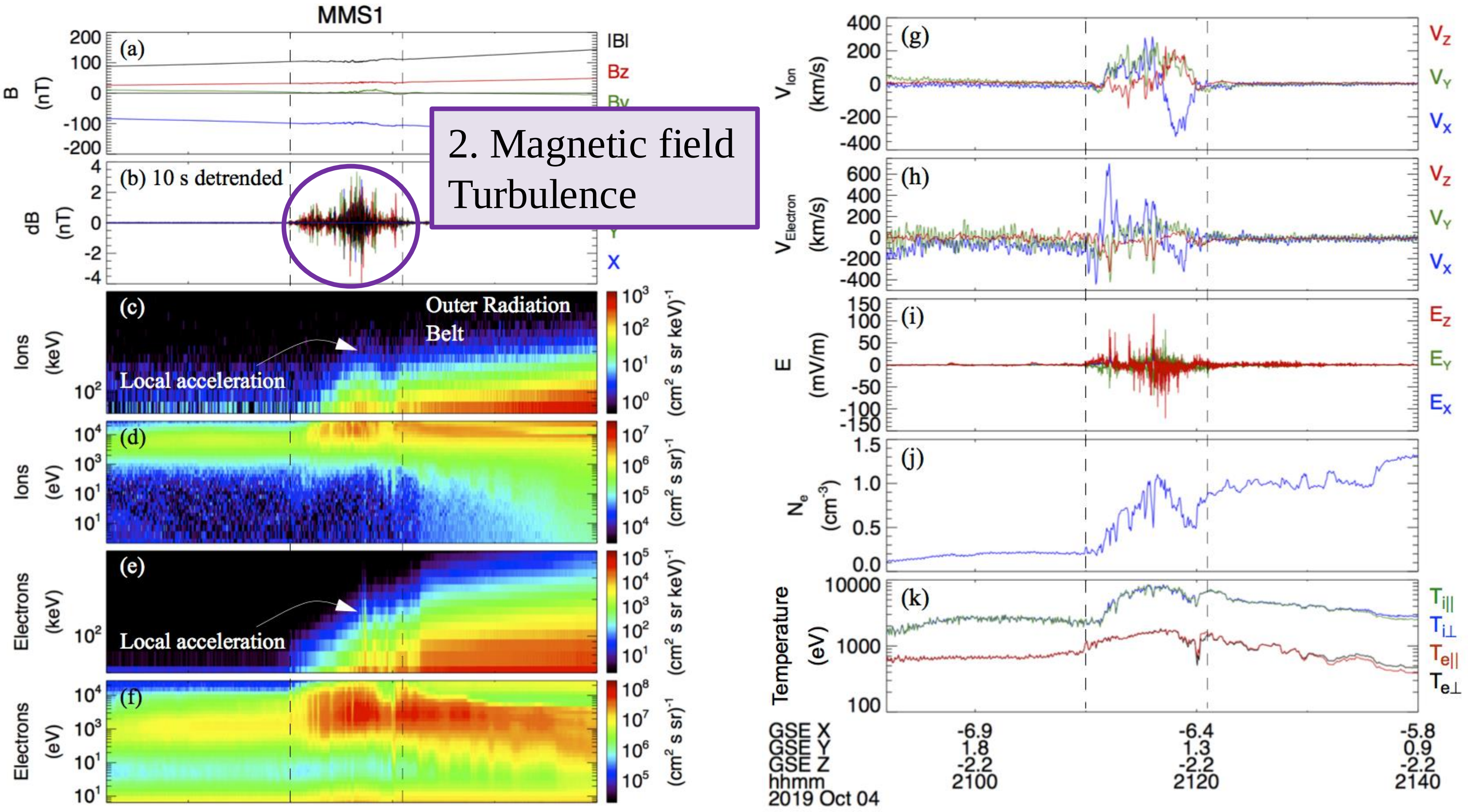
Electron Acceleration: Near-Earth Event



1. Electric field Turbulence

Ergun, Usanova, et al., 2022; Usanova & Ergun, 2022

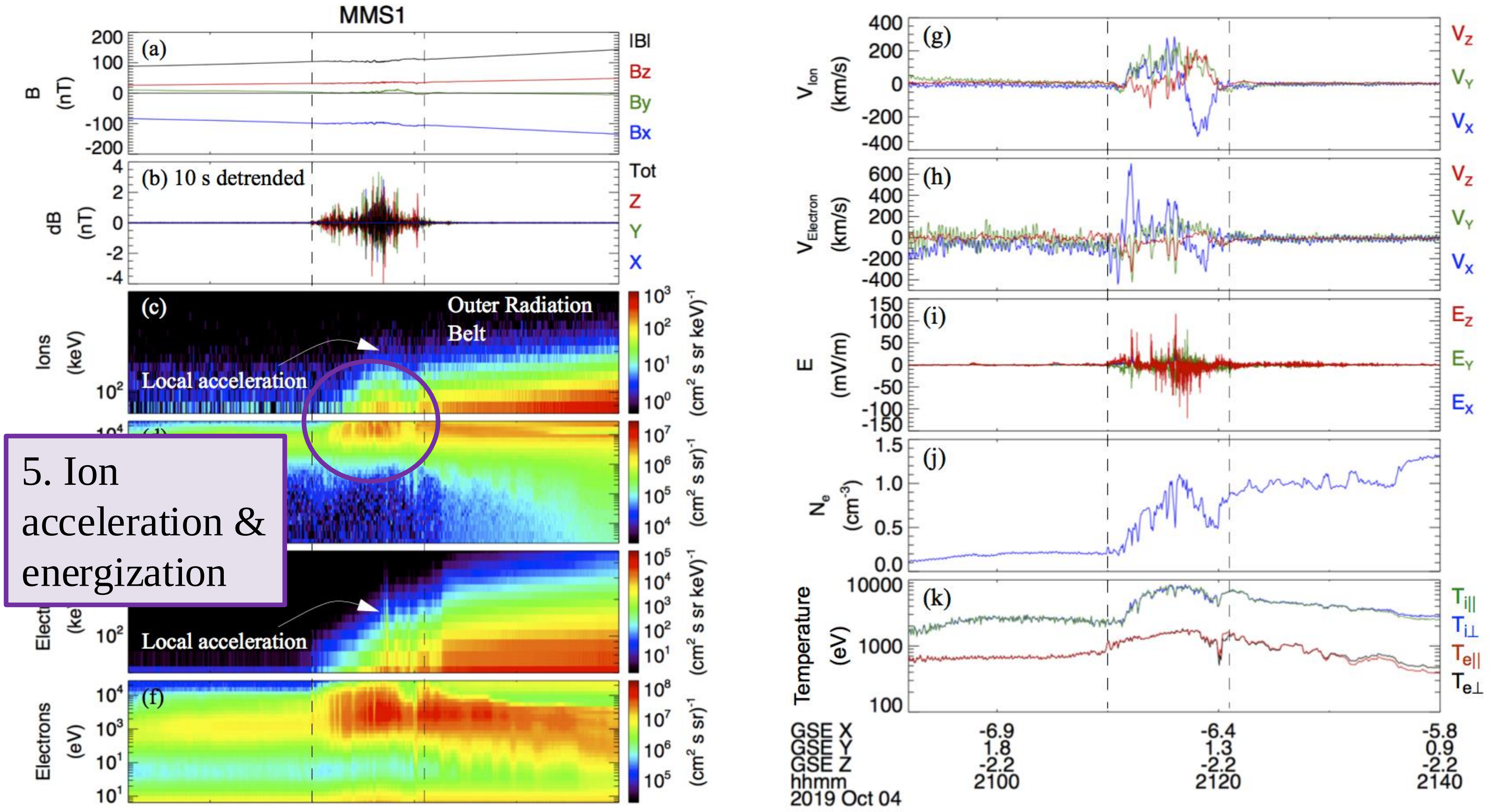
Electron Acceleration: Near-Earth Event



2. Magnetic field Turbulence

Ergun, Usanova, et al., 2022; Usanova & Ergun, 2022

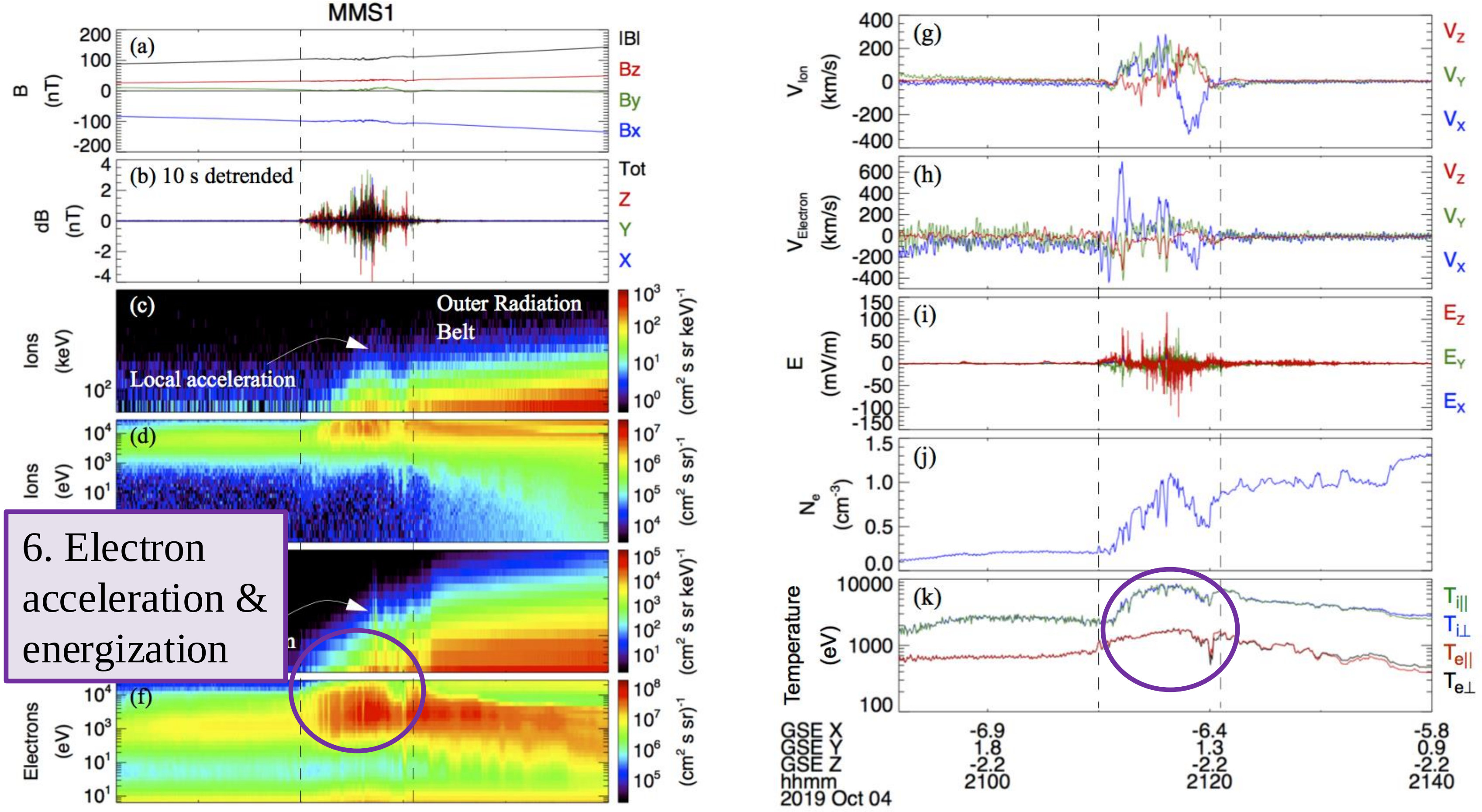
Electron Acceleration: Near-Earth Event



5. Ion acceleration & energization

Ergun, Usanova, et al., 2022; Usanova & Ergun, 2022

Electron Acceleration: Near-Earth Event



6. Electron acceleration & energization

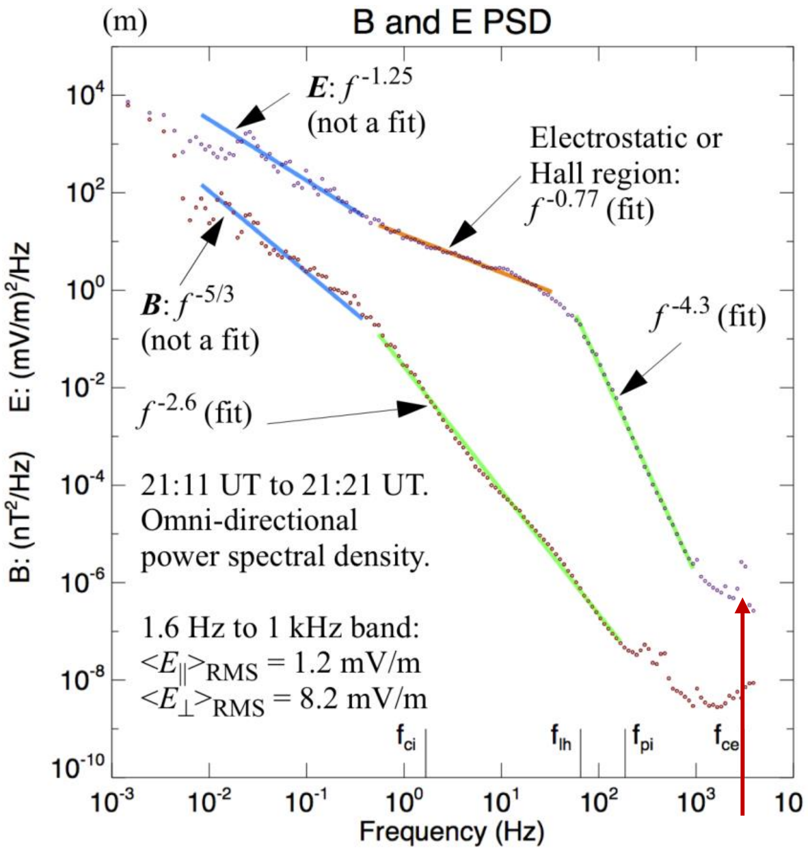
Electron Acceleration from Turbulence?

