What have we actually learned from MMS about collisionless reconnection?

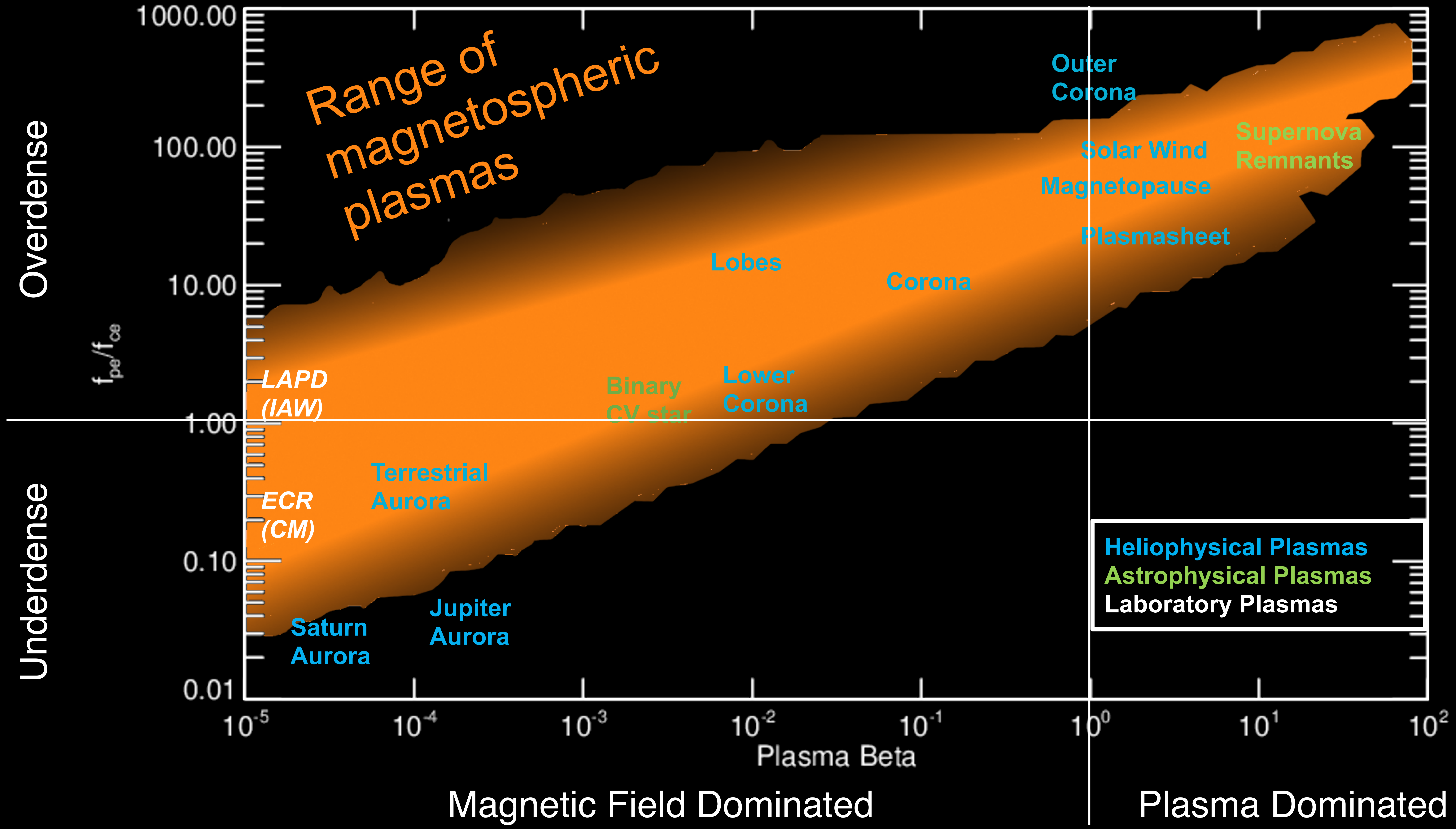
Yuri Khotyaintsev
Swedish Institute of Space Physics, Uppsala, Sweden

yuri@irfu.se

NORDITA 2026-05-18

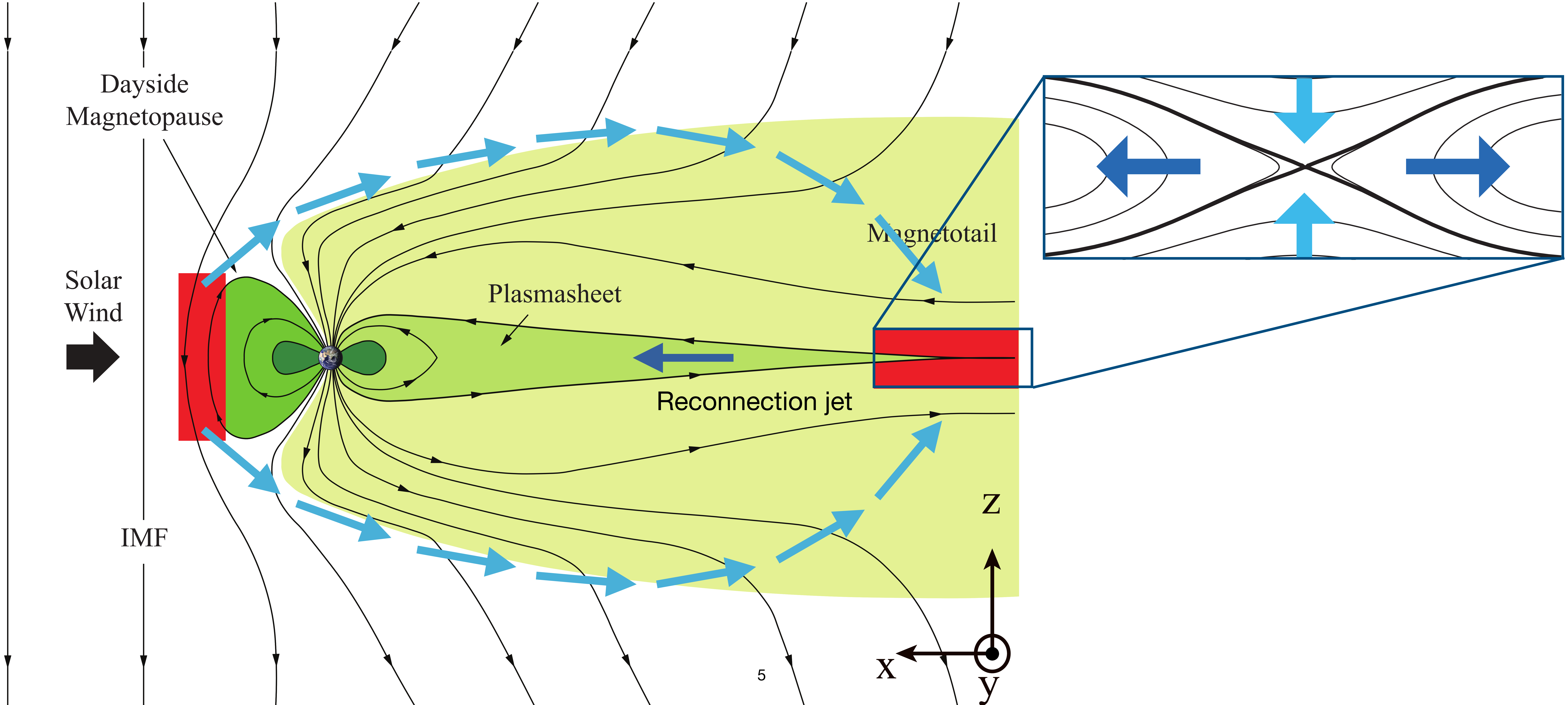
Collisionless reconnection is intrinsically **multiscale**, **structured**, and often **turbulent**, with energy conversion distributed far beyond the diffusion region.

Diversity of plasma – universal physics



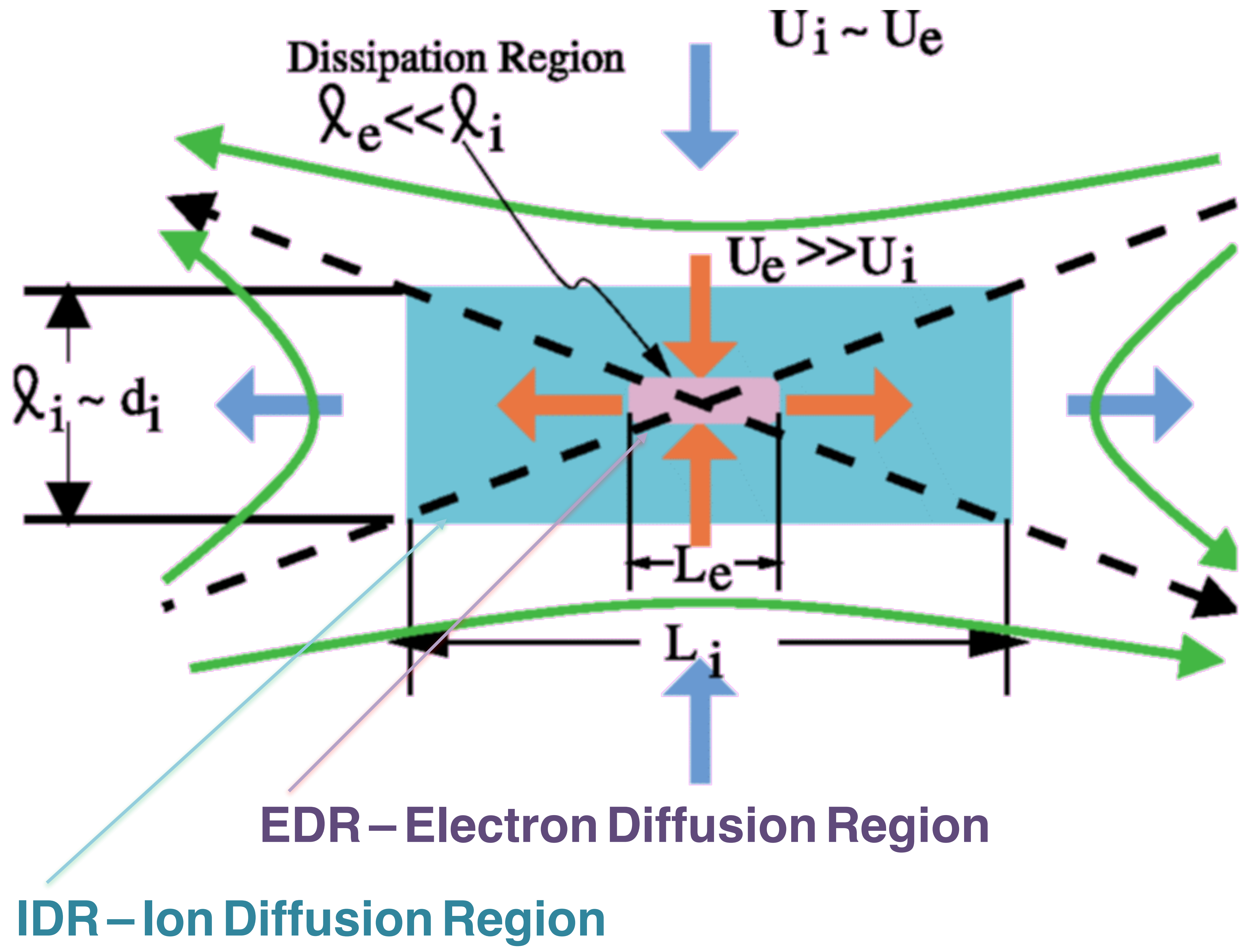
Diverse plasmas – similar properties in terms of dimensionless parameters