(1) The ***B*** spectra is consistent with turbulence.

(2) The ***E*** spectra has the characteristic electrostatic “shoulder”.

(3) Perpendicular energization requires circumvention of the first adiabatic invariant ($\mu = p_\perp^2/2\gamma m_o B$).

(4) However, there is little power at $f \geq f_{ce}$, which, at first glance, suggests that perpendicular electron energization should be negligible.

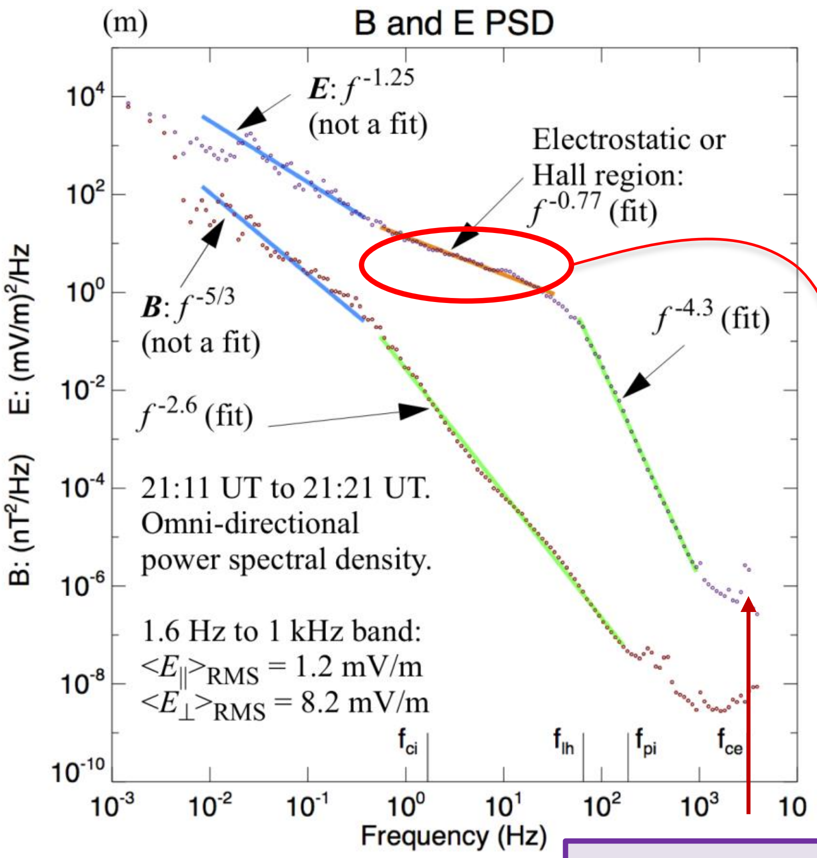


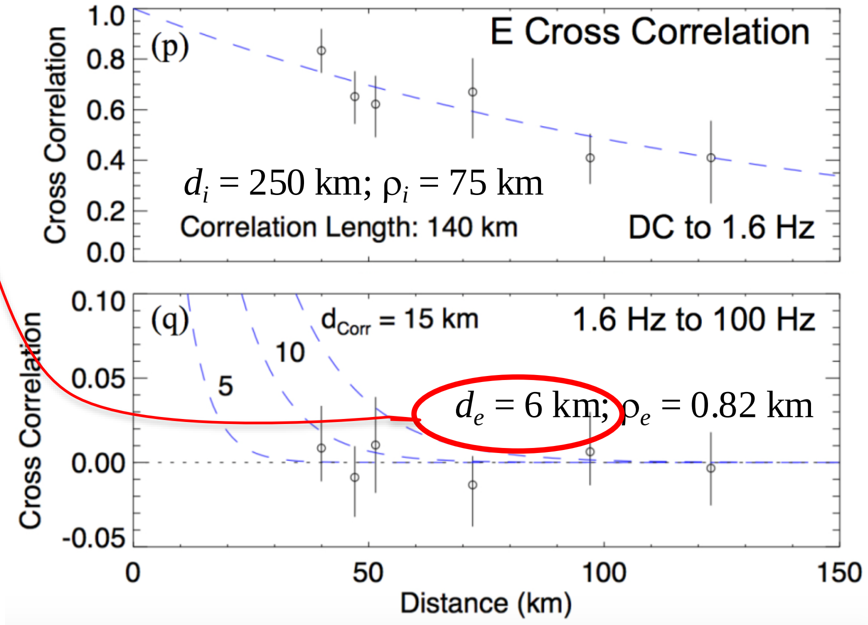
Little power at f_{ce}.

$$\mu \equiv \frac{W_\perp}{B}$$

Electron Acceleration from Turbulence?

If $f < f_{ci}$, $\boldsymbol{E}$ and $\boldsymbol{B}$ show correlation distance between d_i and ρ_i.