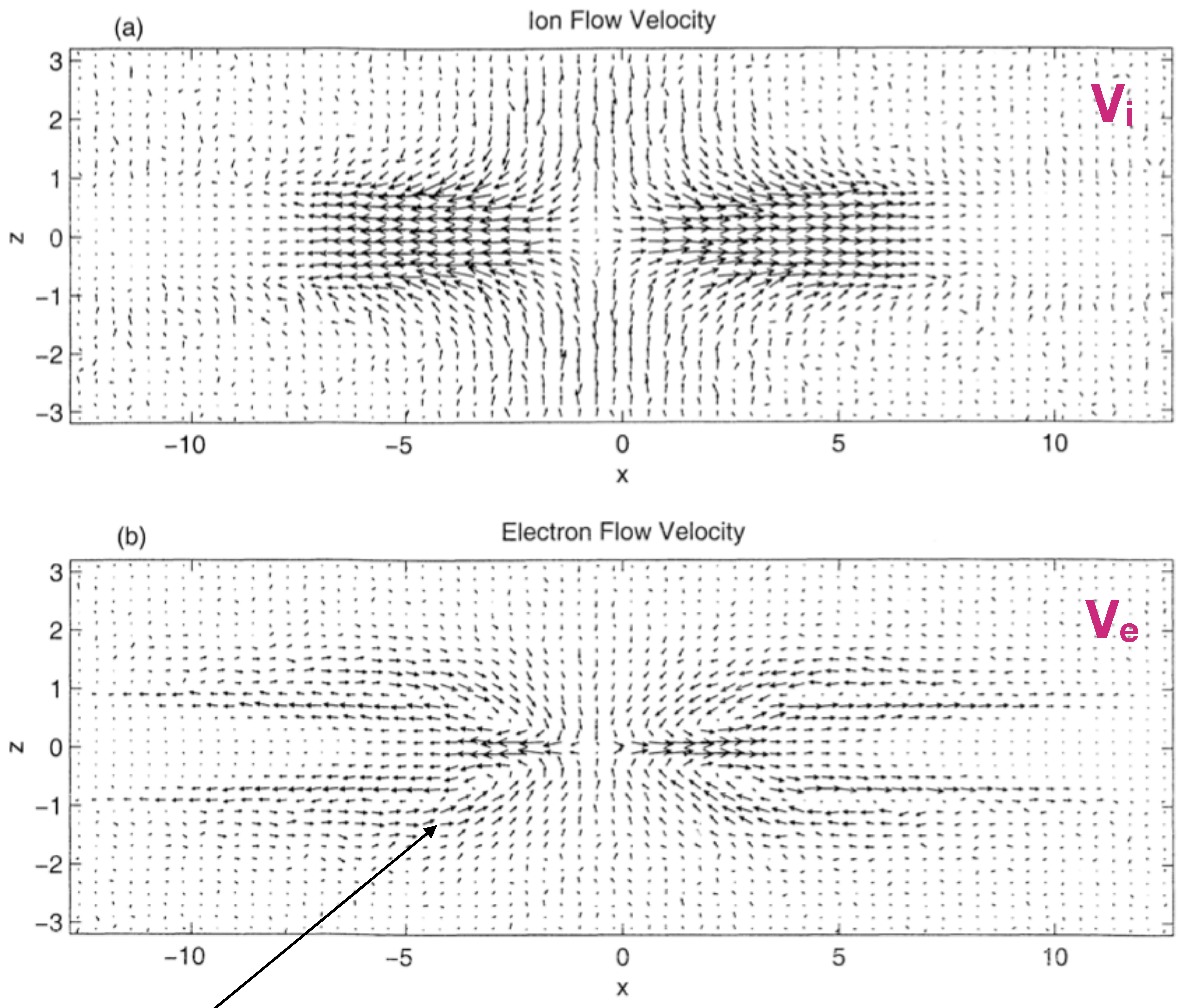
The Earth's Magnetotail as a Plasma Lab



Hall reconnection

2-fluid (Hall) reconnection

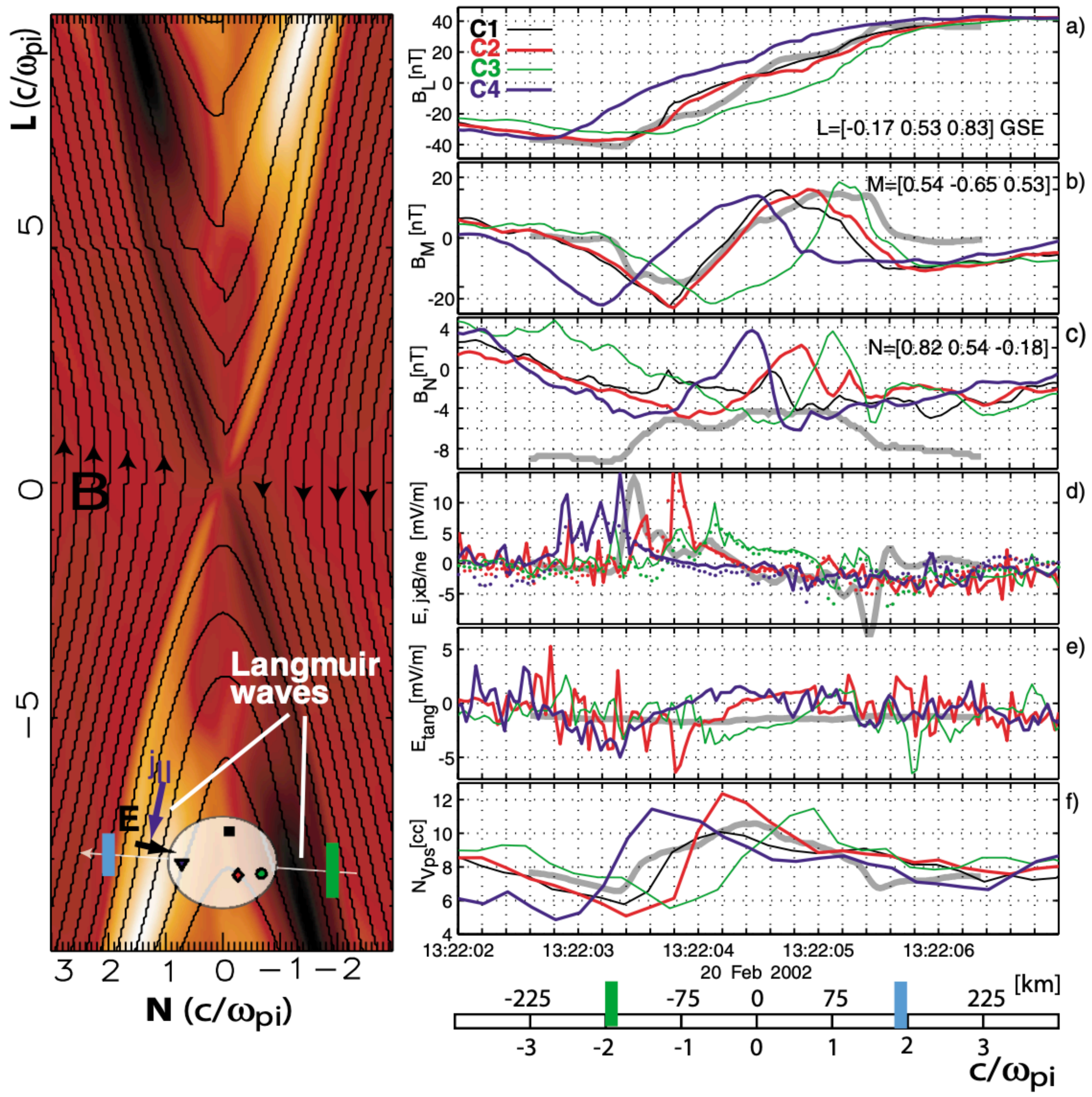


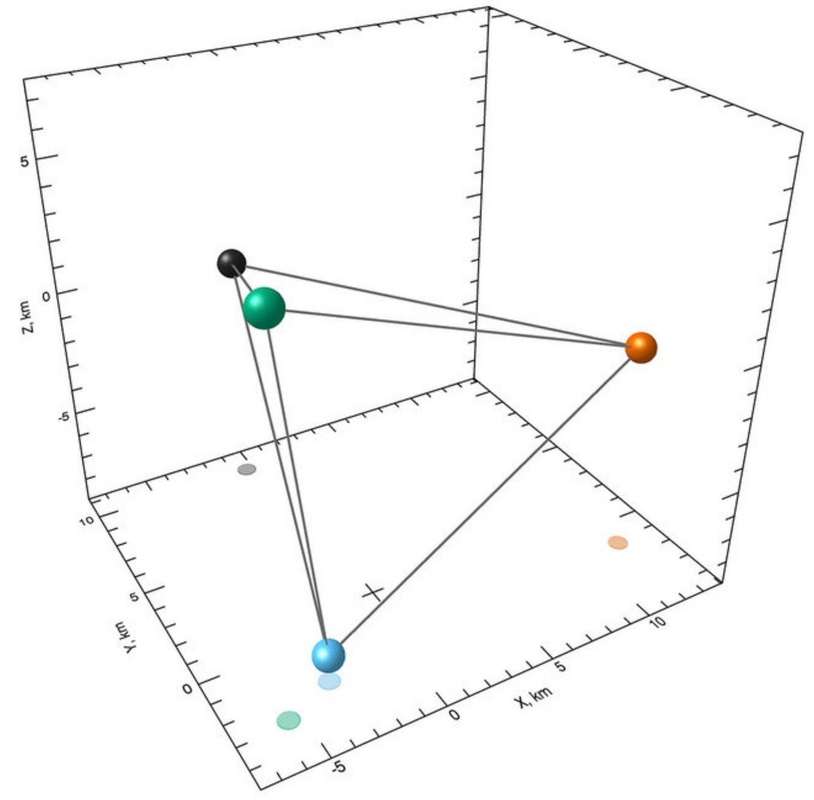


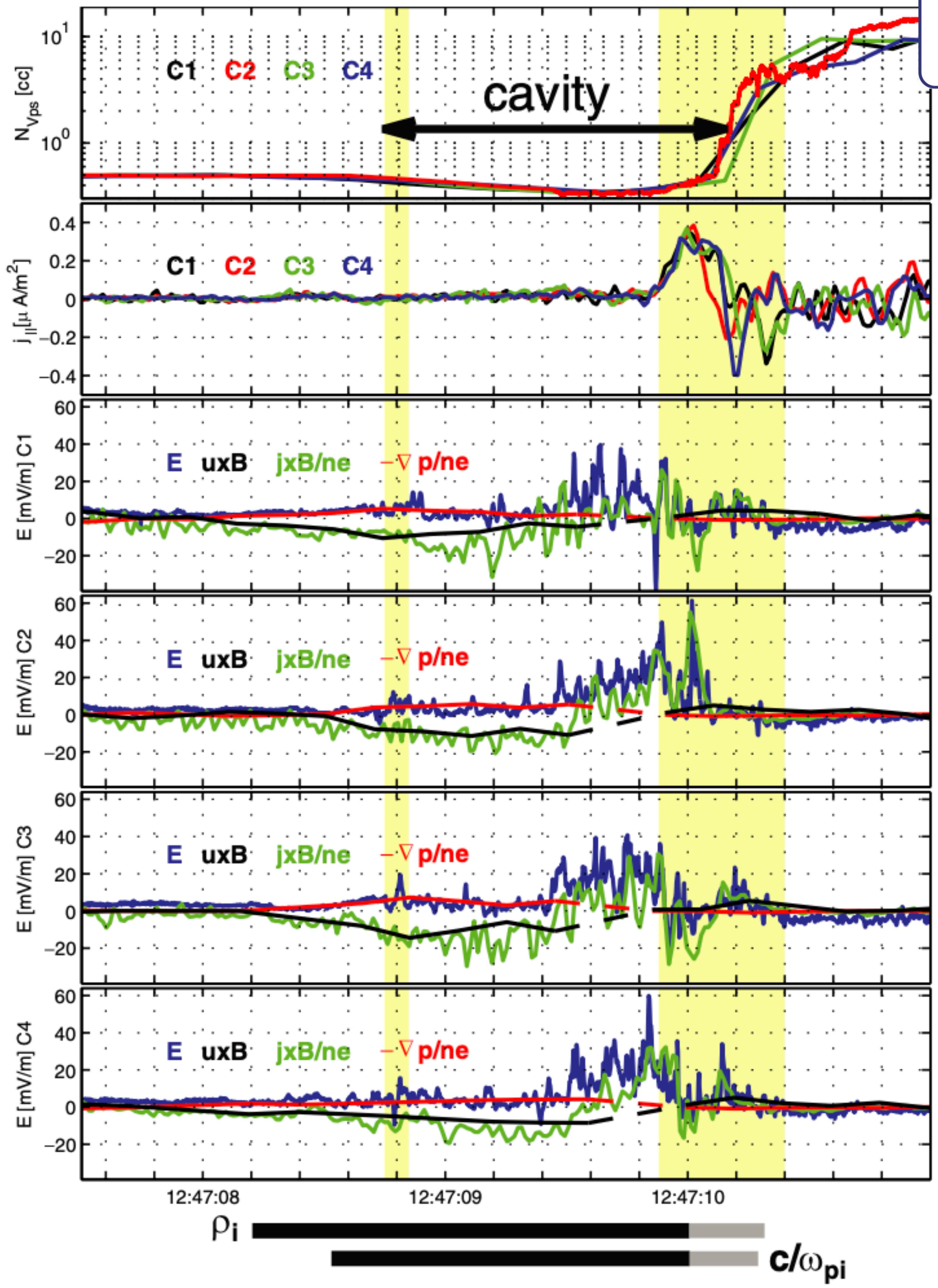
Streaming at separatrices

[Pritchett, 2002]

Hall physics with Cluster







$$\mathbf{E} + \mathbf{u}_i \times \mathbf{B} = \frac{1}{ne}\mathbf{j} \times \mathbf{B} - \frac{1}{ne}\nabla p_e.$$

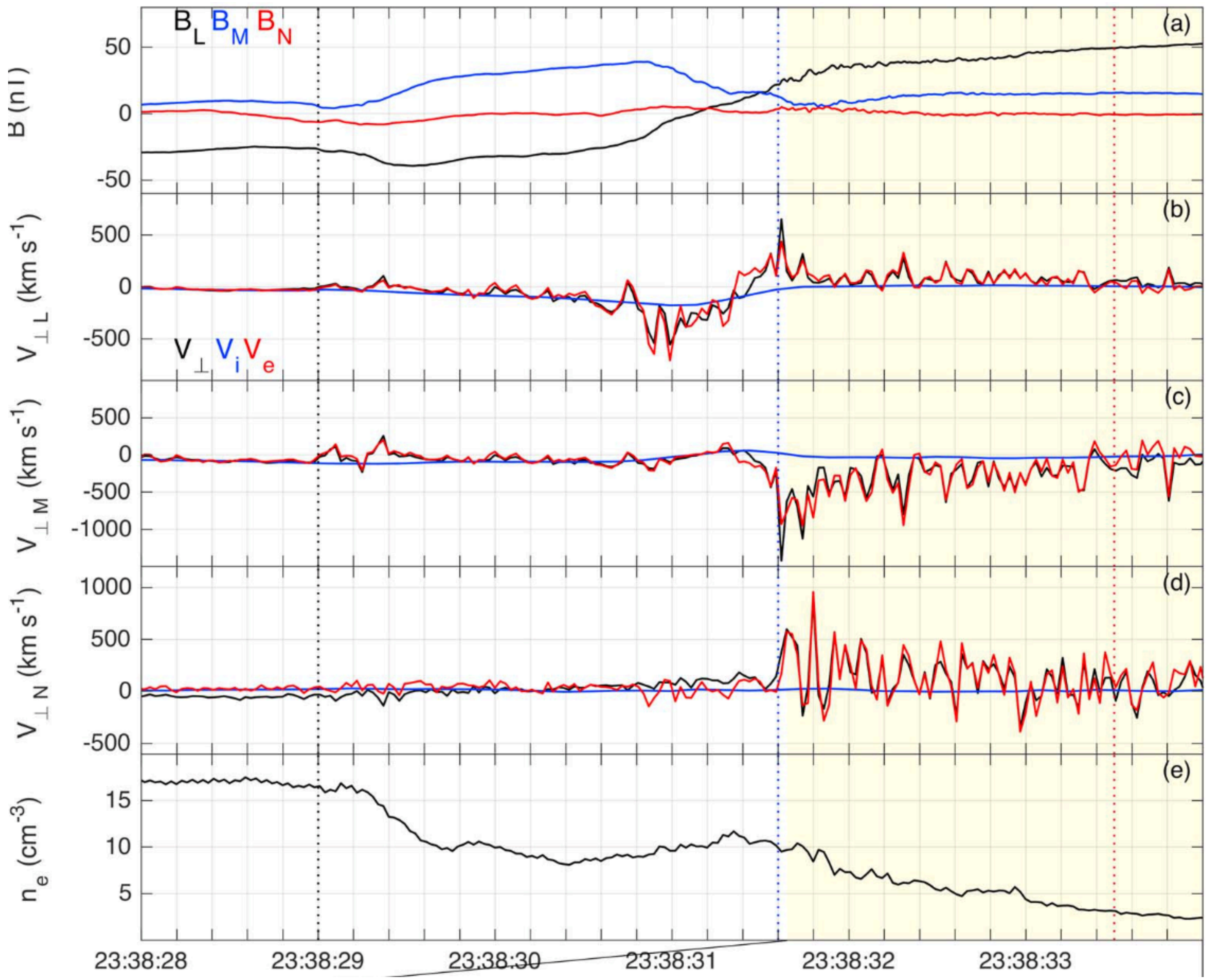
[Vaivads, Khotyaintsev et al, PRL, 2004]

[Khotyaintsev, Vaivads et al, PRL, 2006]

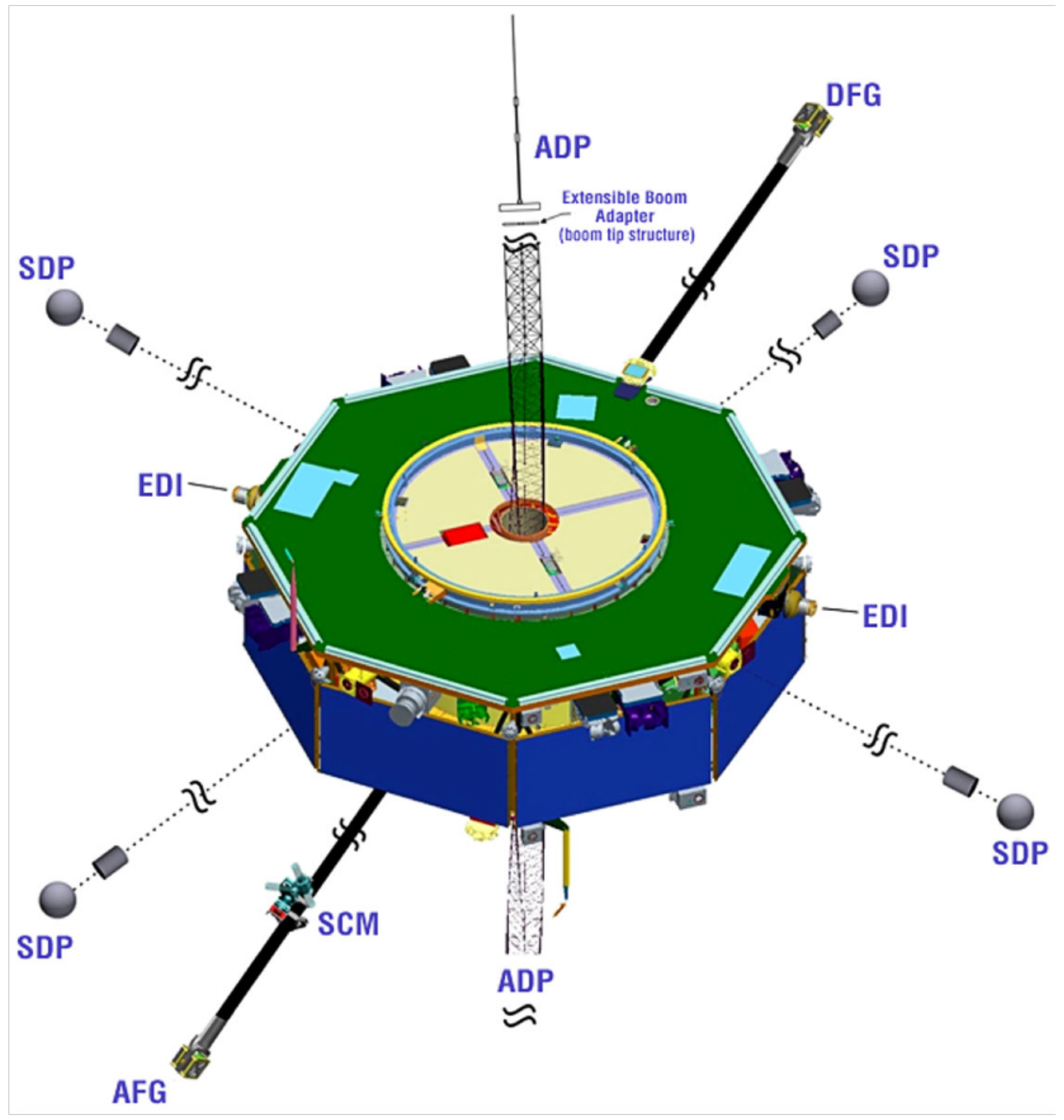
MMS Launched on March 12, 2015 at 10:44pm

MMS
Magnetospheric Multiscale
NASA
SwRI
Goddard Space Flight Center

MMS: fast particle measurements



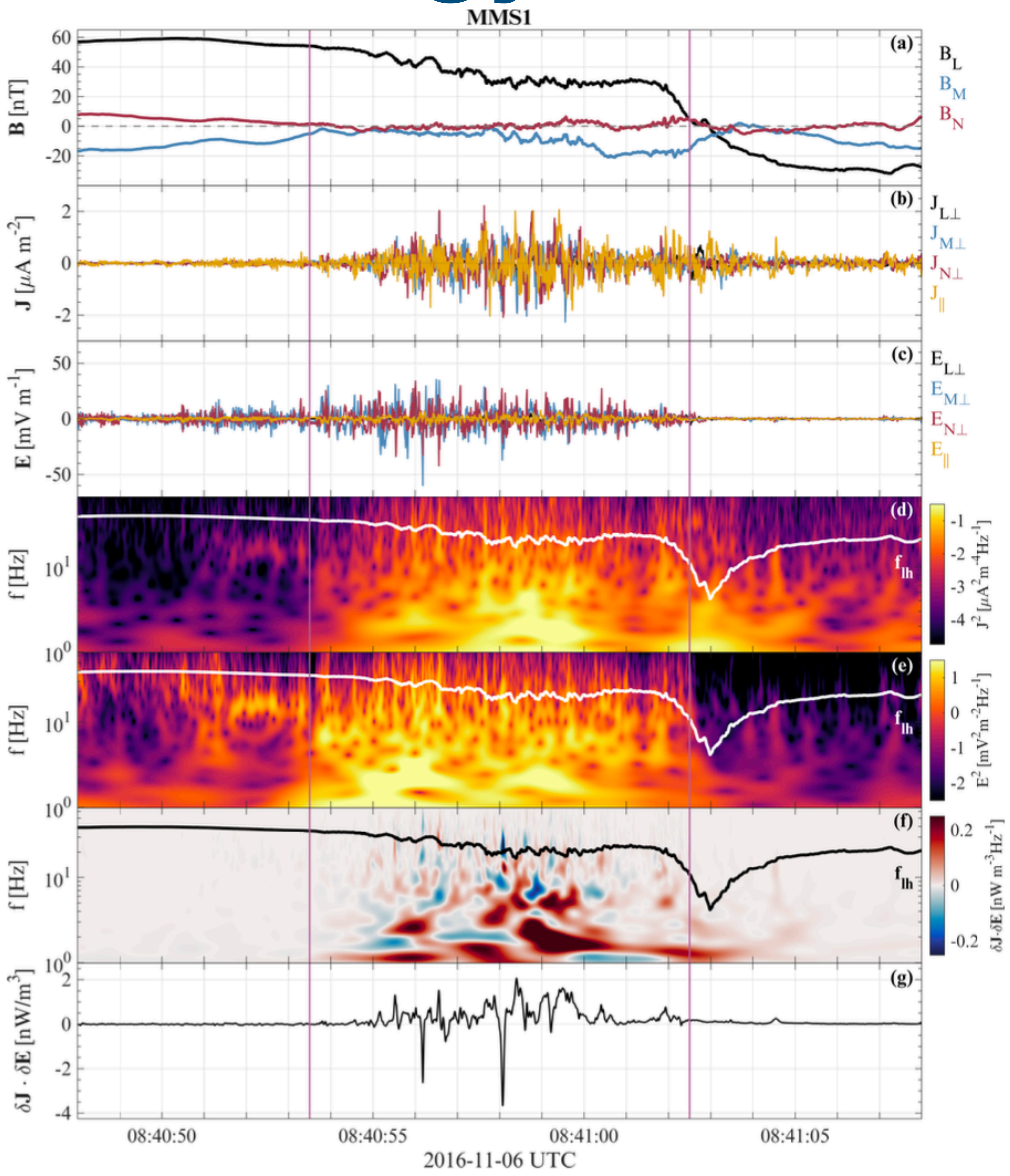
- LHDI fully resolved in fields and particles
- $\mathbf{V} = \mathbf{E} \times \mathbf{B}/B^2$



[Khotyaintsev, Graham, et al, GRL, 2016]

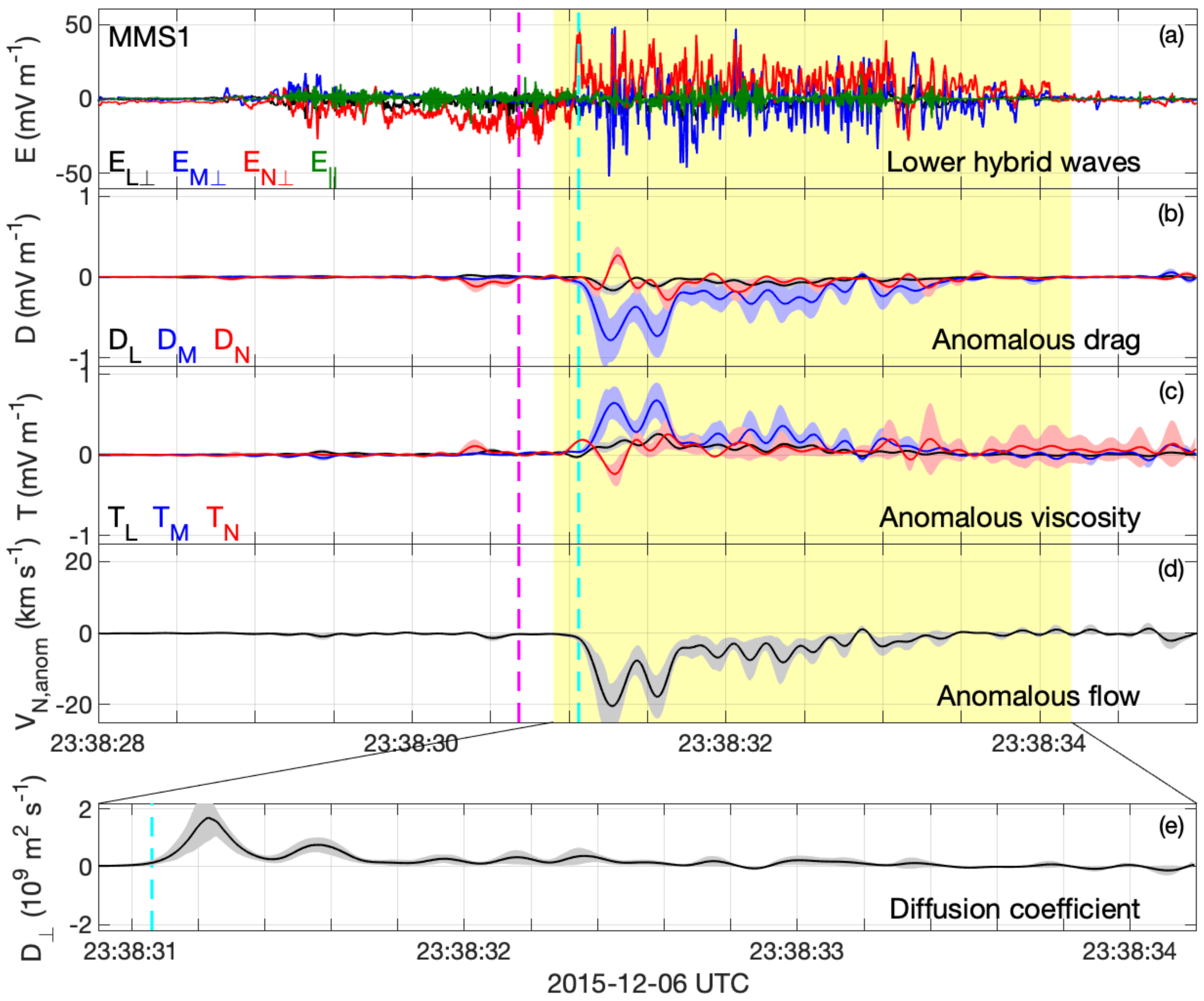
Anomalous resistivity, diffusion, kinetics, multi-scale 3D structure

Energy conversion and anomalous terms



$$\langle \delta \mathbf{J} \cdot \delta \mathbf{E} \rangle$$

Strong energy conversion due to waves.



$$\mathbf{D} = -\frac{\langle \delta n_e \delta \mathbf{E} \rangle}{\langle n_e \rangle}, \quad \mathbf{T} = -\frac{\langle n_e \mathbf{V}_e \times \mathbf{B} \rangle}{\langle n_e \rangle} + \langle \mathbf{V}_e \rangle \times \langle \mathbf{B} \rangle.$$

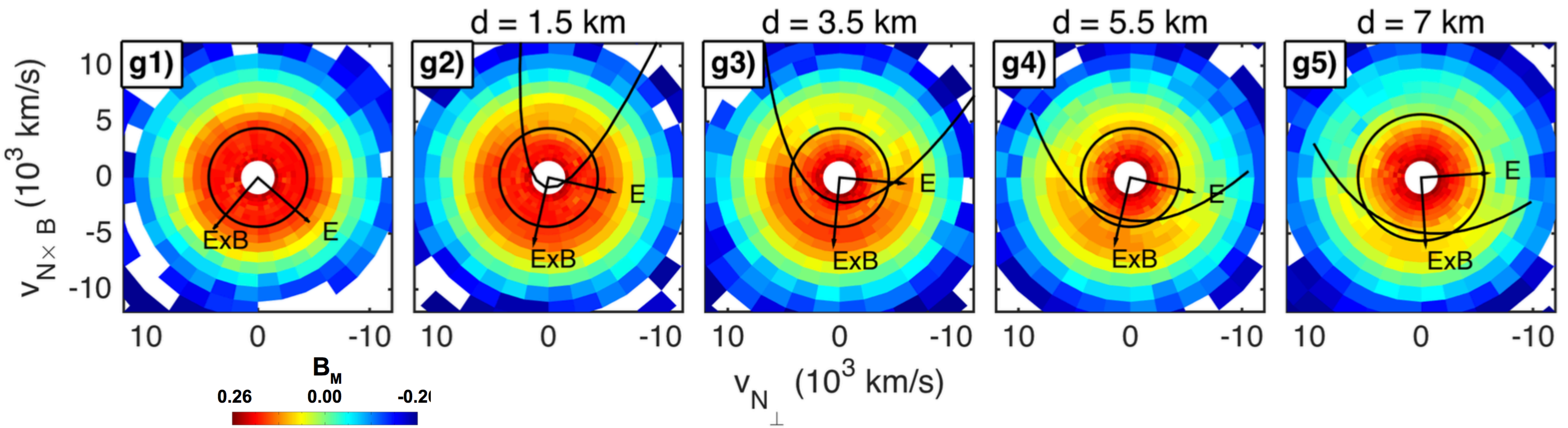
$$D_\perp = -\frac{\langle \delta n_e \delta V_N \rangle}{\langle \nabla n_e \rangle}. \qquad V_{N,anom} = \frac{\langle \delta n_e \delta V_N \rangle}{\langle n_e \rangle}.$$

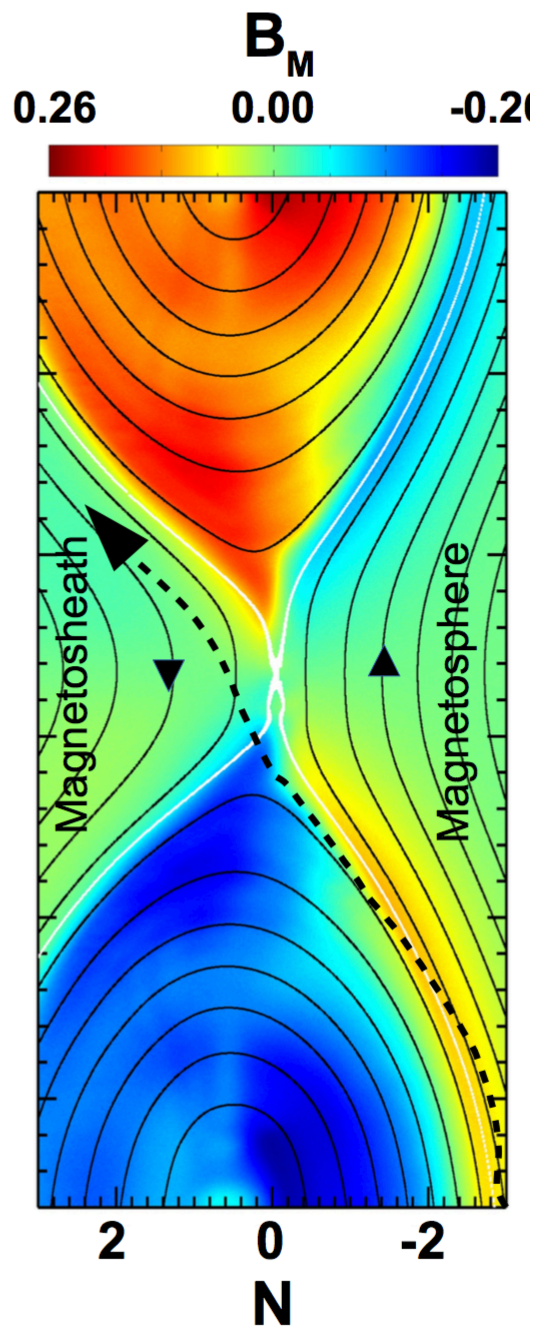
Diffusion coefficient | Anomalous flow

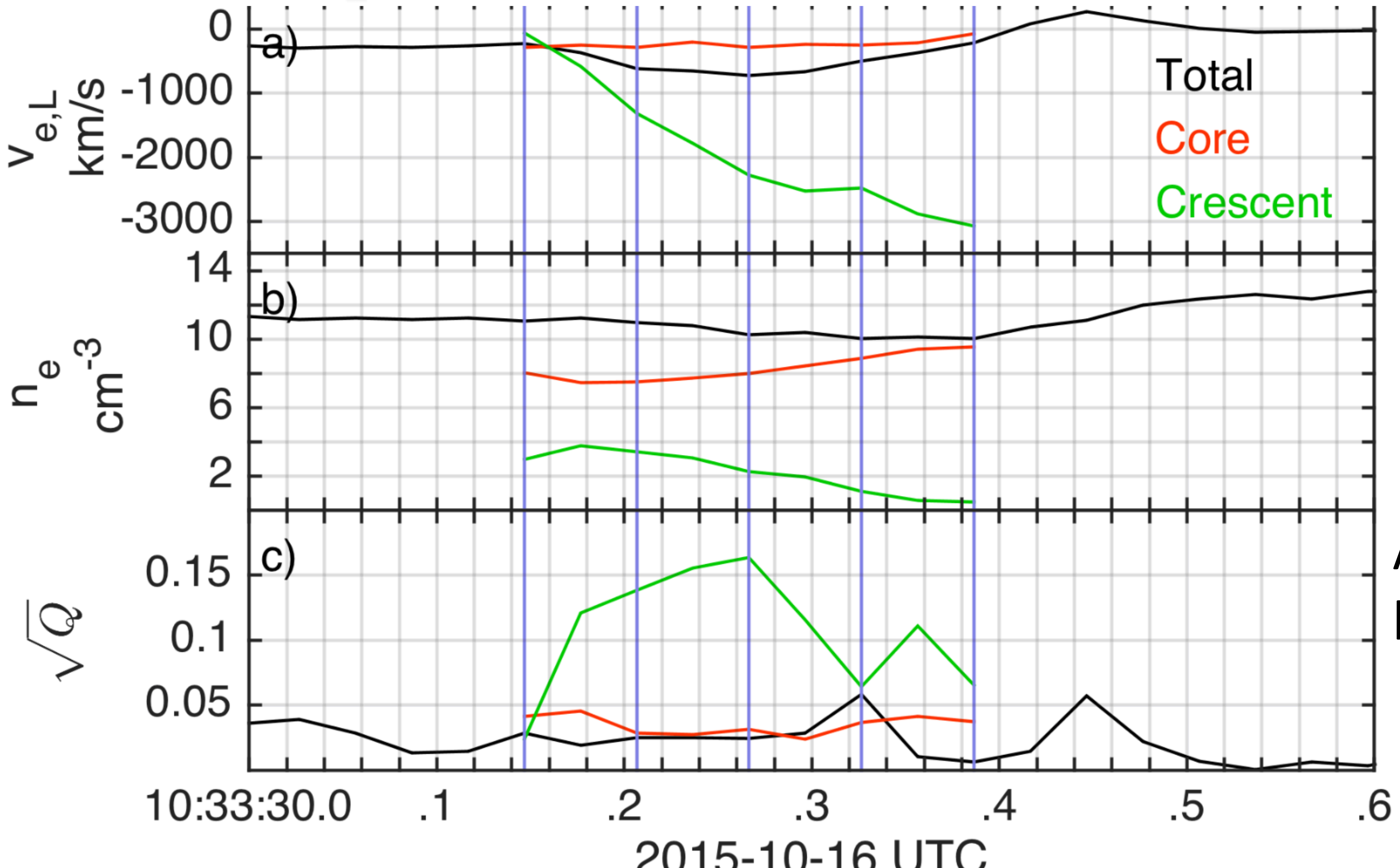
[Tigik, Graham, et al, JGR, 2025]

[Graham, Khotyaintsev et al, Nat Comm, 2022]

Electron crescent distributions







Agyrotropy measure by *Swisdak*, 2016.

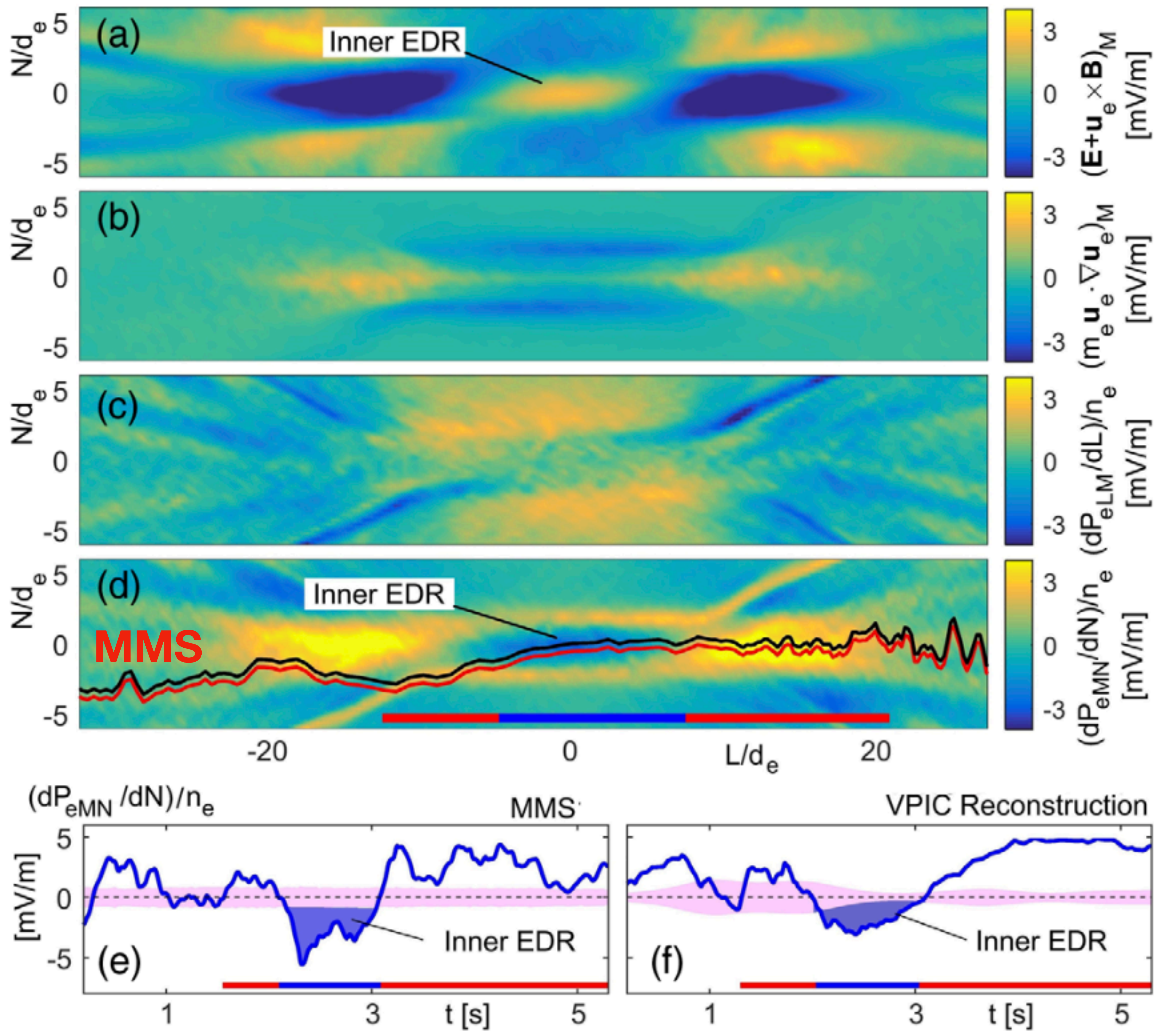
[Norgren, Graham et al, GRL, 2016]

Contributions to the reconnection electric field

$$\mathbf{E} + \mathbf{u}_e \times \mathbf{B} + \frac{1}{ne}\nabla \cdot \mathbf{p}_e + \frac{m_e}{e}\mathbf{u}_e \cdot \nabla \mathbf{u}_e = 0.$$

off-diagonal stress in the electron pressure tensor breaking the frozen-in law

$$ne\,(\mathbf{E} + \mathbf{v} \times \mathbf{B})_M \approx -\left(\frac{\partial P^e_{LM}}{\partial L} + \boxed{\frac{\partial P^e_{MN}}{\partial N}}\right)$$



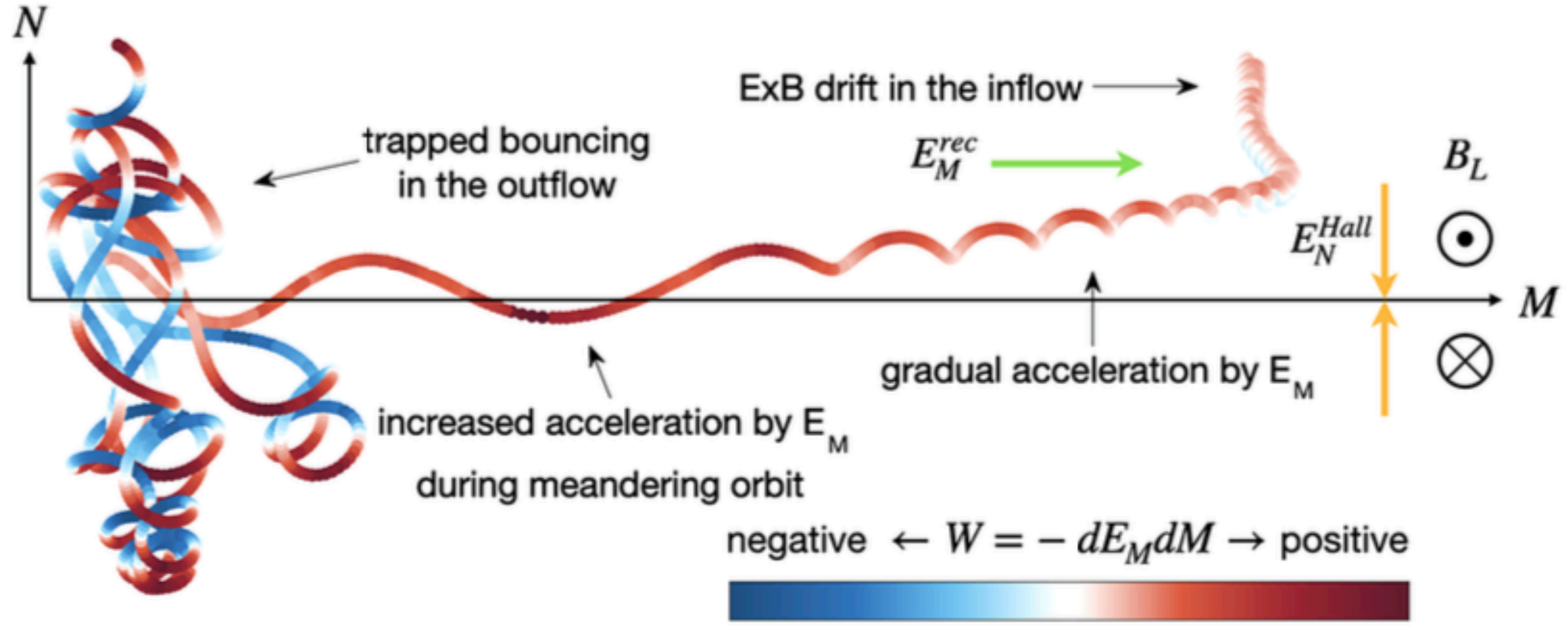
[Egedal et al, PRL, 2019]