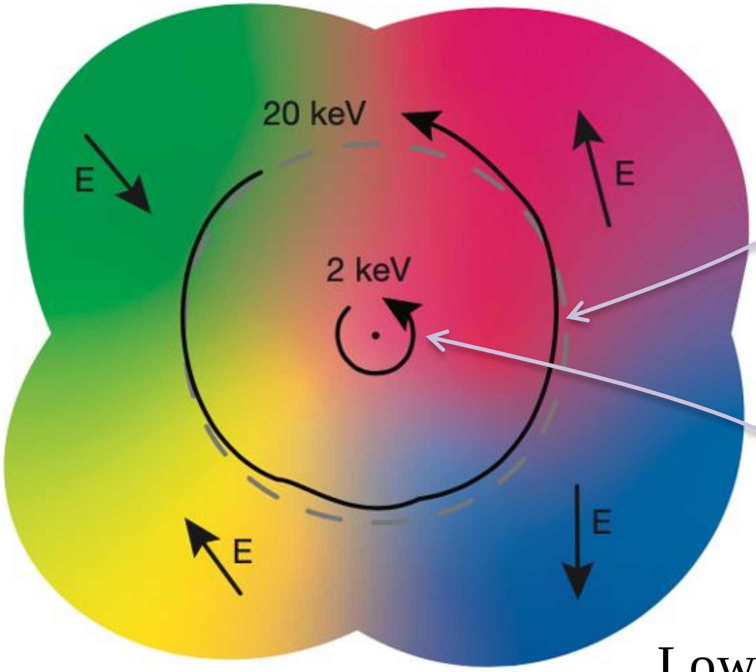
Little power at f_{ce}.

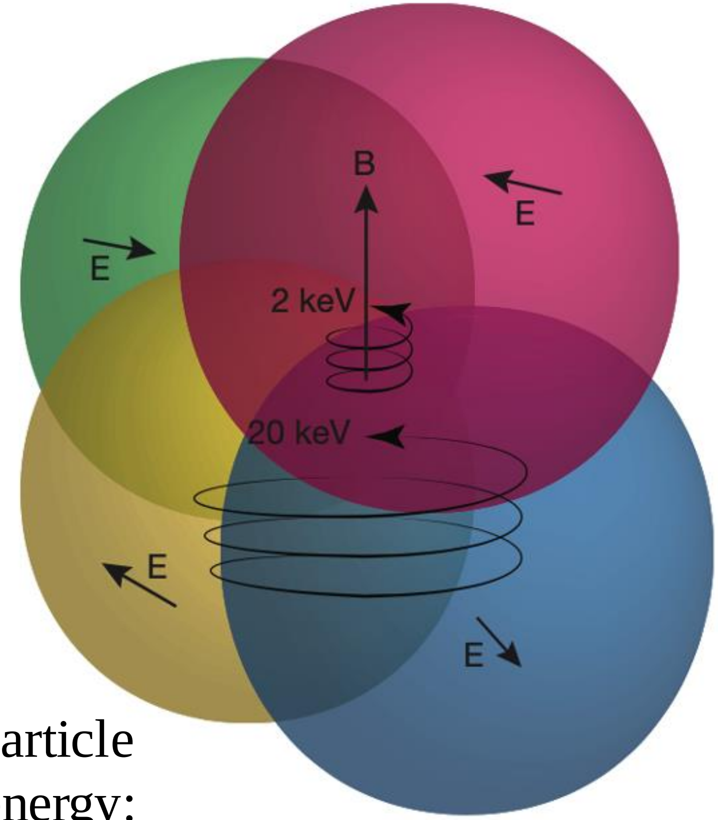
If $f > f_{ci}$, $\boldsymbol{E}$ and $\boldsymbol{B}$ show correlation distance consistent with d_e and ρ_e.

Electron Acceleration from Turbulence

"The rich get richer."

High-energy particles are energized: they experience changes in ***E*** faster than the gyro-period.

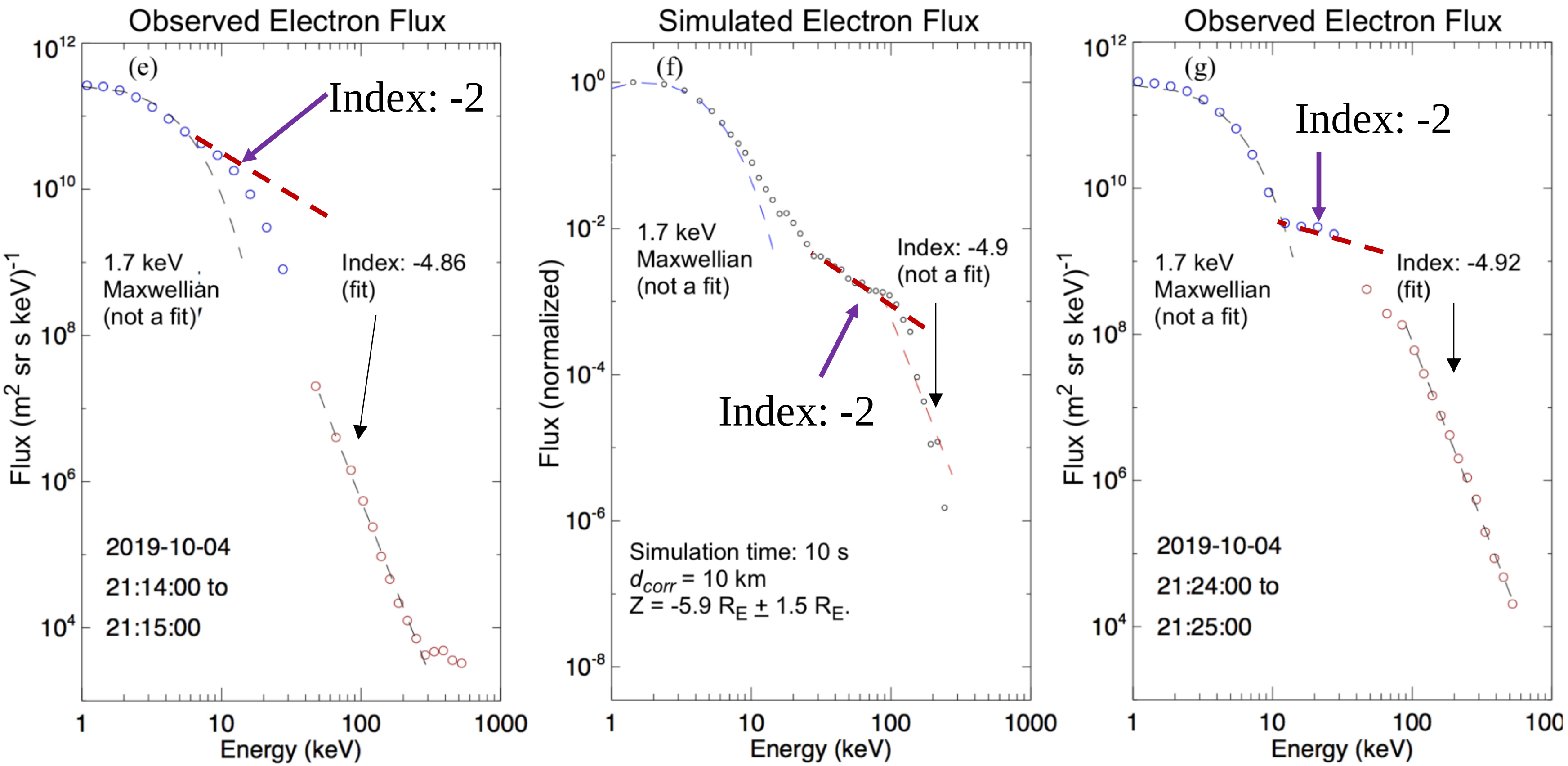




Low-energy particle receive little energy: they experience a near-constant ***E***.

Credit: Usanova

Verified by Test-Particle Simulations



Ergun, Usanova, et al., 2022; Usanova & Ergun, 2022

Electron Energization in Turbulence

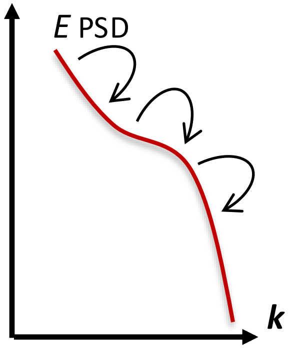
A. Electron acceleration is a natural consequence of turbulence: higher-energy particles are first in line receiving dissipated energy.

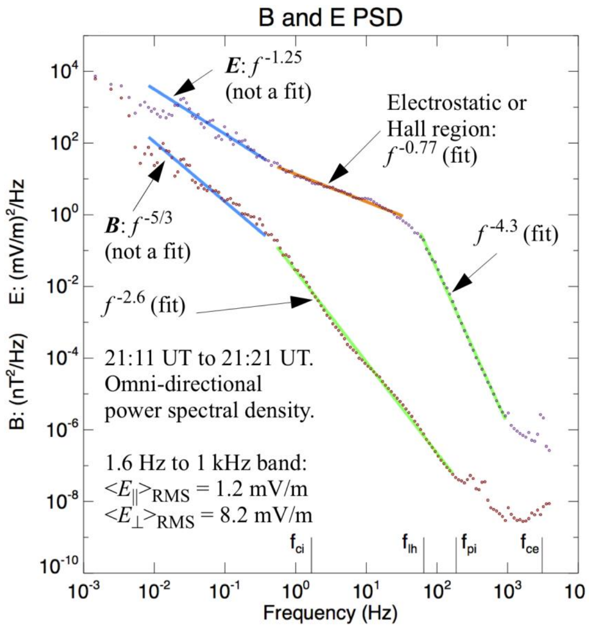
B. Stochastic electron acceleration can be greatly amplified by trapping in a magnetic depletion.