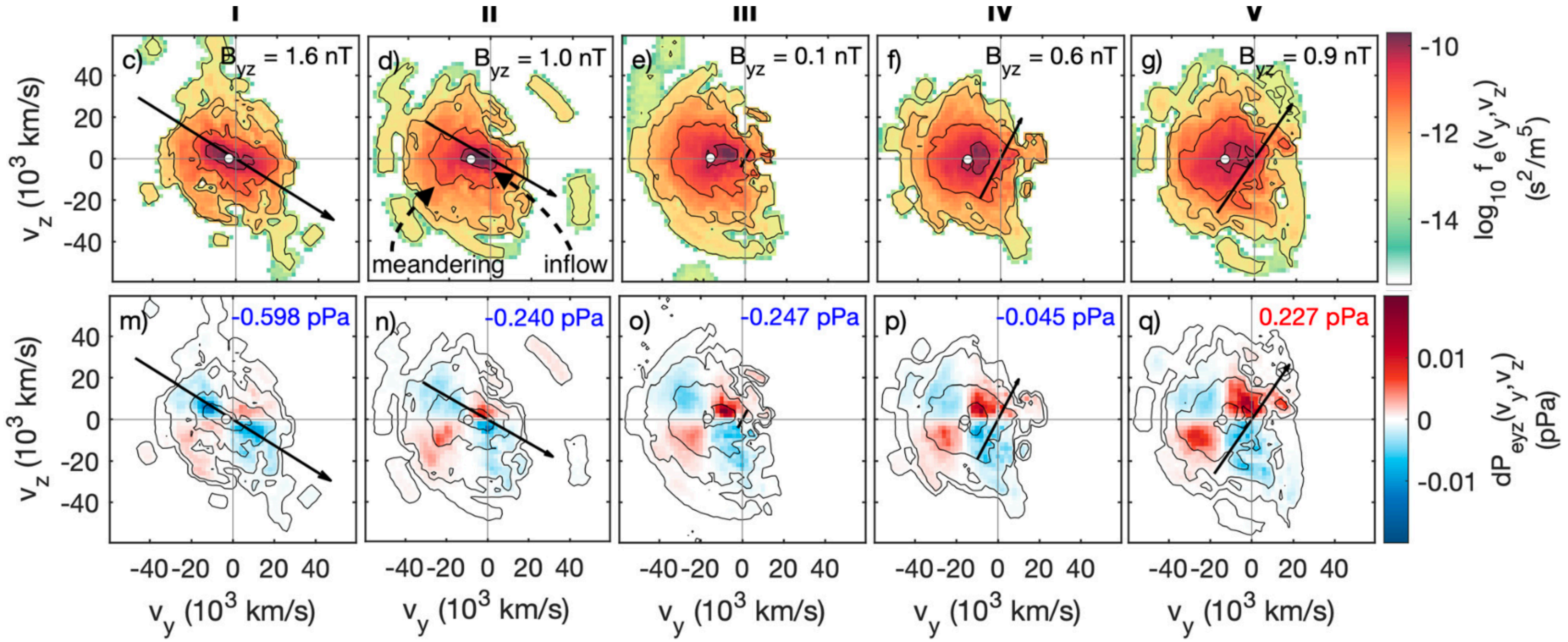
Contributions to the reconnection electric field

- The differential pressure:

$$dP^e_{xy} = m_e f(v_x, v_y)(v_x - \bar{v}_x)(v_y - \bar{v}_y)dv_x dv_y$$

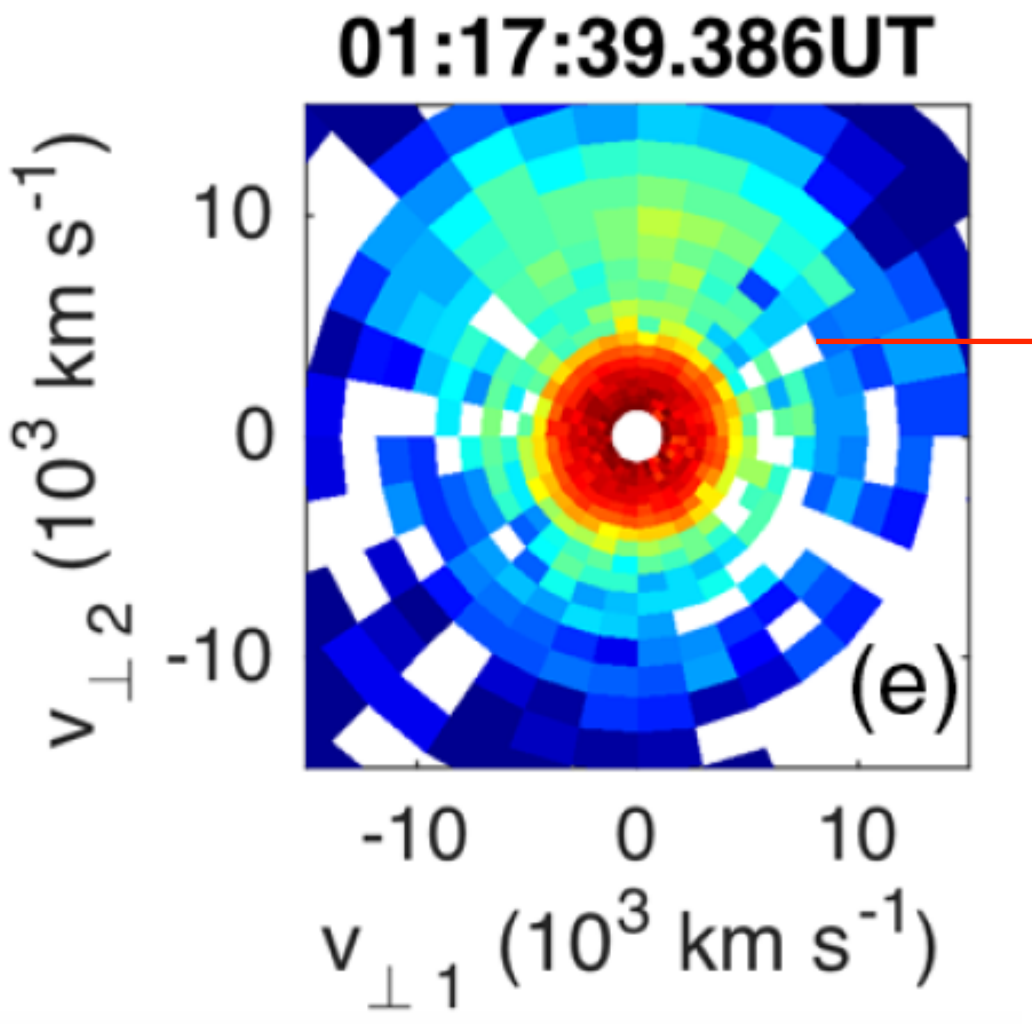
shows how different parts of velocity space (and thus different electrons populations and trajectories) contribute to the pressure.





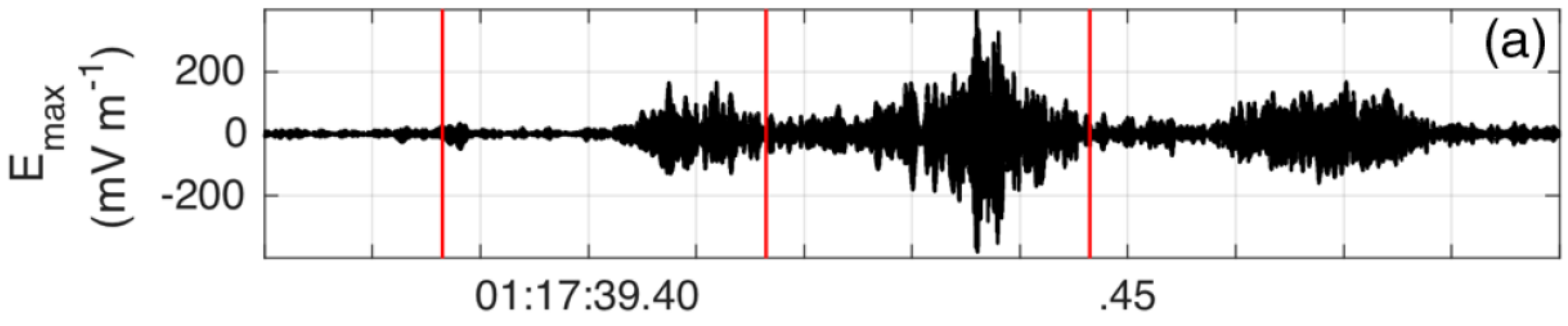
[Norgren et al, PoP, 2025]

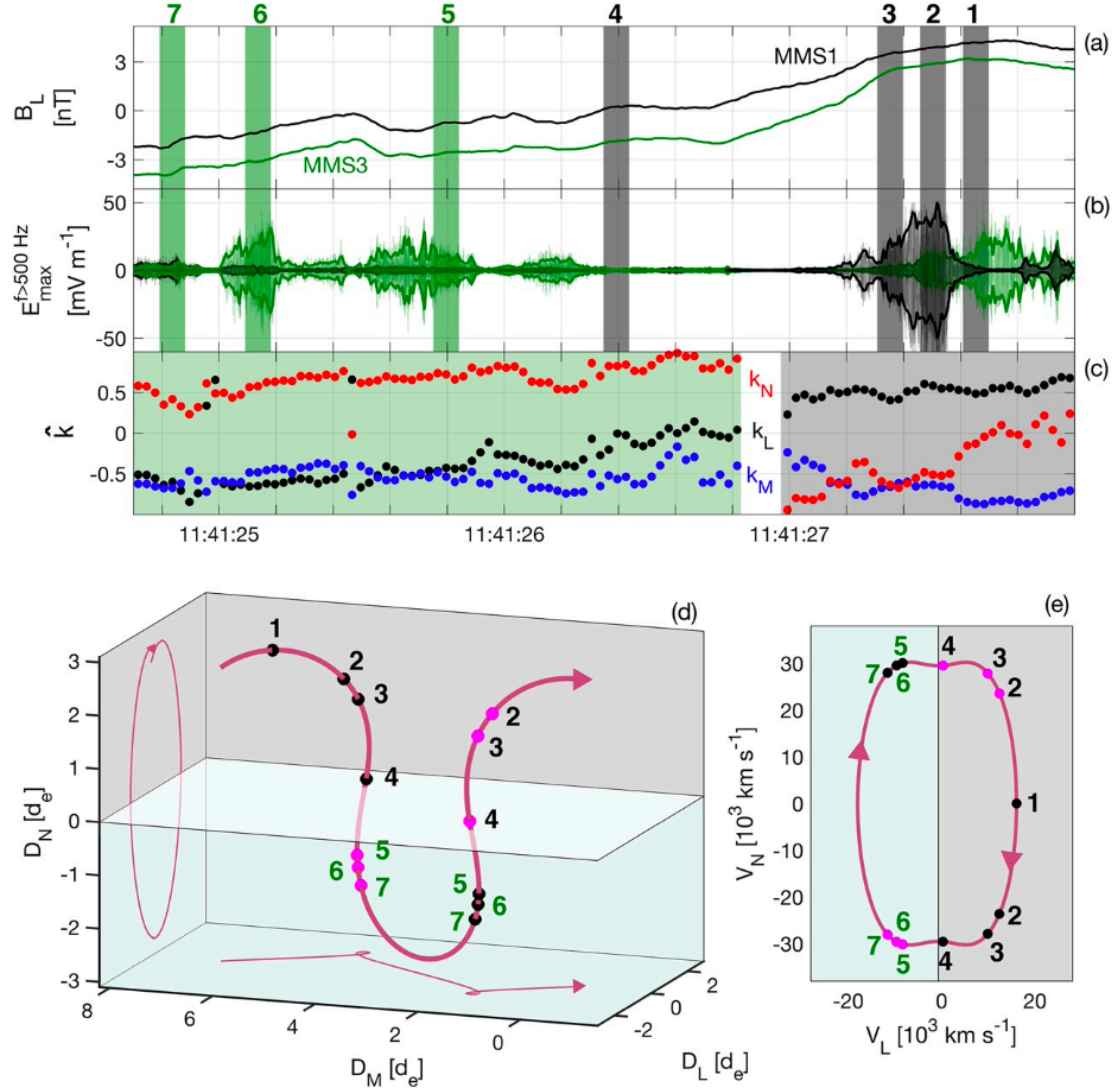
Discovery: crescents generate UH and Bernstein waves



Agyrotropic electron beam:

- 5% of total density, perpendicular to **B**
- drive UH waves
- ~ 300 mV/m **E**



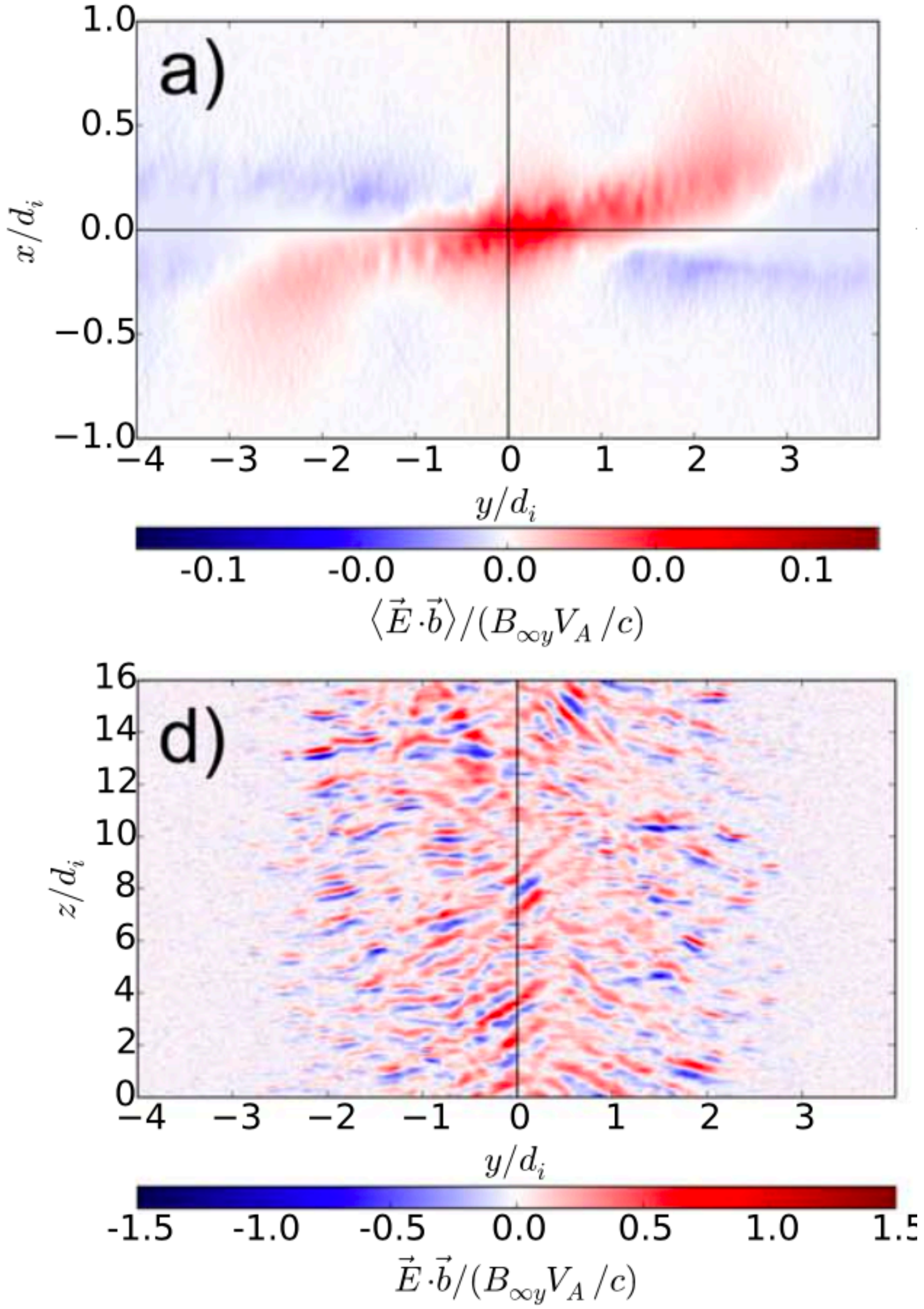


[Graham, Khotyaintsev et al, PRL, 2017] [Li, Graham et al, Nat Comm, 2020]