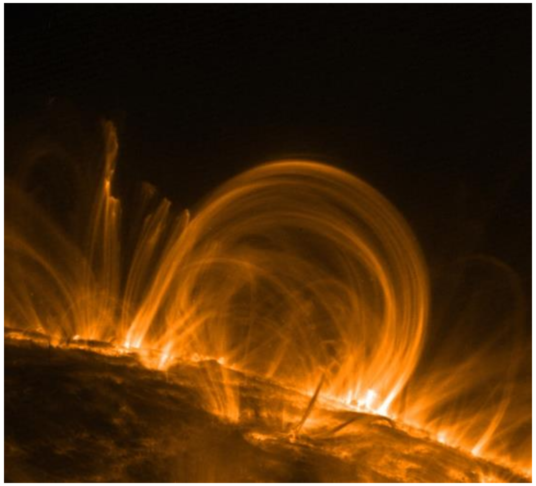
Energization that favors a higher-energy particles can lead to acceleration and the development of an energetic tail.

(1) Turbulence, by its very nature, cascades energy in driven systems to smaller scales at which dissipation takes place.

(2) Small-scale structures/waves in electric field (***E***) stochastically energize higher-energy electrons.







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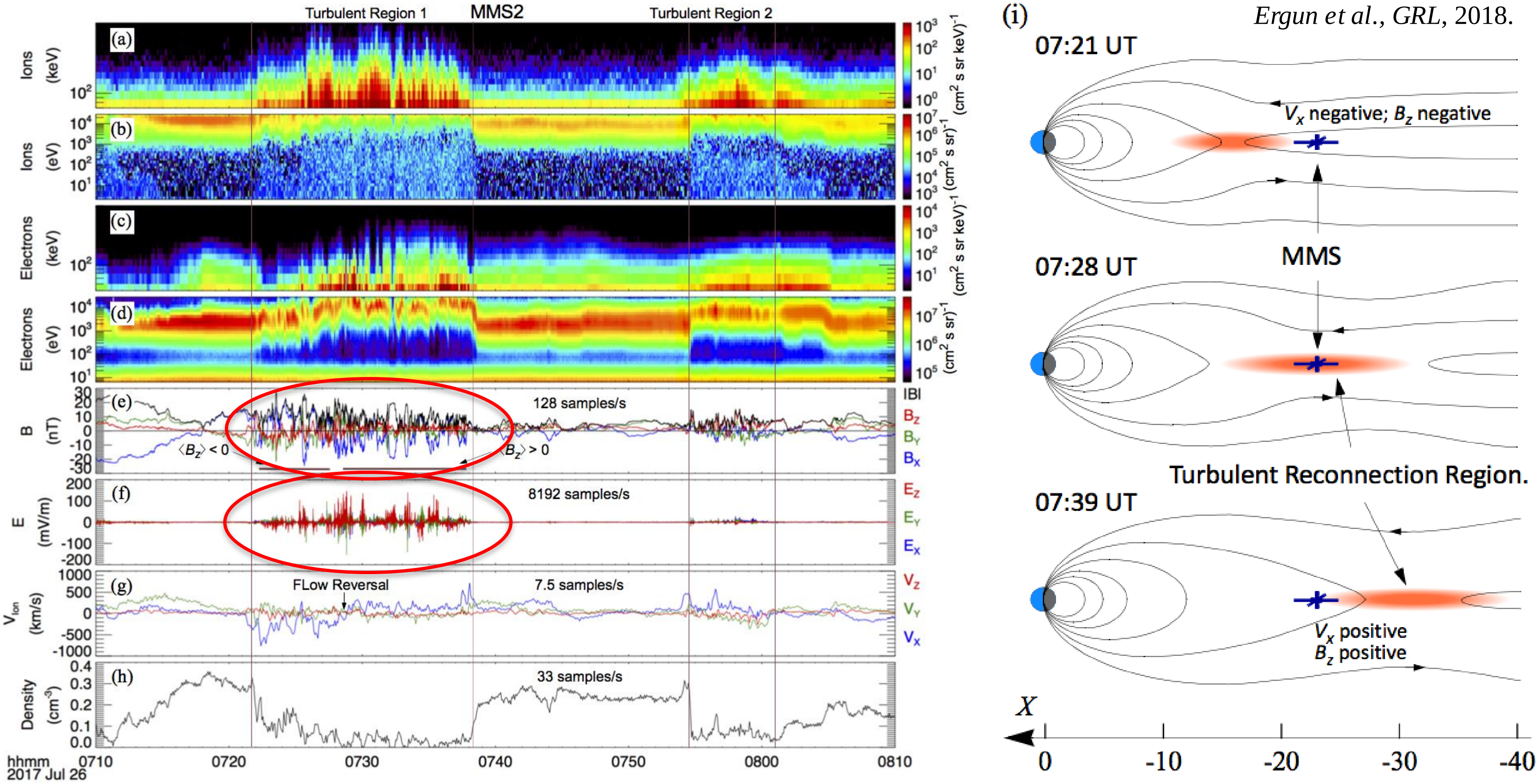
Ion Acceleration in Turbulent Reconnection

Ion Acceleration

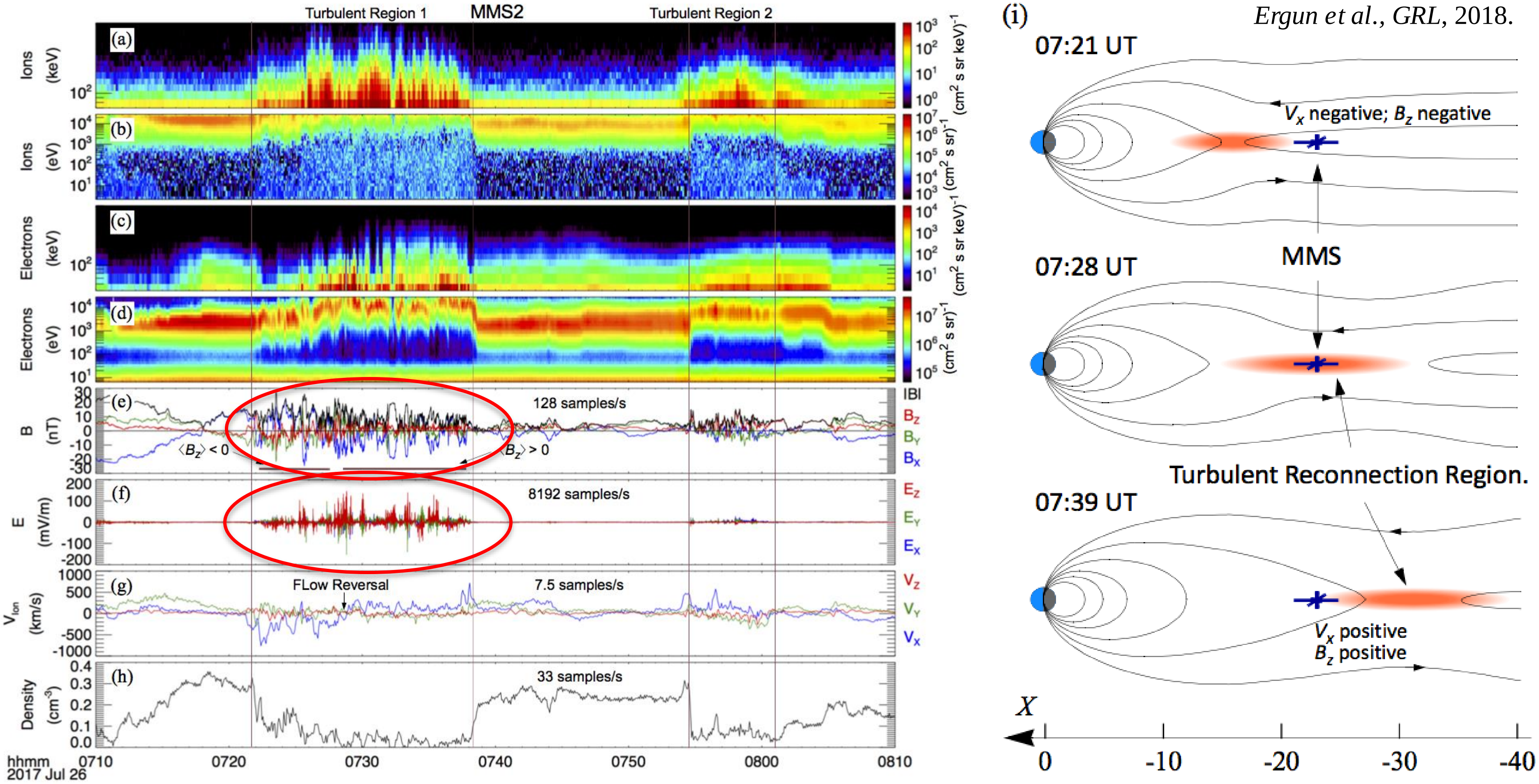
- Ion energization comes from both stochastic energization in strong turbulence and by Speiser motion along the current sheet.
- The energetic tail is primarily from stochastic energization.
- The power-law index is controlled by the energization process and the escape process.
- A significant fraction of escaping fluxes in the magnetotail exit in the $+Y$ direction (along the X-line).

Turbulent Magnetic Reconnection in the Magnetotail



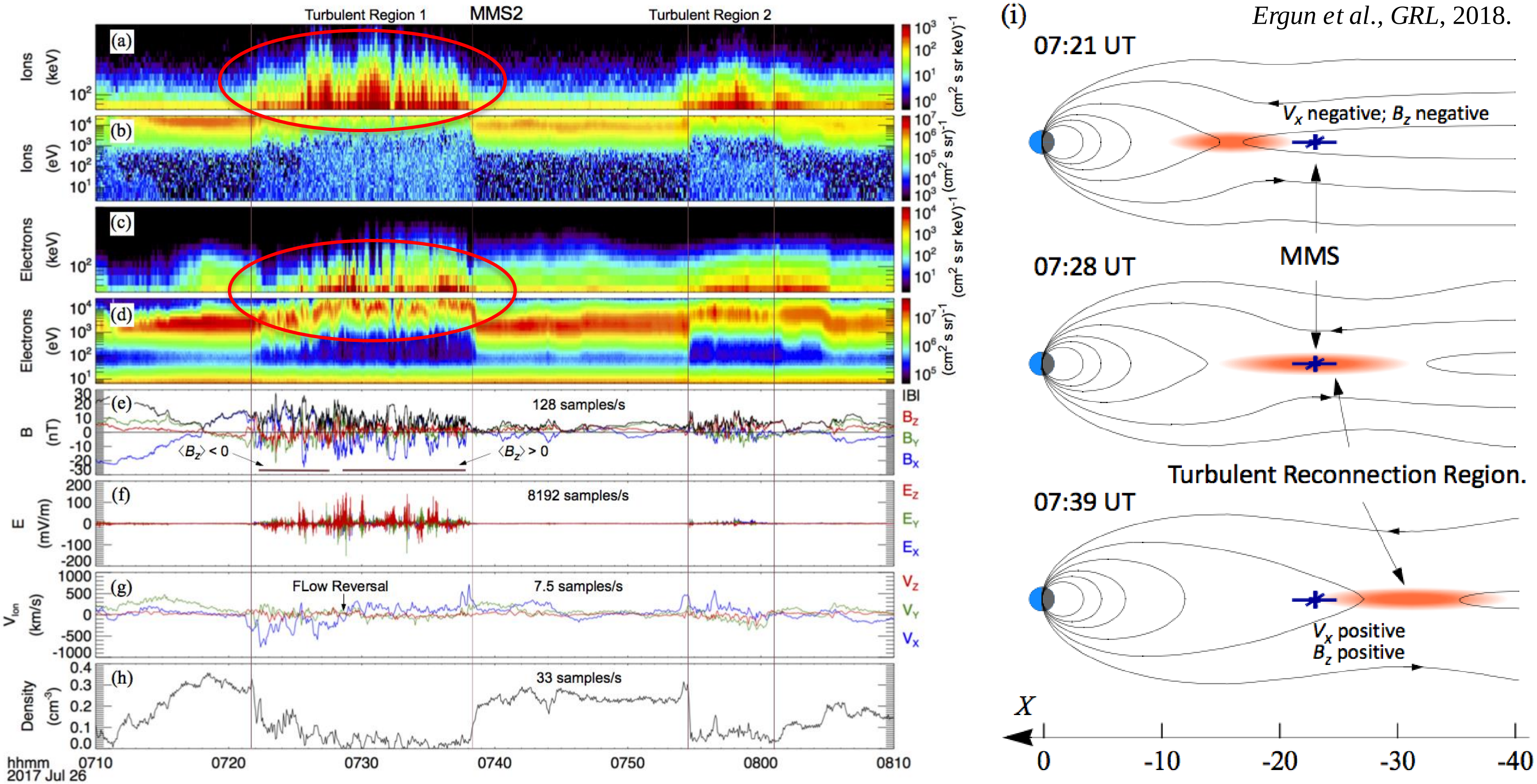
Ergun et al., GRL, 2018.

Turbulent Magnetic Reconnection in the Magnetotail



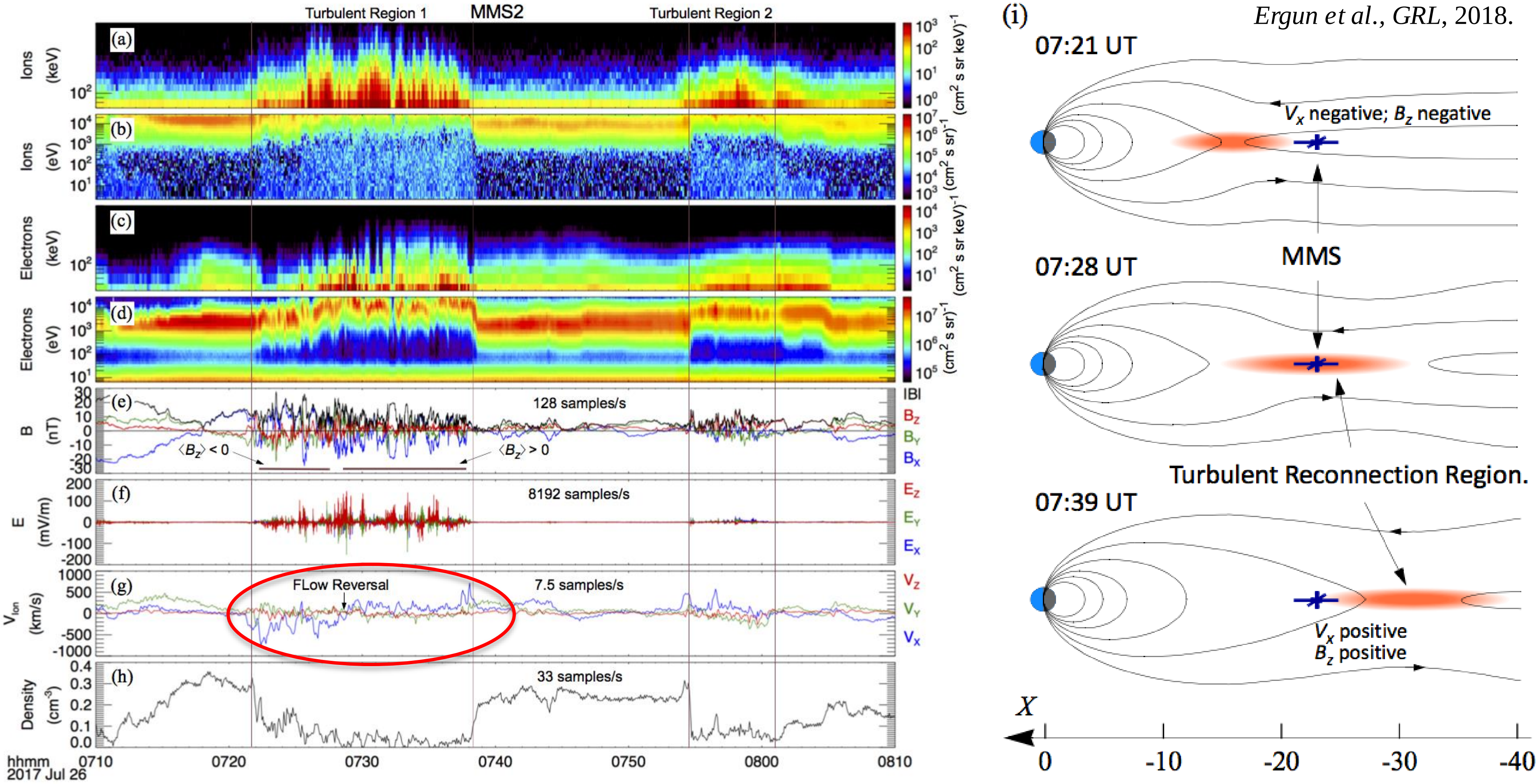
Ergun et al., *GRL*, 2018.

Turbulent Magnetic Reconnection in the Magnetotail



Ergun et al., *GRL*, 2018.

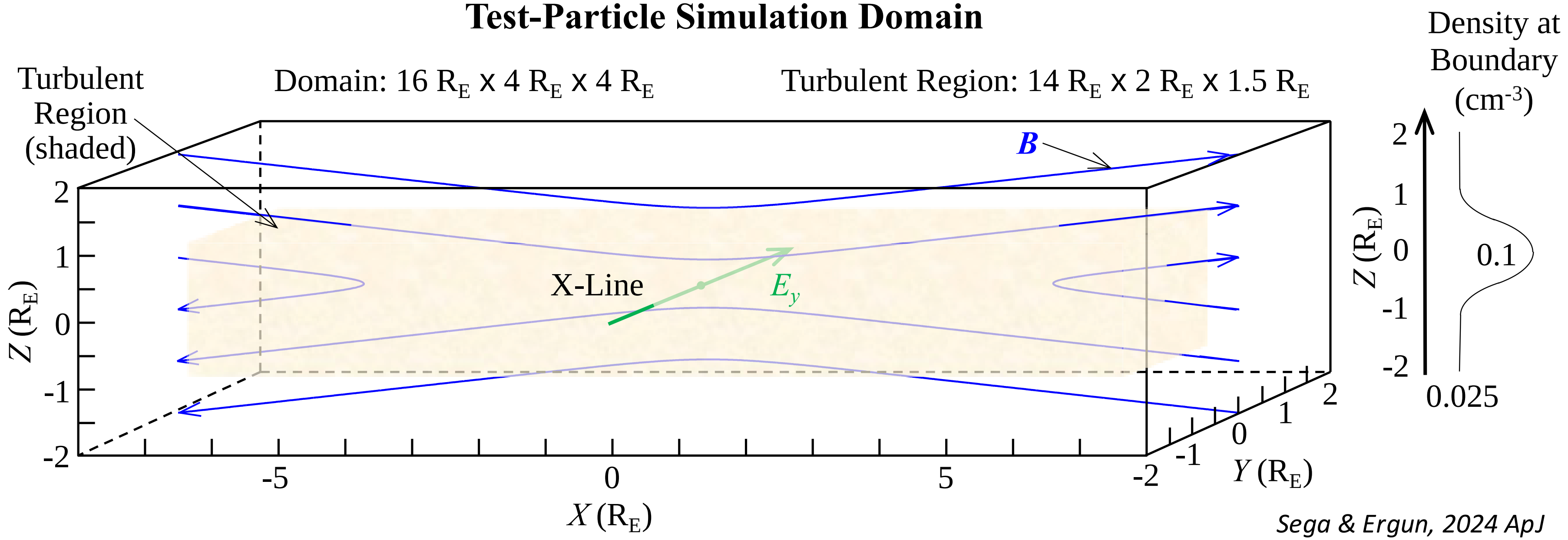
Turbulent Magnetic Reconnection in the Magnetotail



Ergun et al., GRL, 2018.