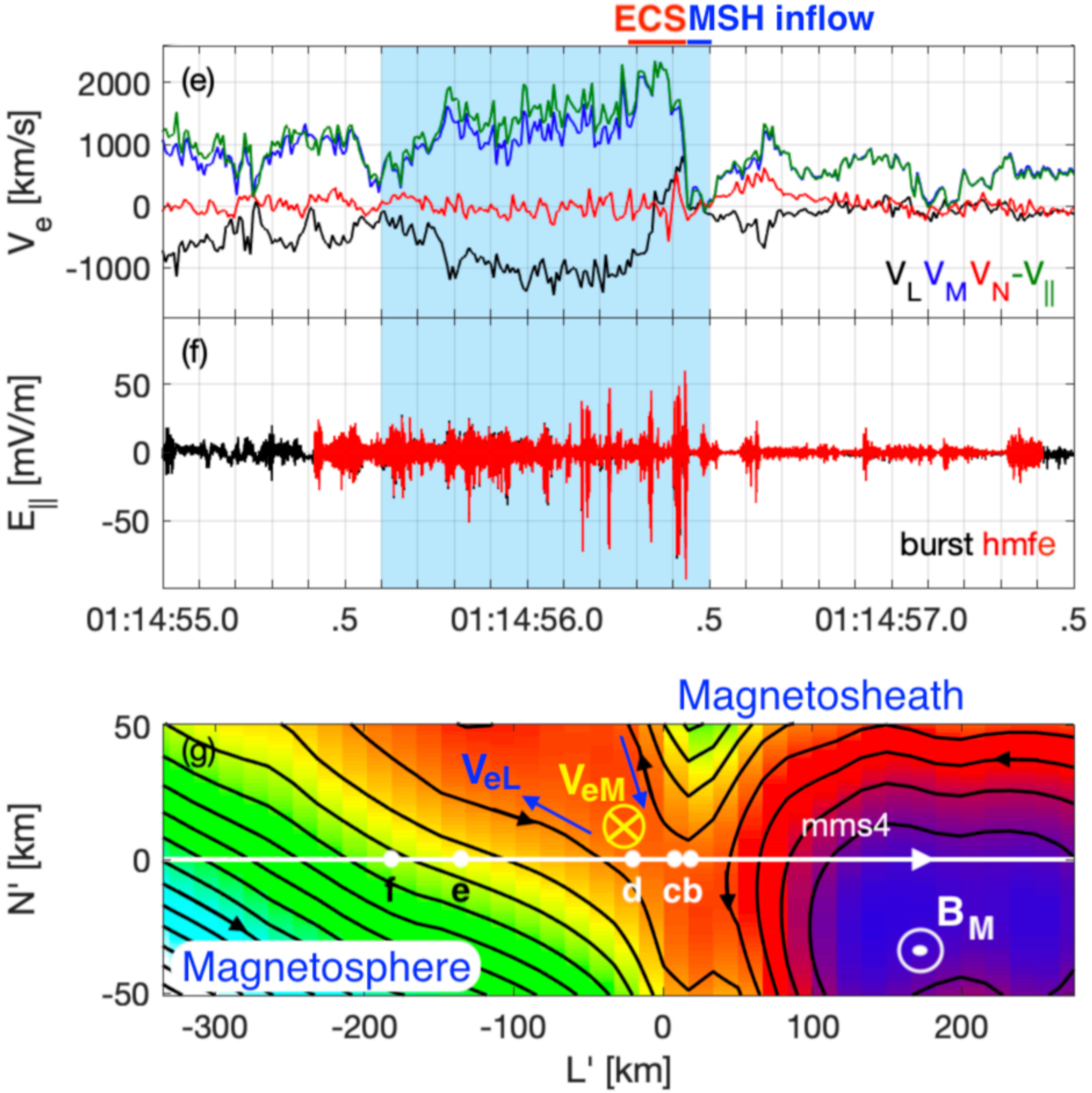
[Li, Khotyaintsev et al, GRL, 2021]

Electron heating in guide-field reconnection

Guide-field X-line (PIC)

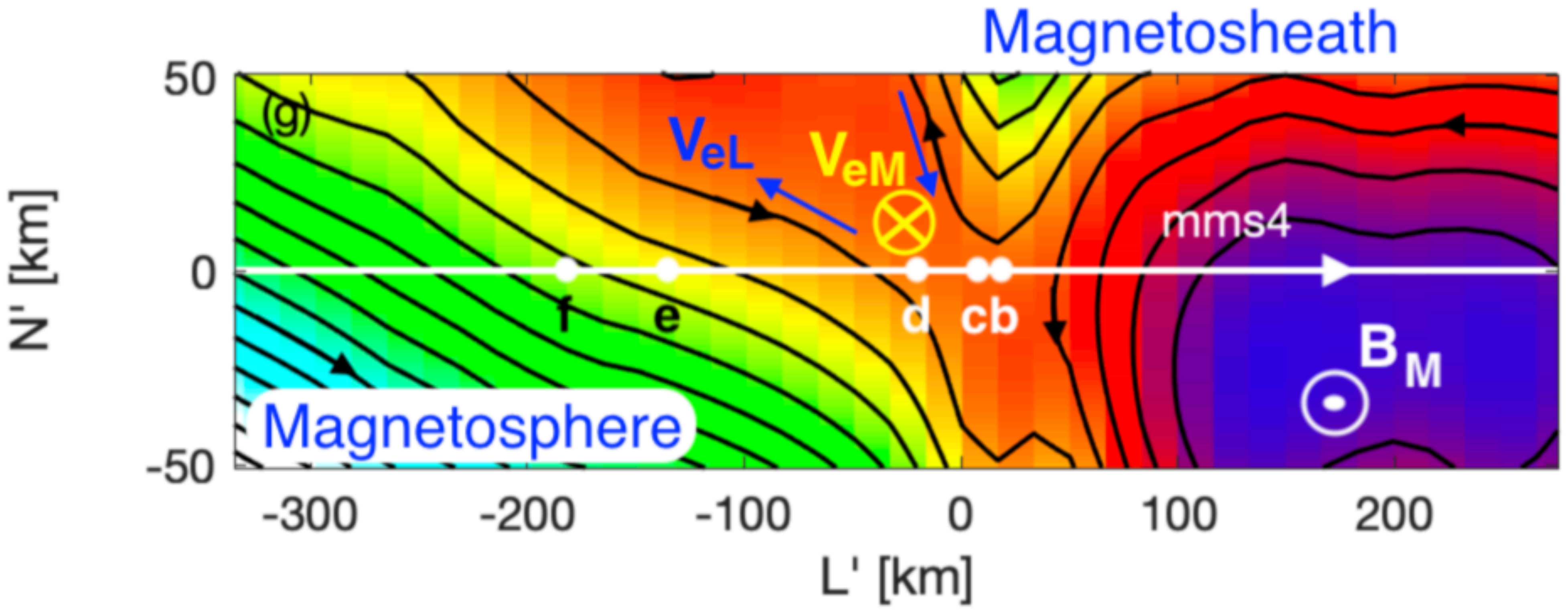


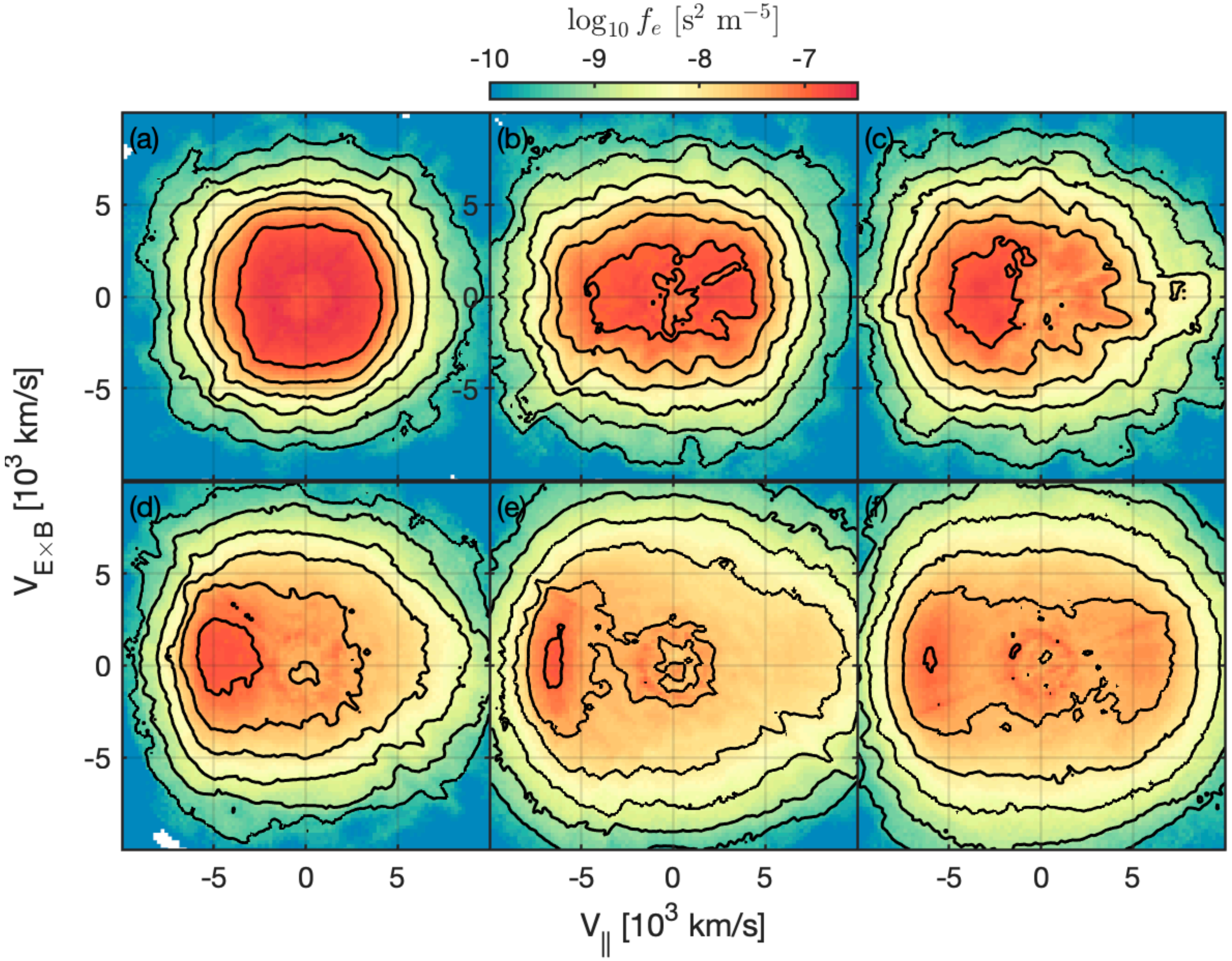
Debye-scale turbulence (MMS)



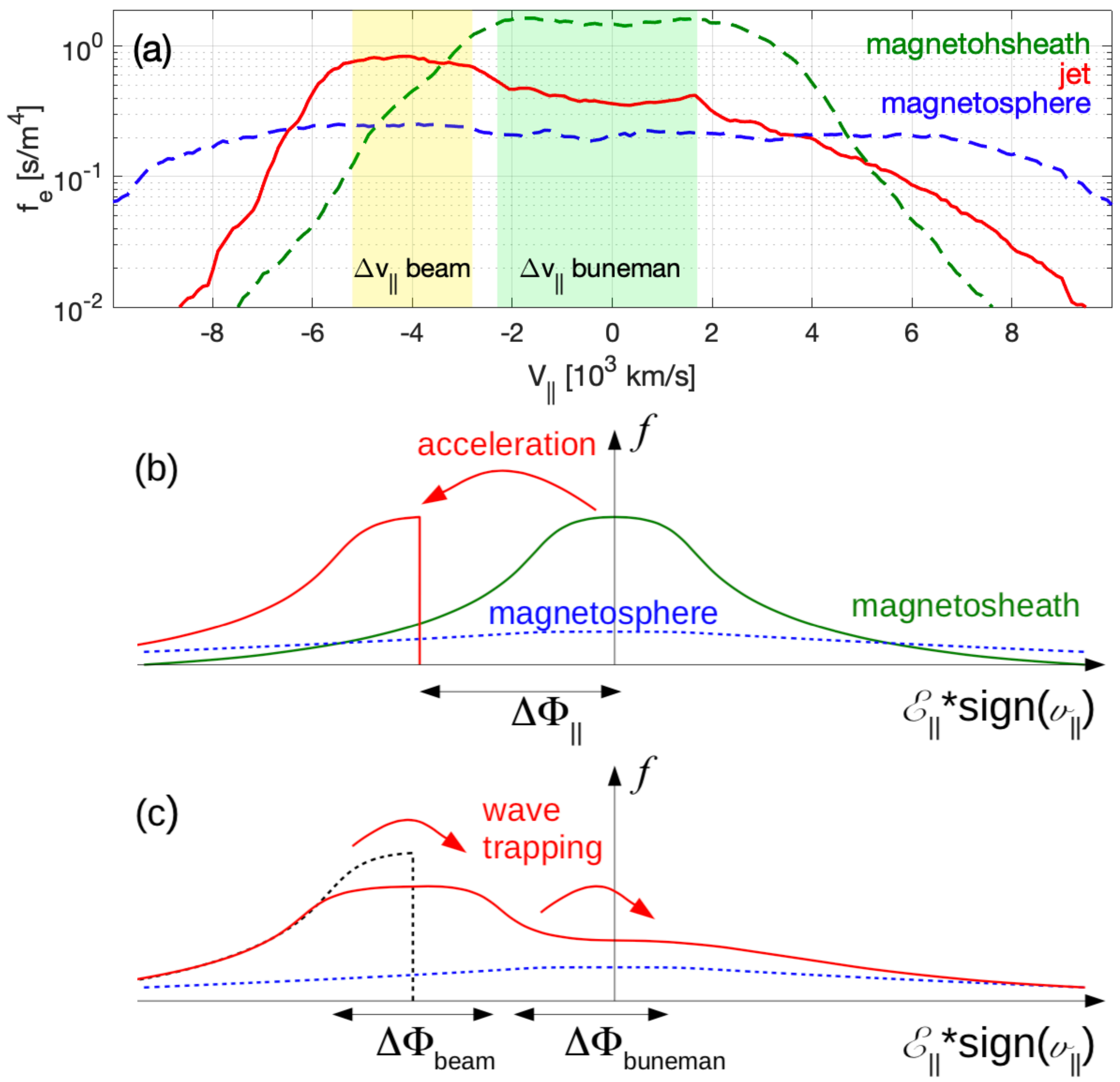
[Munõs & Büchner, ApJ, 2018]

[Khotyaintsev, Graham et al, PRL, 2020]



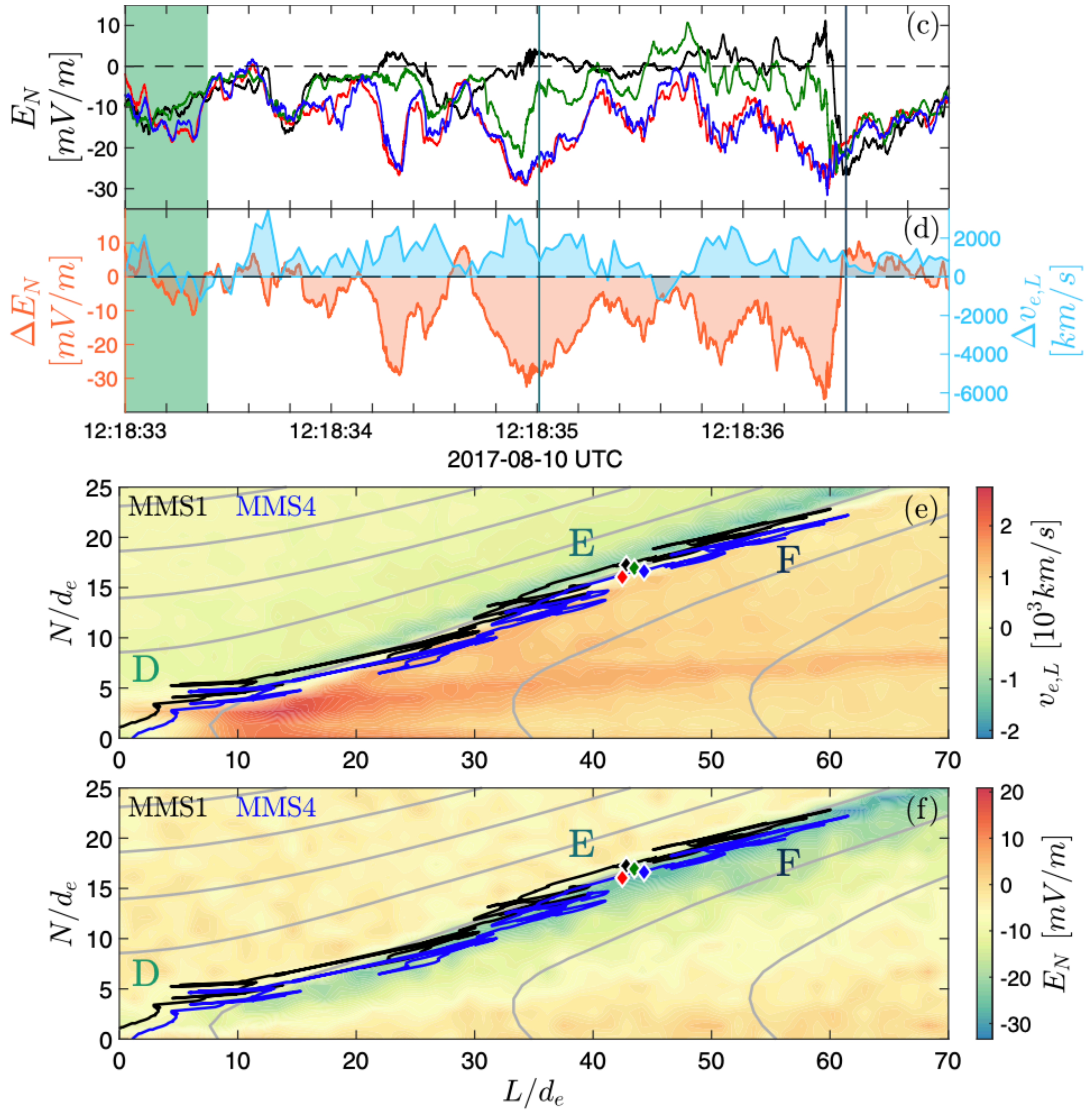


Development of the Debye-scale turbulence leads to rapid thermalization of the electron jet

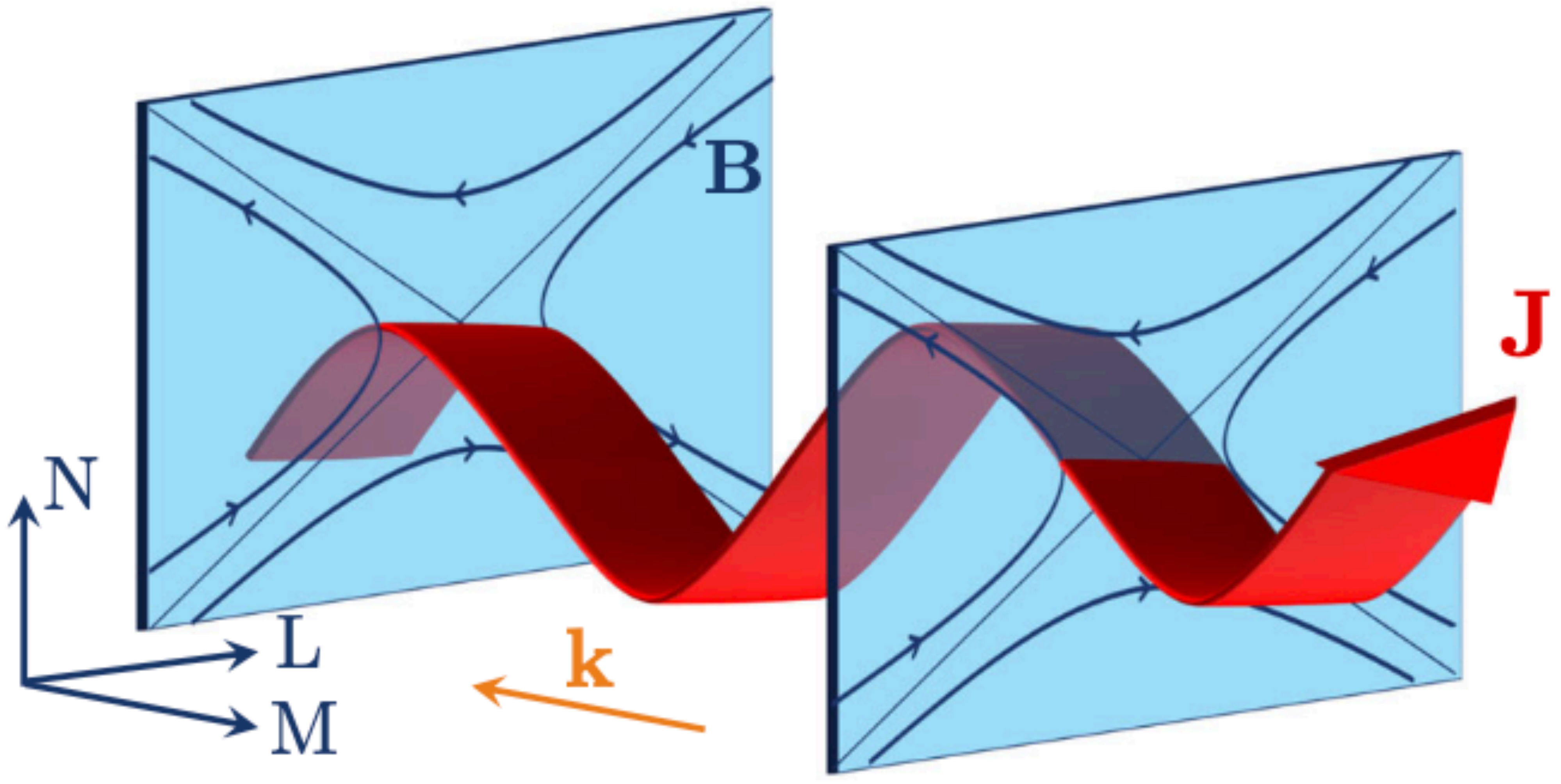


[Khotyaintsev, Graham et al, PRL, 2020]

3D structure — CS kinking



current sheet kinking propagating in the out-of-reconnection-plane direction



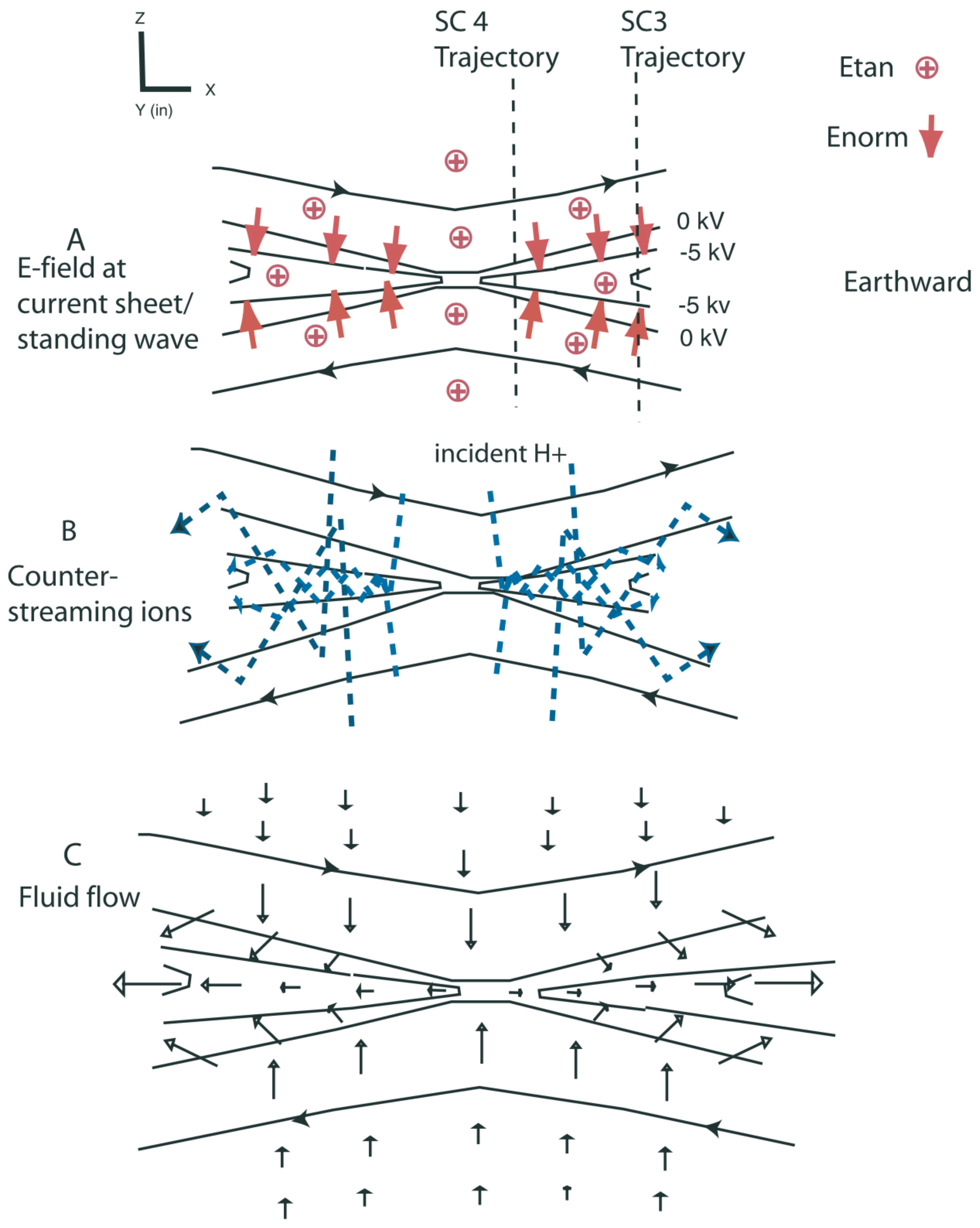
[Cozzani, Khotyaintsev et al, PRL, 2021]

Ion and electron heating

Ion Heating in Reconnection Jets

- Ions in the reconnection jet are accelerated by the Hall electric field, forming counter-streaming beams [e.g., Wygant+2005, JGR].
- Multiple reflections form the reconnection outflows
- Predisted temperature in the outflow for cold inflow [Drake+2009, JGR]:

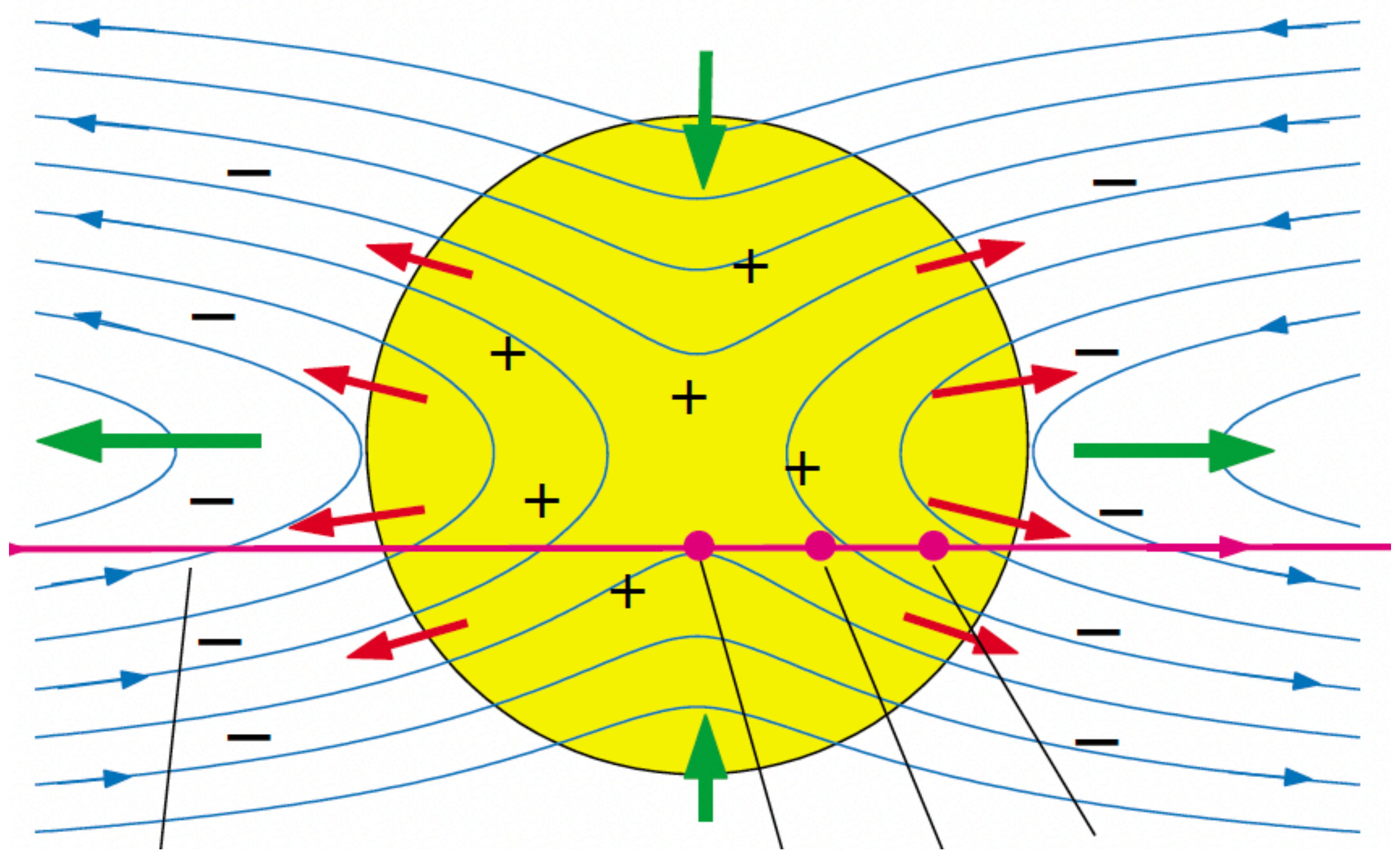
$$T_i = \frac{1}{3} m_i v_0^2;$$



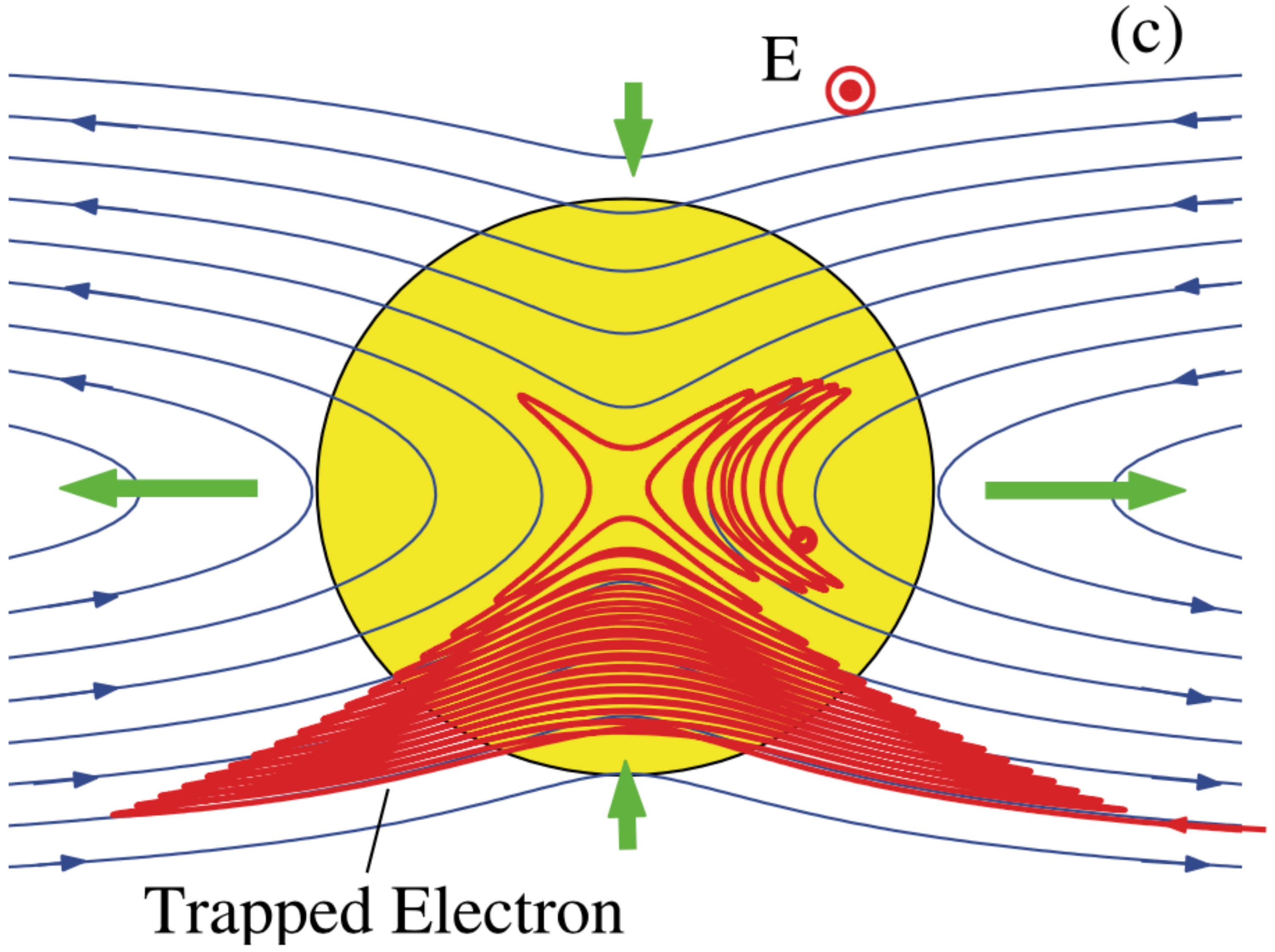
Electron Heating by Parallel Electric Fields in Reconnection

Large-scale acceleration potential $e\Phi_{\parallel} = \int_x^{\infty} E_{\parallel} dl$ associated with magnetic reconnection

[Egedal et al., 2005]



Electrons are trapped by the potential in order to maintain quasi-neutrality near the diffusion region