Test-Particle Simulation

Test-Particle Simulation Domain

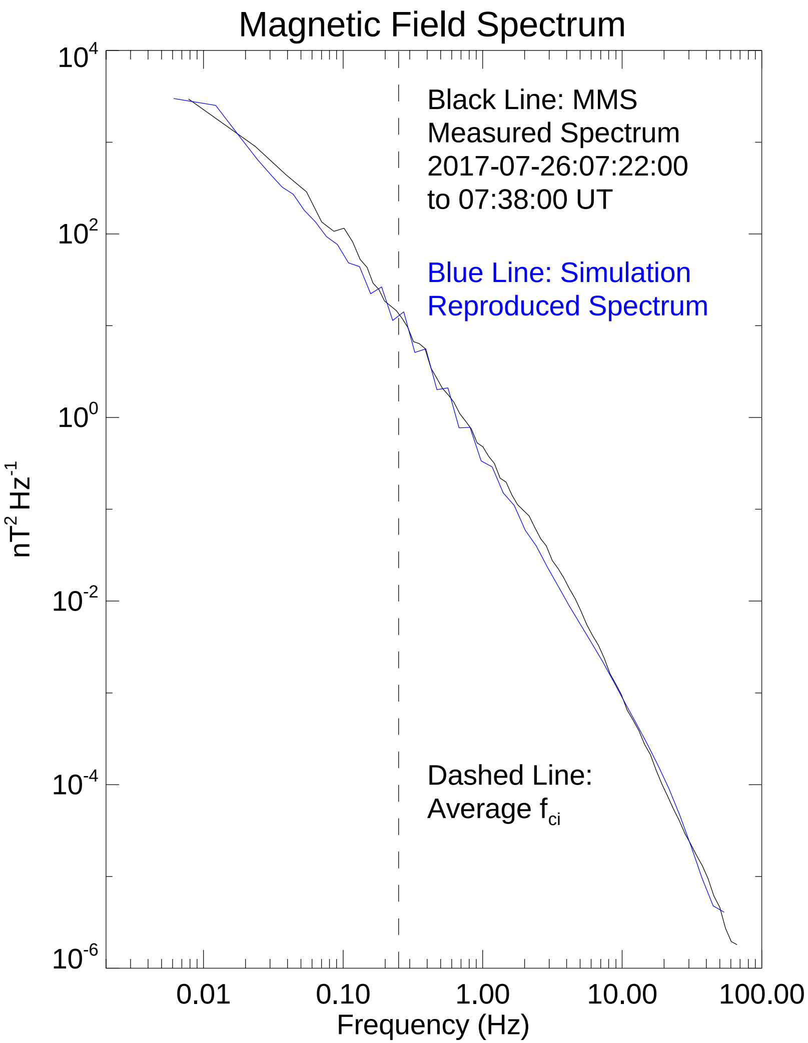


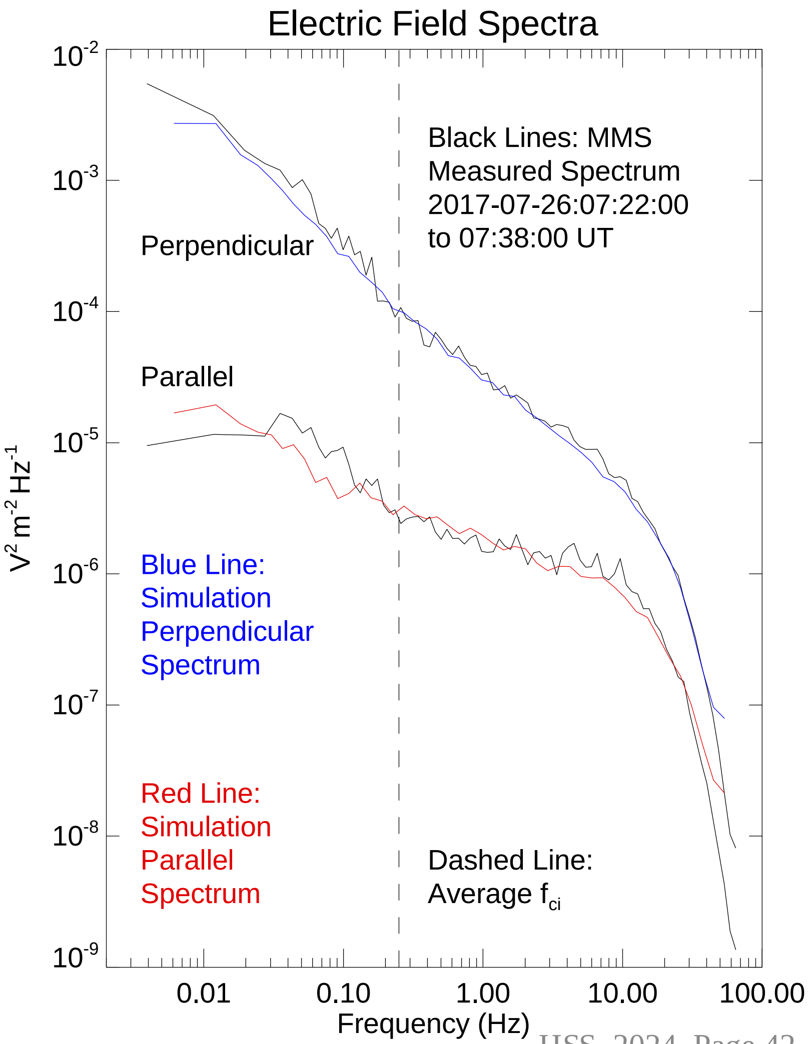
Sega & Ergun, 2024 ApJ

The test-particle domain is 3D, has fully open boundaries, and boundary conditions are based on measured densities & temperatures.

B and *E* Are Derived from Observations

The imposed δ***B*** and δ***E*** fluctuations are based ***on measured signals reproducing the observed amplitudes, spectra, speeds, coherence times, and coherence scales***.

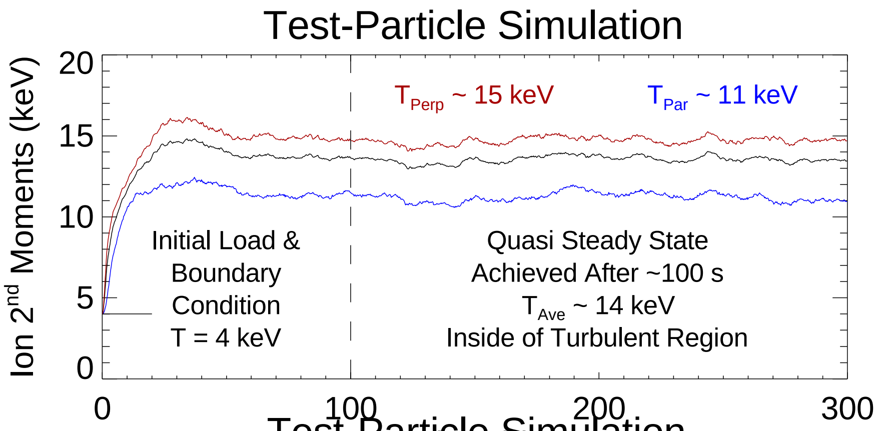




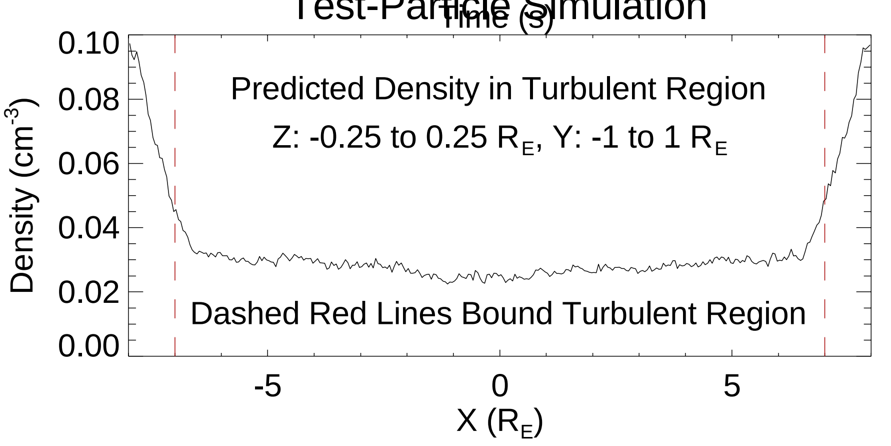
Setting the Length of the X-line

An x-line length of ~2 R_E yields a quantitatively close match between simulation and observations in:

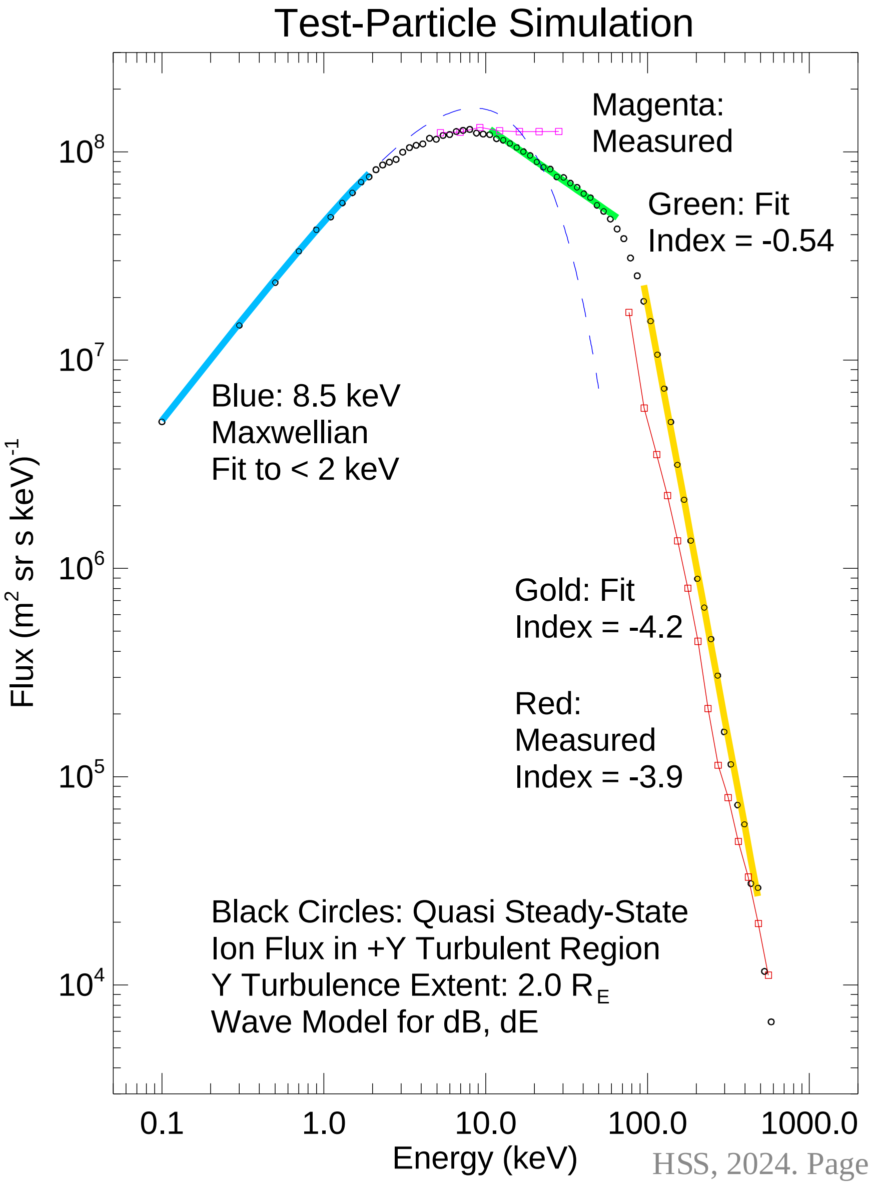
- Ion distribution
- Ion temperature
- Density profile



Test-Particle Simulation



Test-Particle Simulation

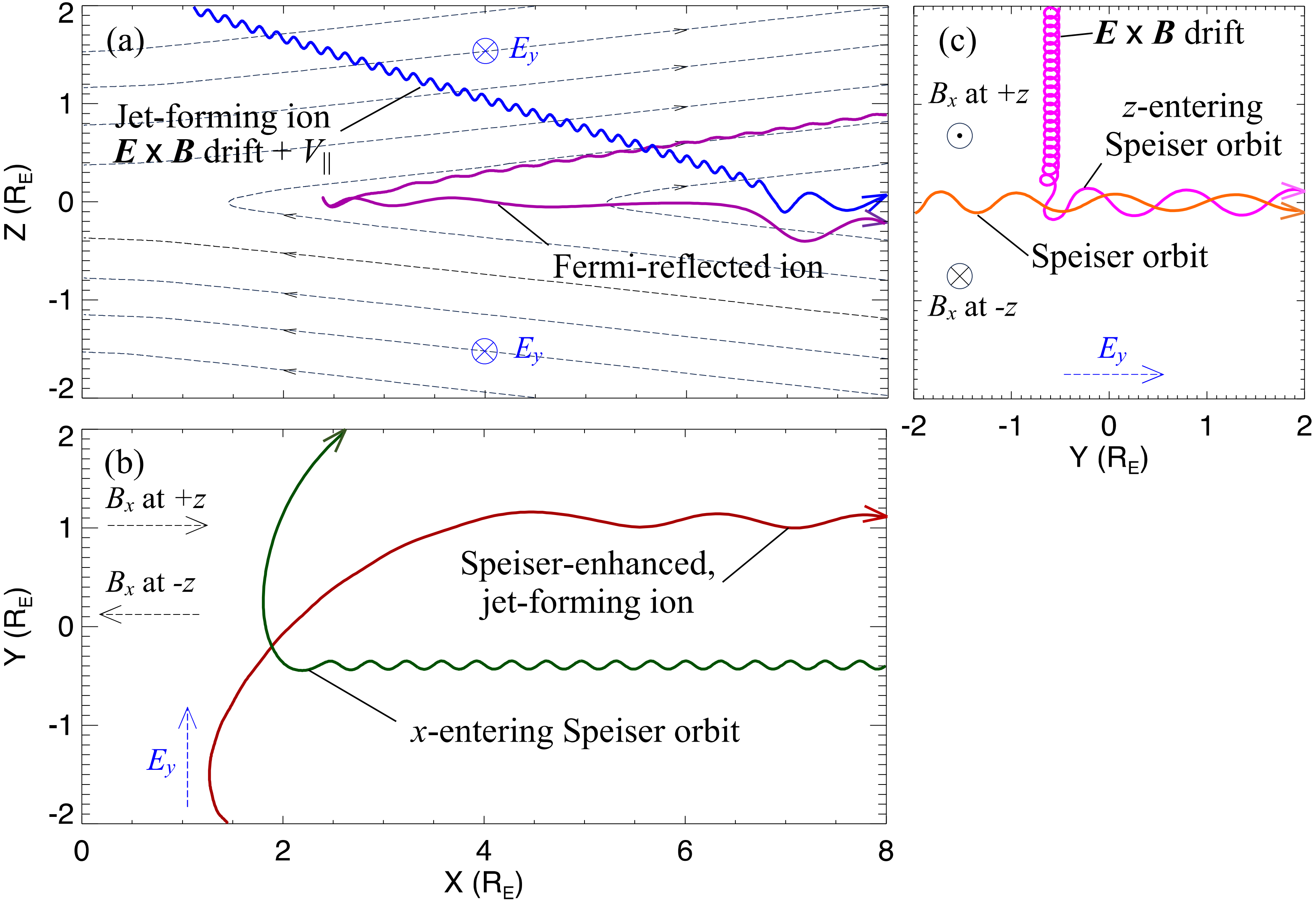


Test-Particle Simulation

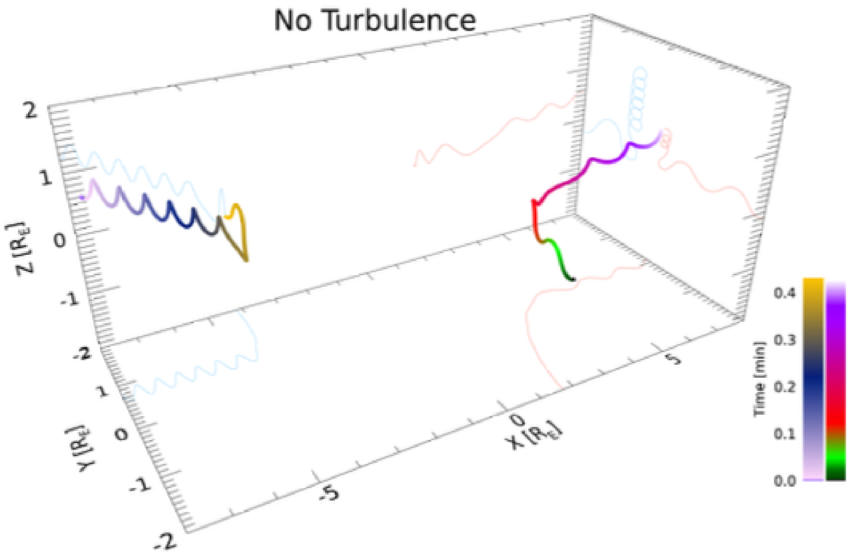
Sega & Ergun, 2024 ApJ

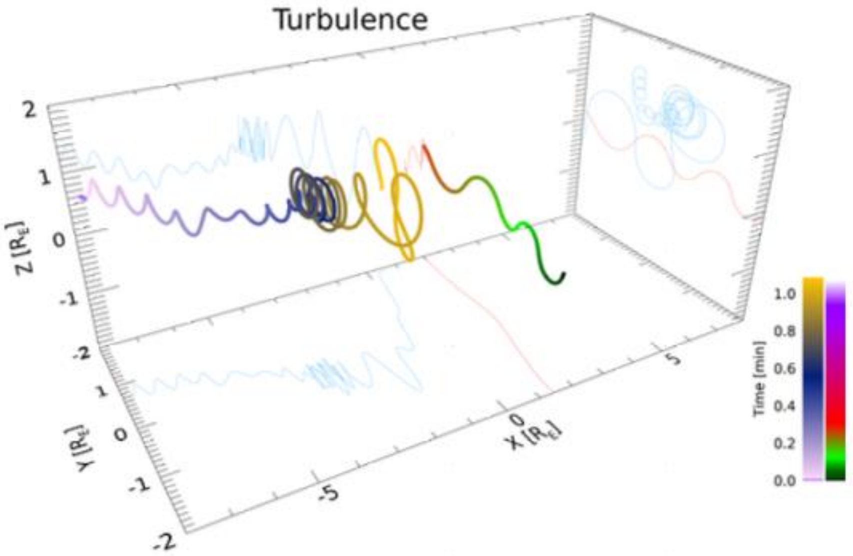
Energization at the Current Sheet

Orbits: No Turbulence



Results: No Turbulence versus Turbulence





No Turbulence:

- Speiser-like energization is significant.
- Energization is conservative in E_y.
- Few ions >80 keV.
- Many energized ions exit the $+y$ face!