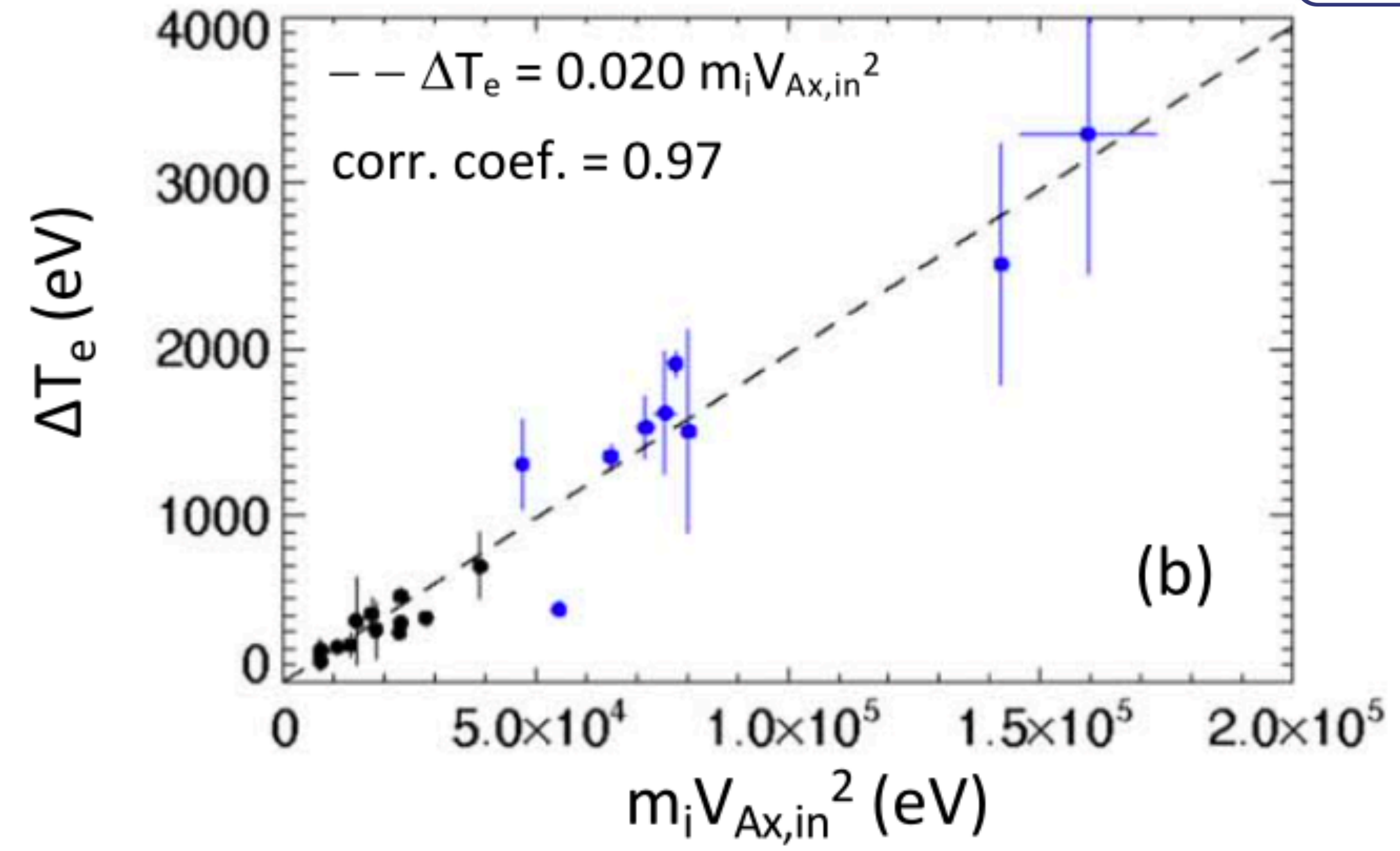


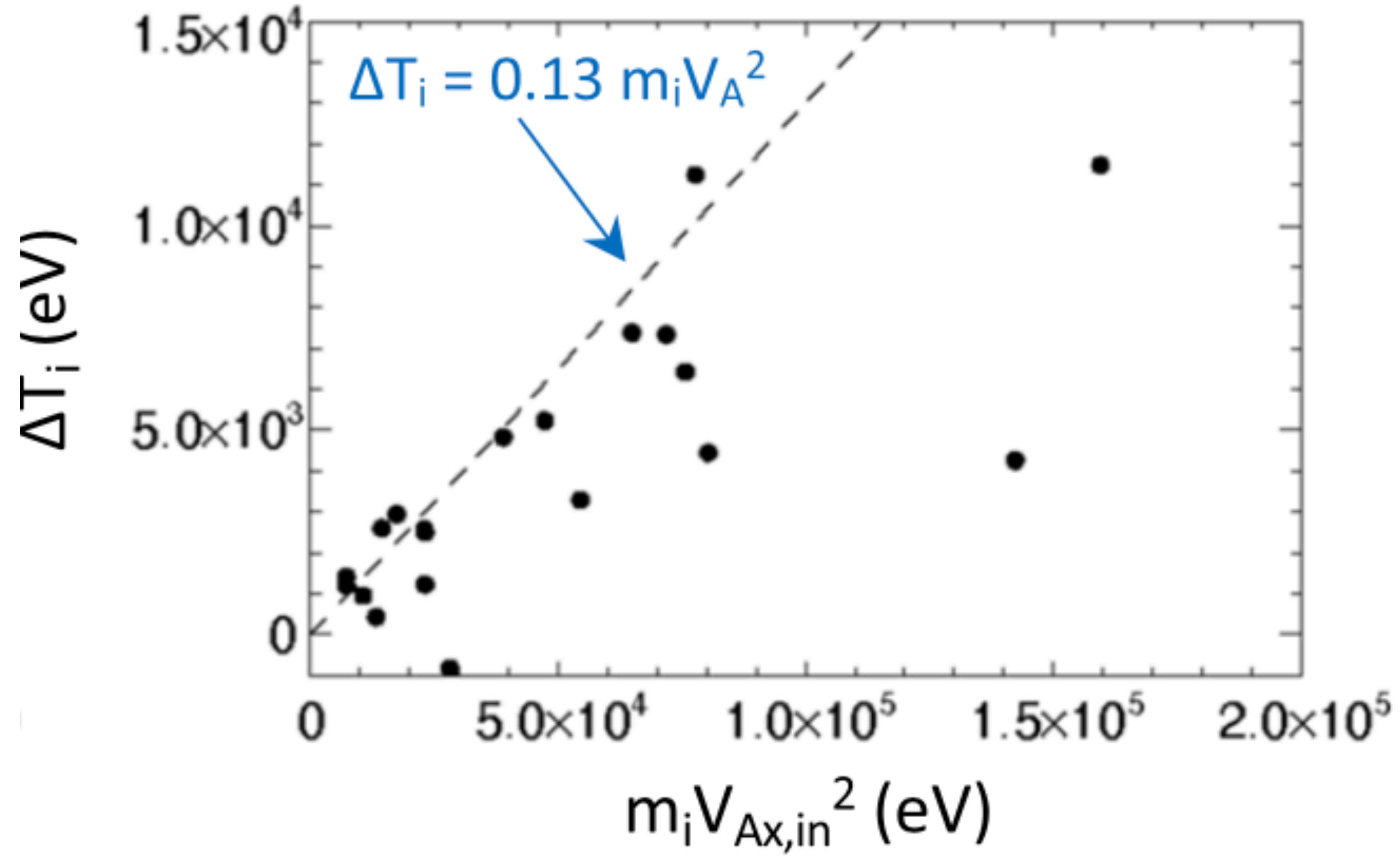
[Egedal et al, JGR, 2008]

Electron and ion heating

- Ions are more heated than electrons
- Electron heating scales linearly with available magnetic energy per particle
- But the ion heating does not
- Haggerty et al (2015) suggested this is because of the potential:

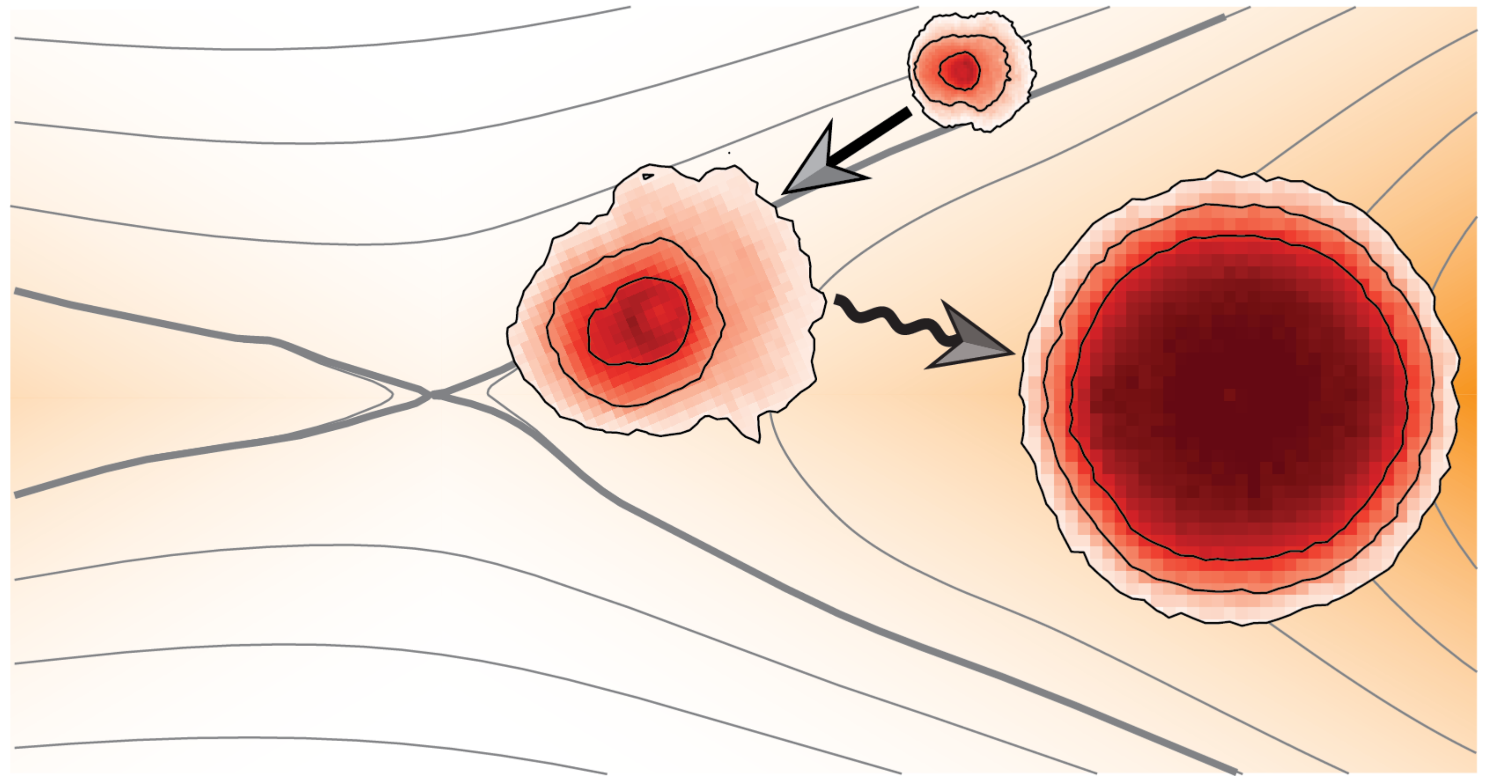
$$\Delta T_i = \frac{1}{3} m_i V_0^2 - \frac{2}{3} e \Delta \phi_n$$

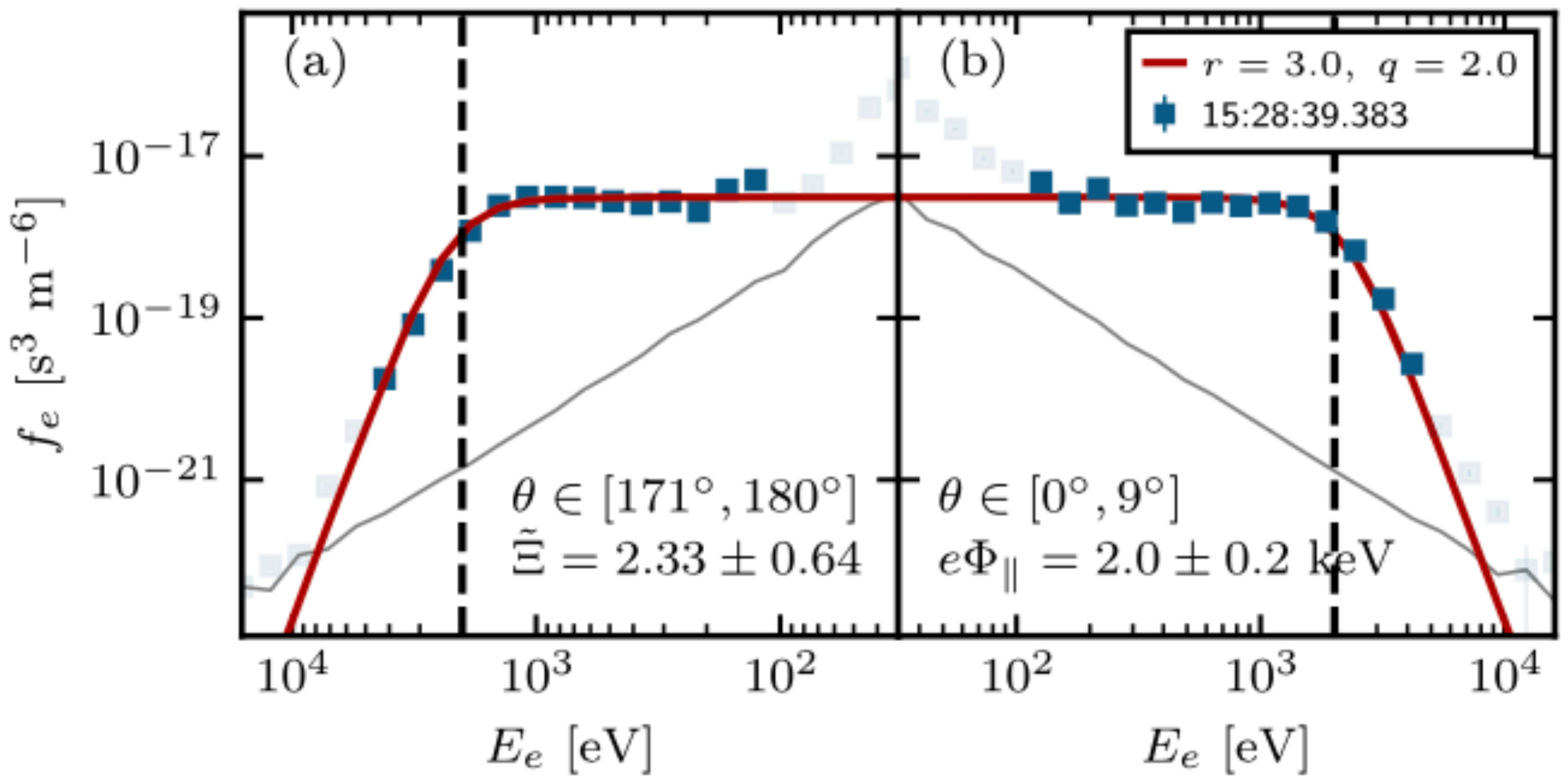




[Øieroset et al, ApJ, 2023, 2024]

Electron Heating in Magnetotail Reconnection

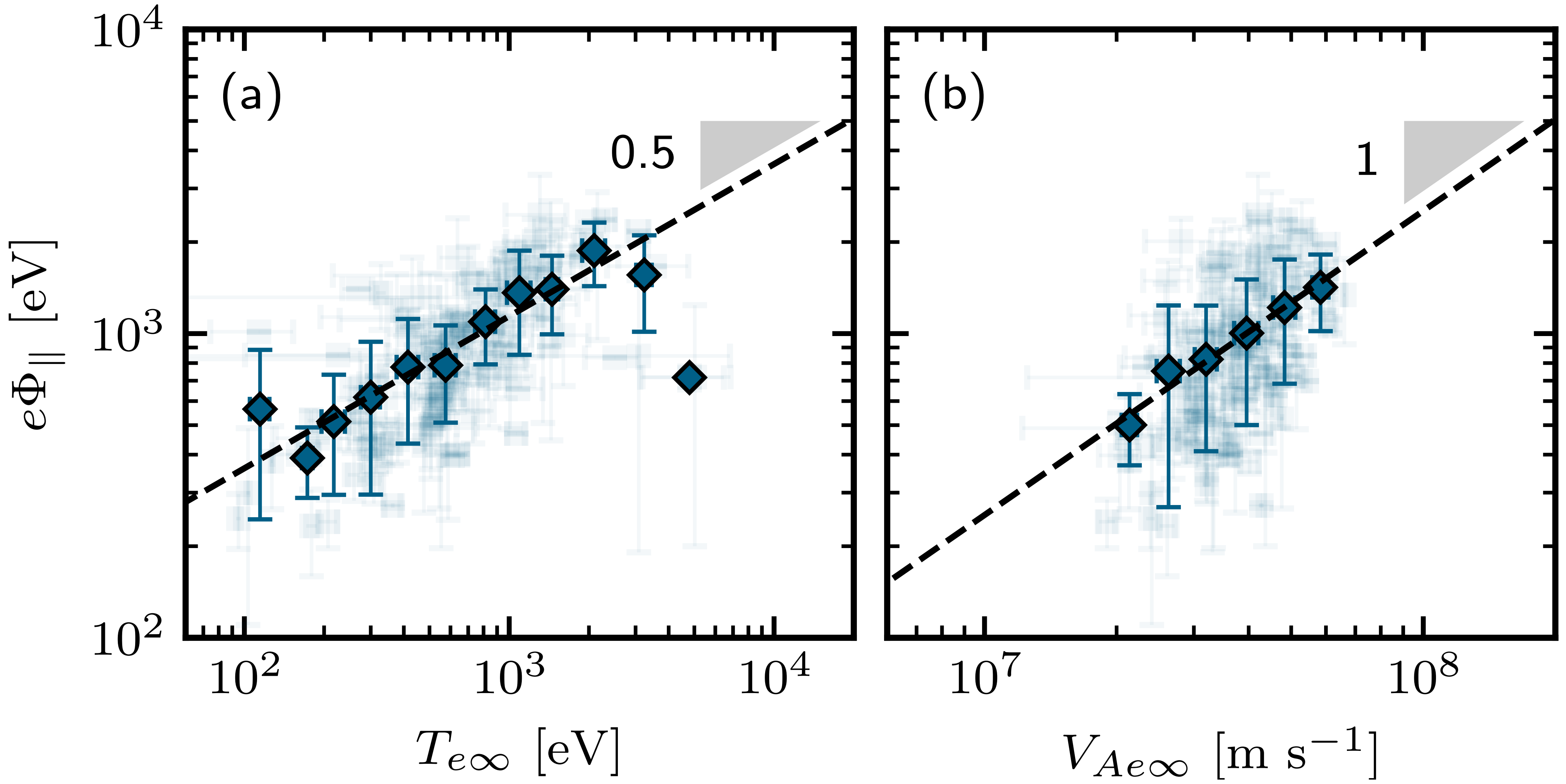




- Parallel electric fields heat plasma up to 10× its initial temperature

- New empirical model for ion-to-electron energy partitioning:

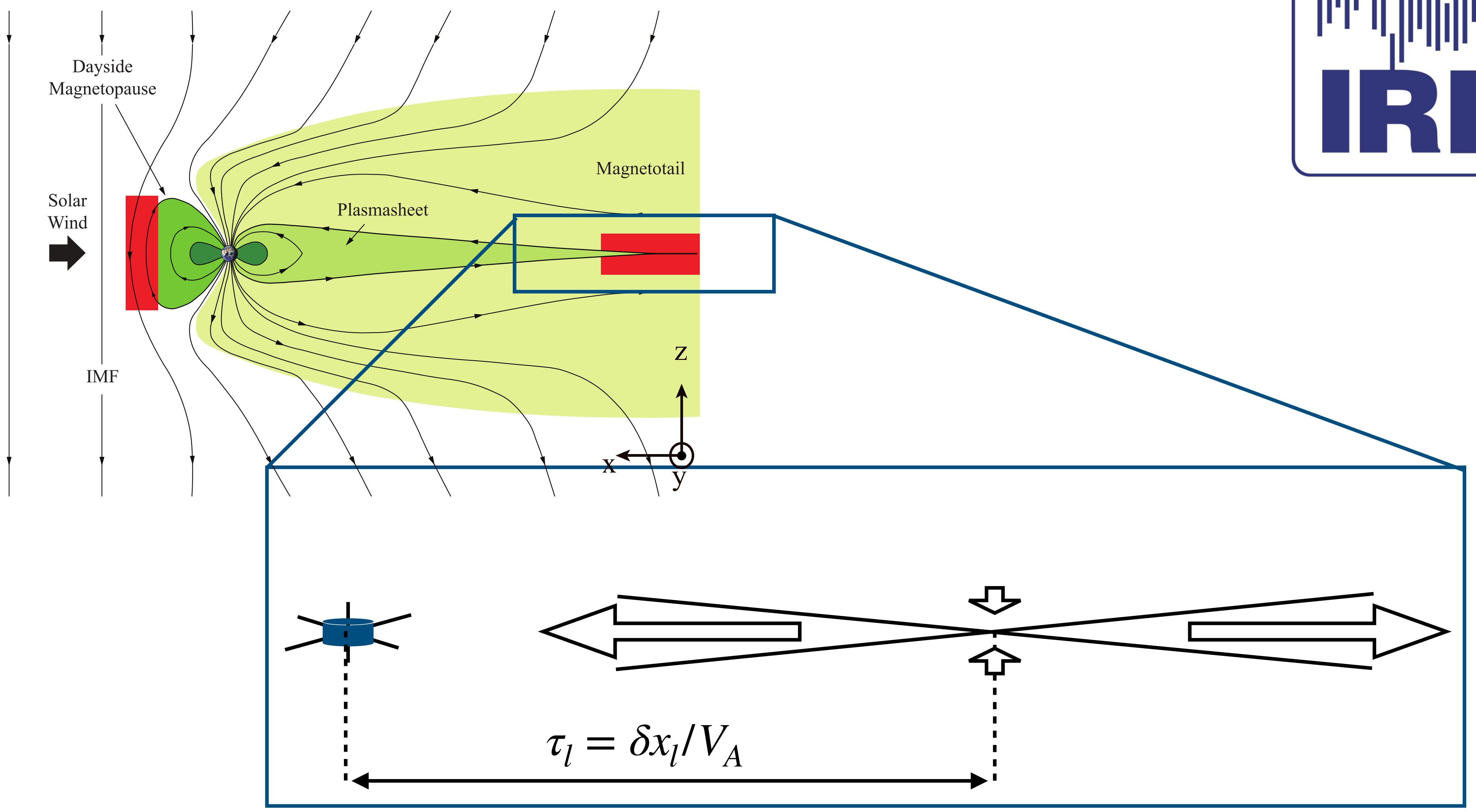
$$\Delta T_i / \Delta T_e \propto 1 - \beta_{e\infty}^{1/2}$$