Turbulence:

- Speiser-like energization is significant.
- Stochastic energization dominates at high-energy!
- Most energetic ions exit the $+Y$ face!

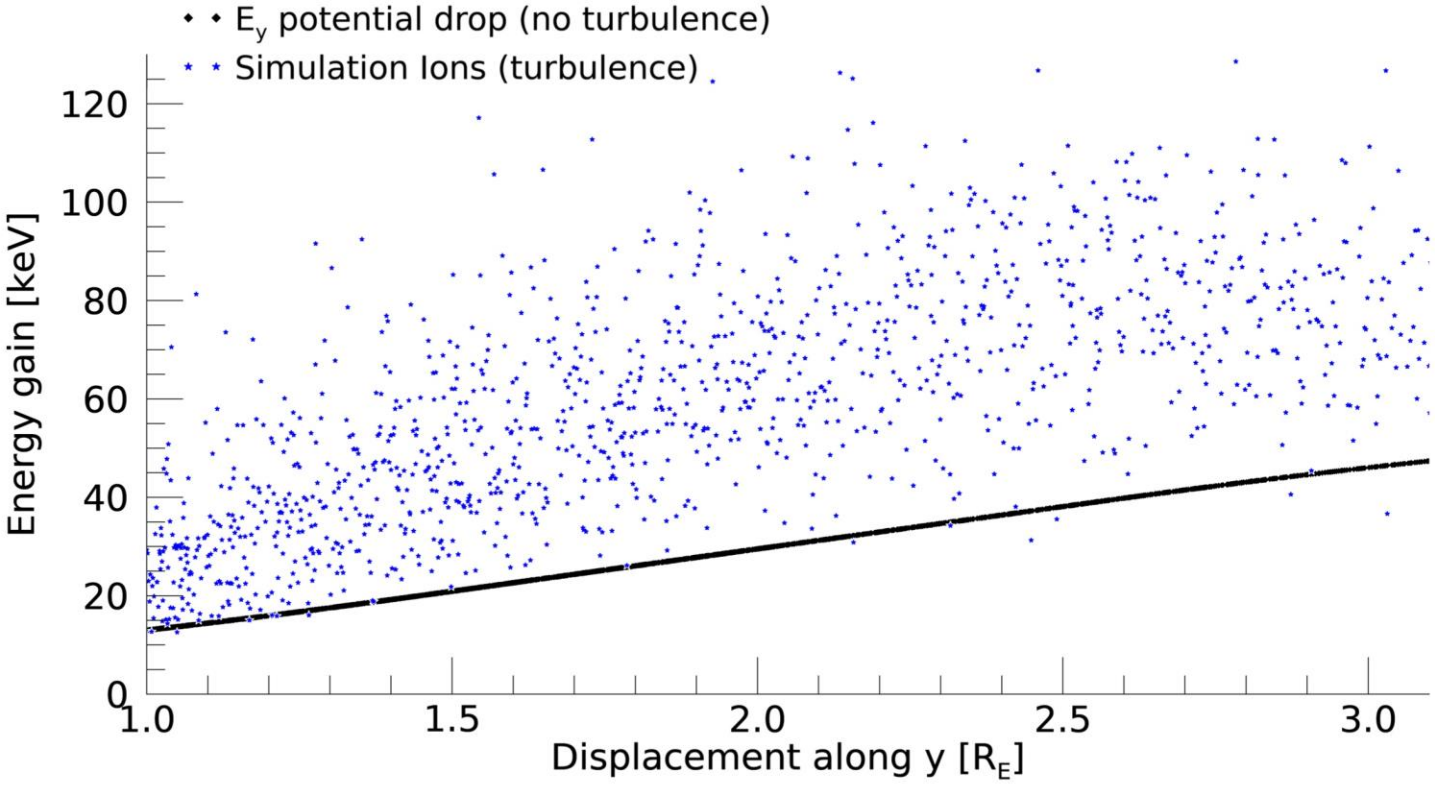
Results: No Turbulence versus Turbulence

No Turbulence:

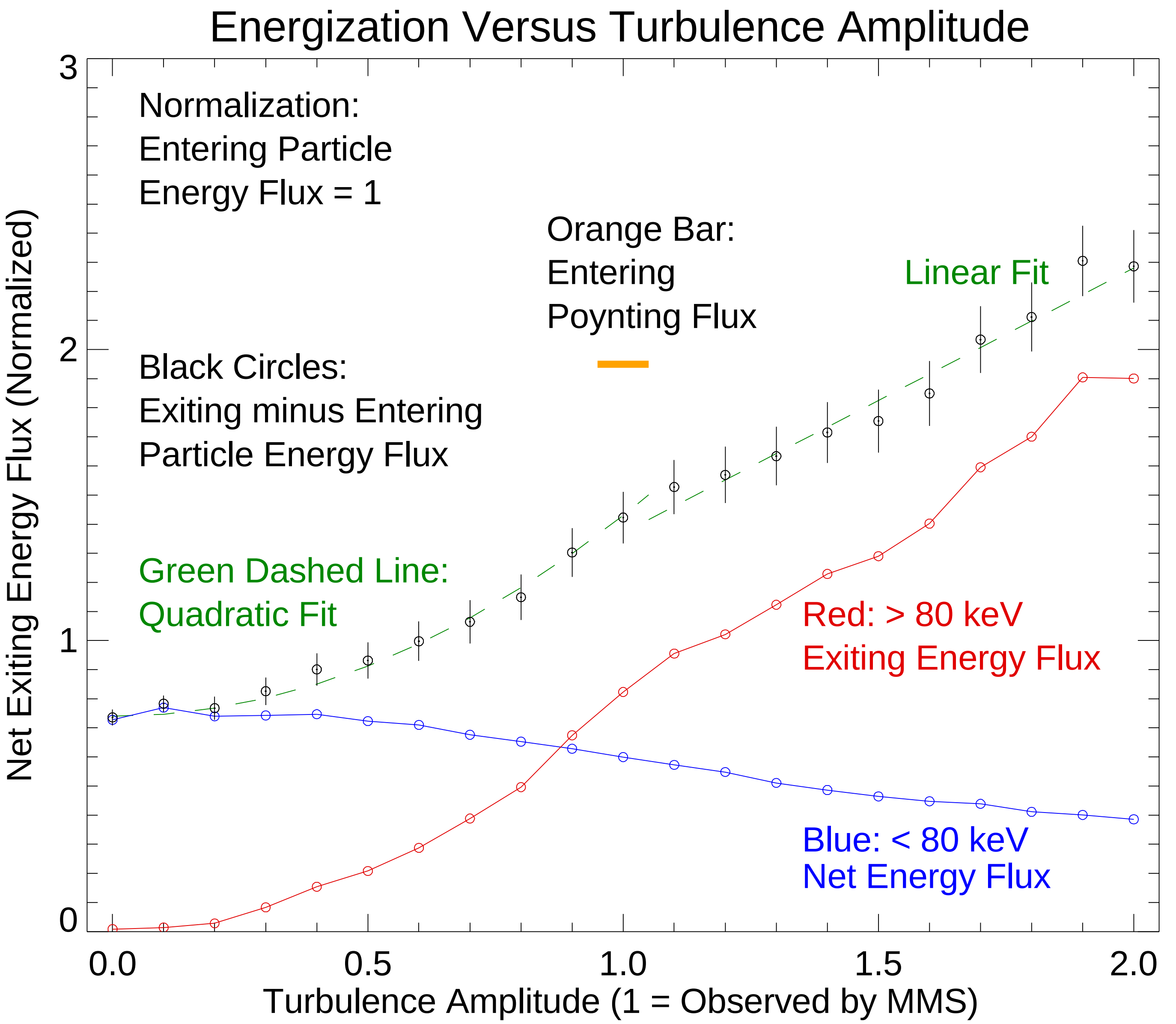
- Energization is conservative in E_y.
- Few ions >80 keV.

Turbulence:

- Stochastic energization can dominate.



Results: Turbulence Amplitude



Two Old Lessons Re-Learned

Energization that favors higher-energy particles is required for to develop a non-thermal, energetic tail (power-law) in a particle distribution.

The spectral index is governed by the energization process combined with the ***escape*** process.

Blandford & Eichler, 1987

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