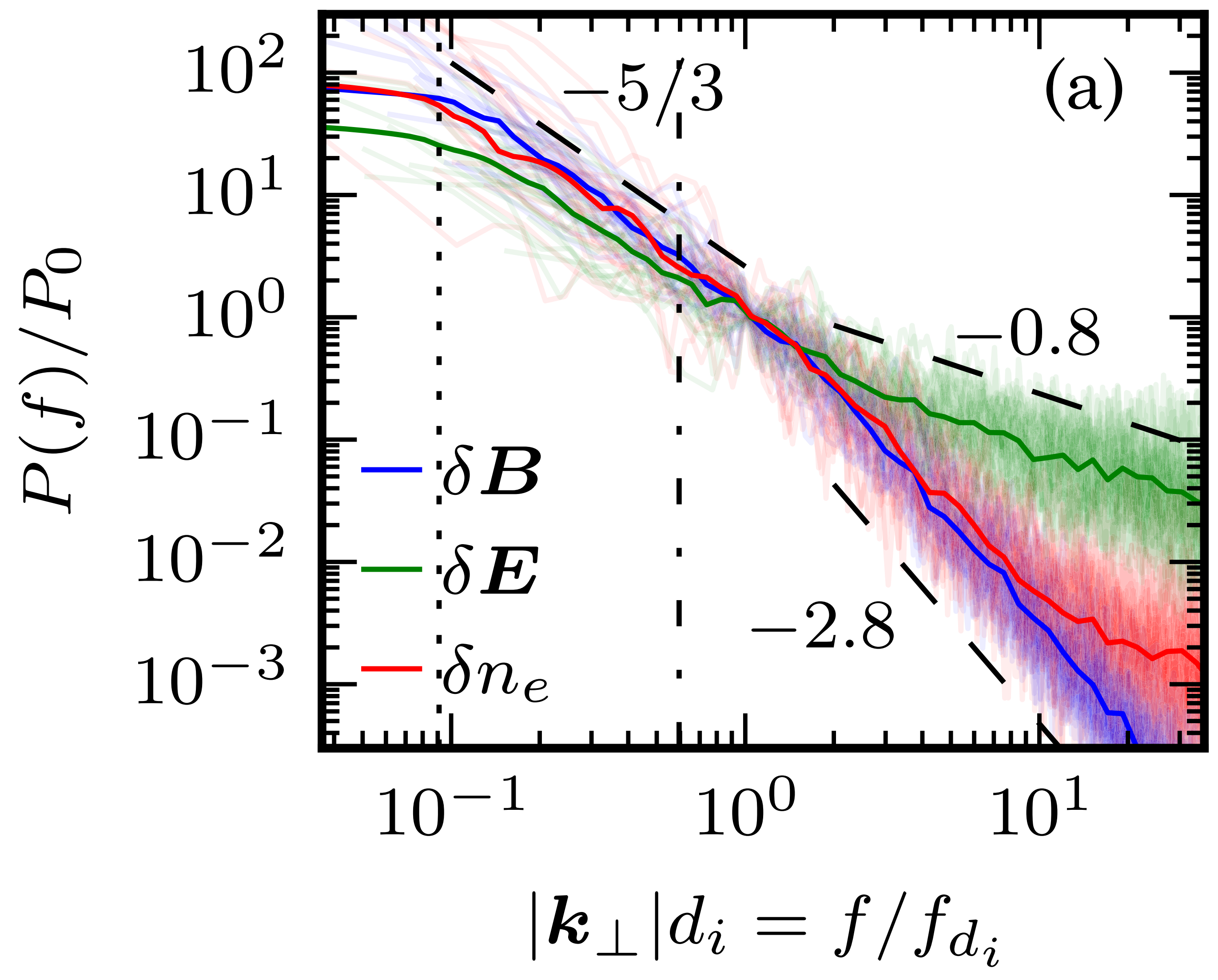


[Richard, Khotyaintsev et al, PRL, 2025]

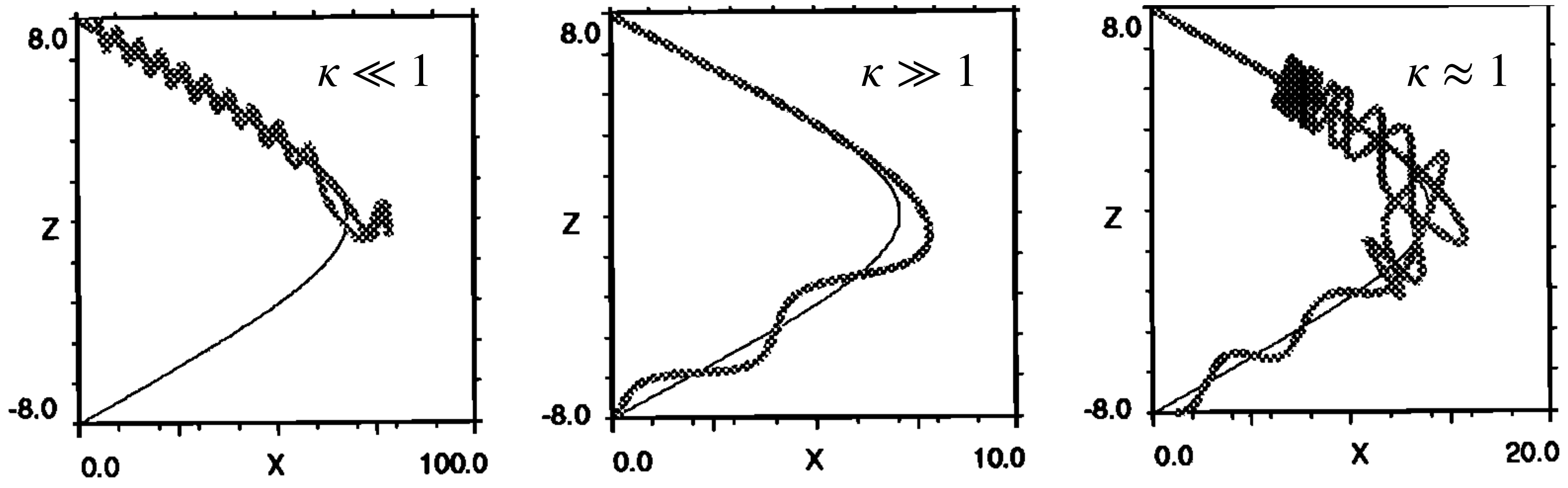
Reconnection jets

- Fully developed turbulence from injection to sub-ion scales
- Develops within a few gyro-periods
- The turbulent energy transfer rate accounts for a substantial fraction of the reconnection energy budget.
- Scattering in curved fields is the primary mechanism for ion iostropization





[Nakamura+199



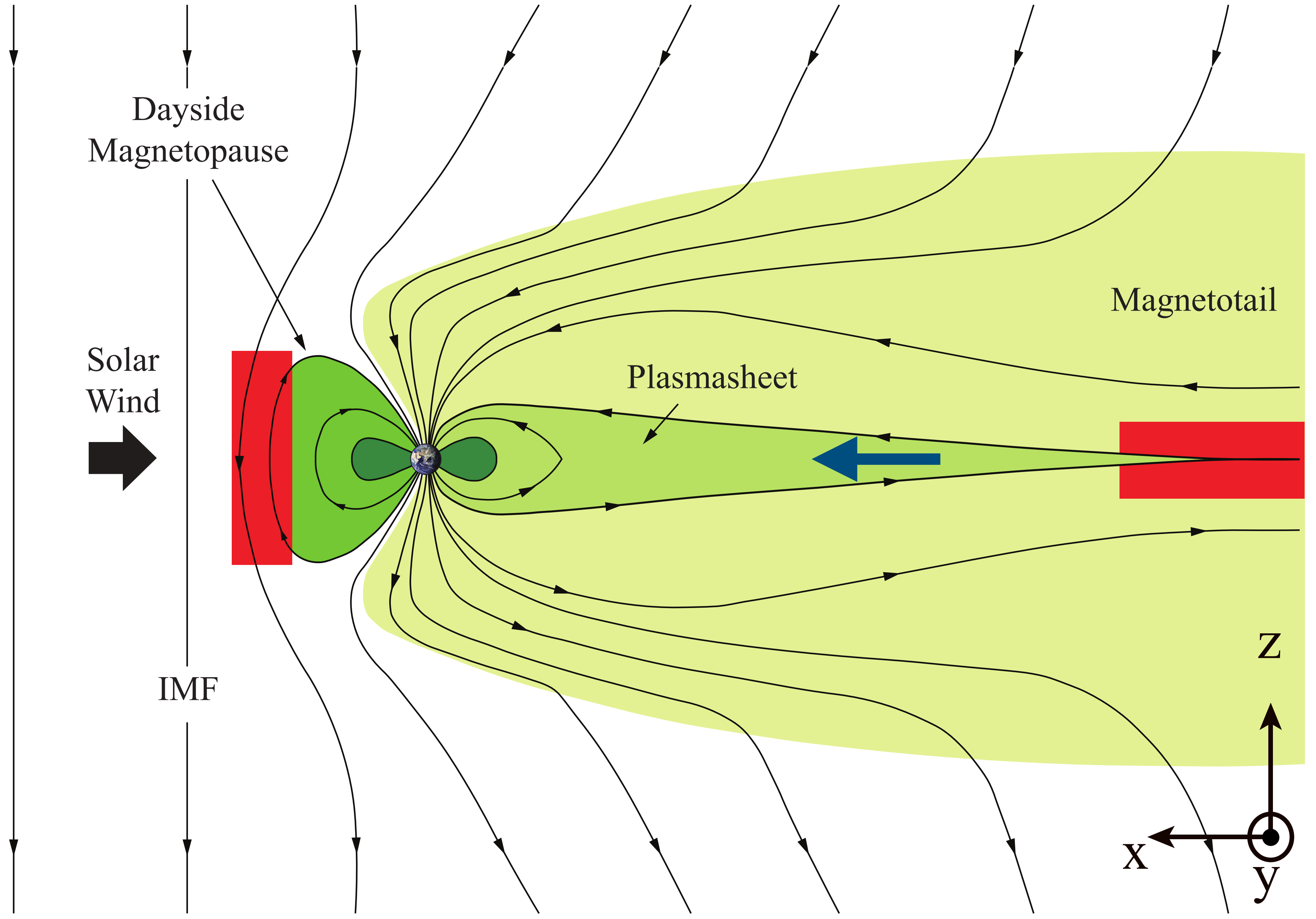
[Richard, Khotyaintsev et al., PRL, 2023]

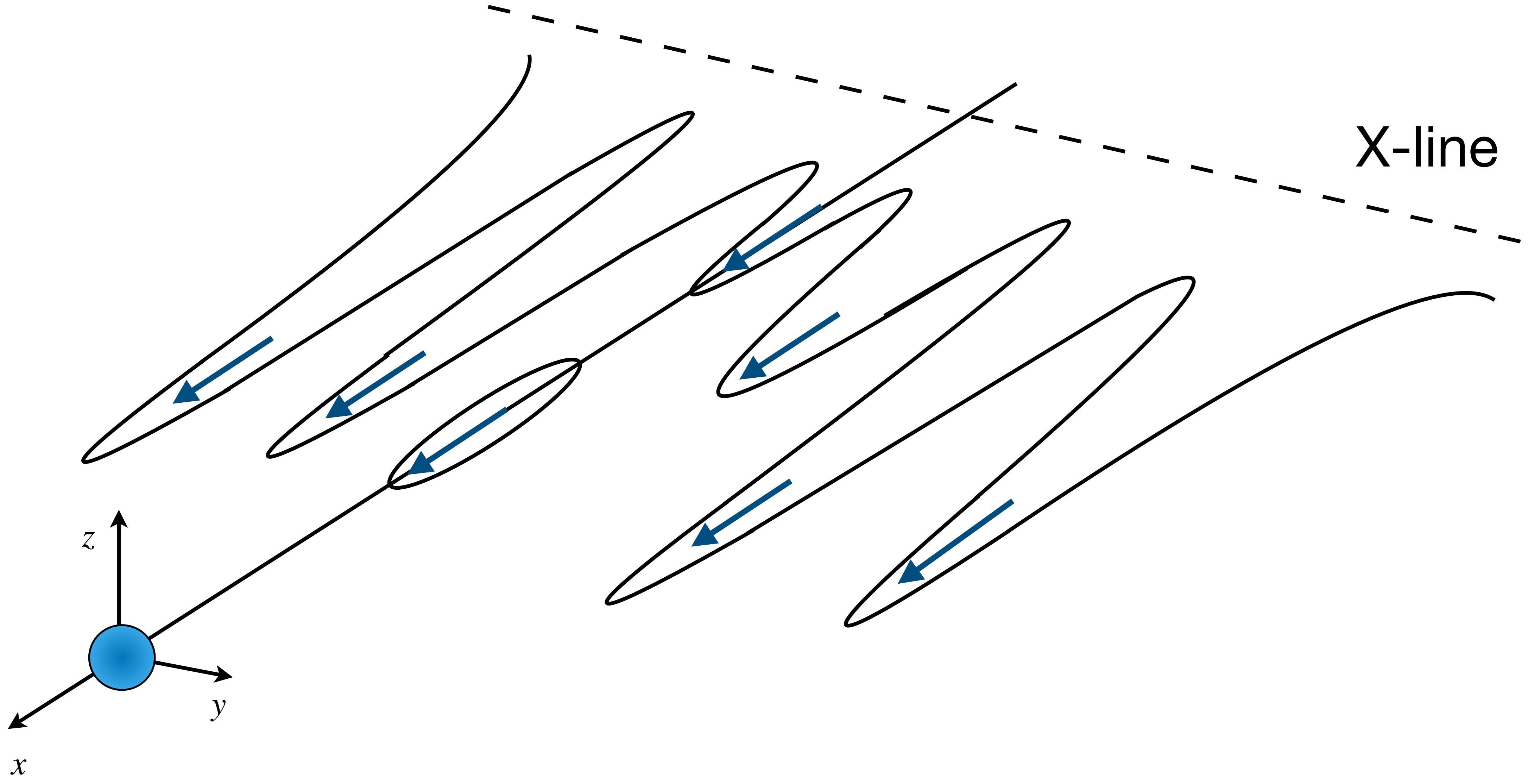
[Richard et al, PRL, 2024]

Larger scales: Dissipation, ion and electron heating

Large-scale 3D structure

Magnetotail Reconnection Jets a.k.a. Bursty Bulk Flows

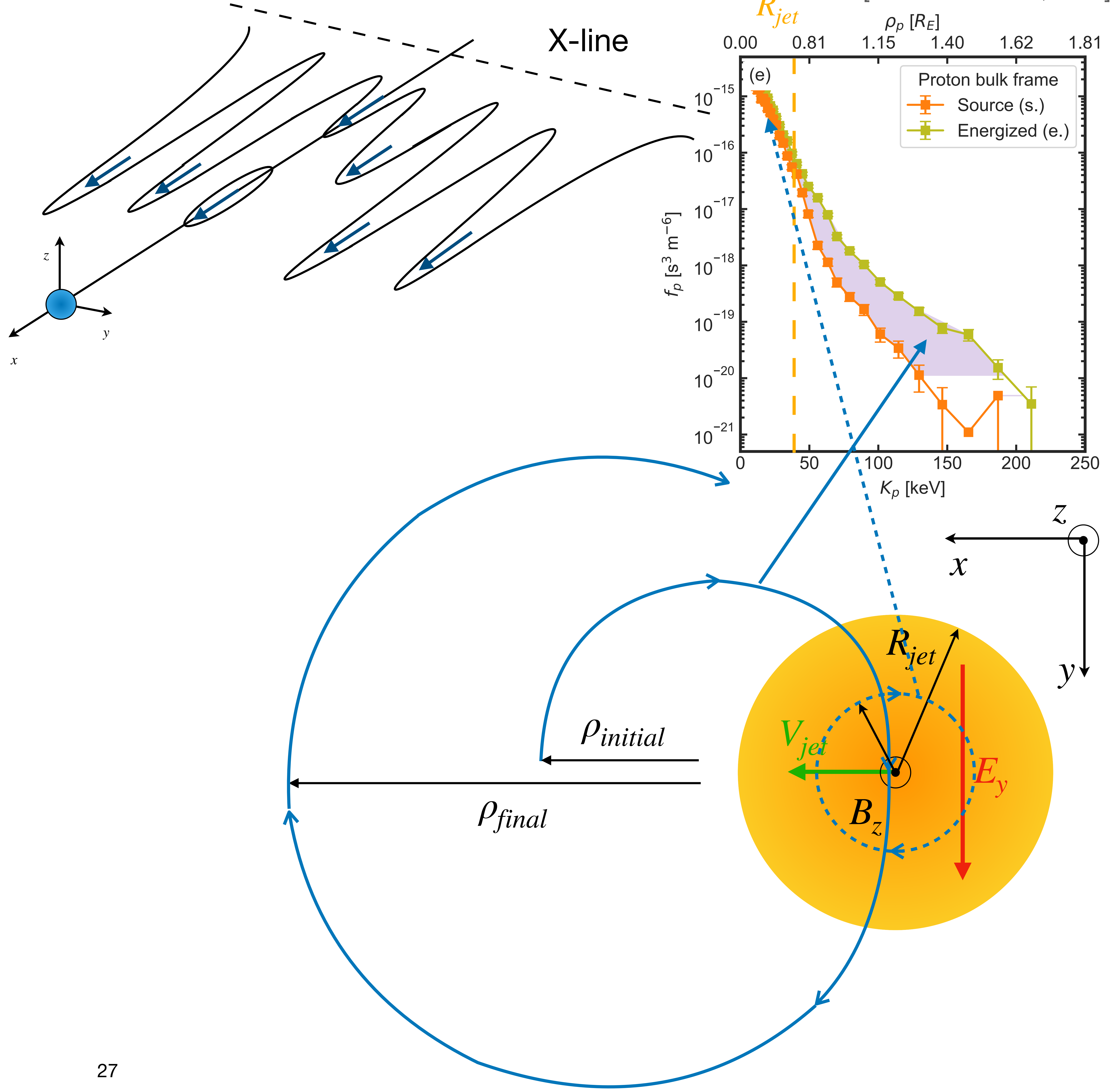




Magnetotail reconnection jets are "narrow" ($\sim R_E$), finger-like, transients.

Ion Acceleration

[Richard+2022a, JGR]

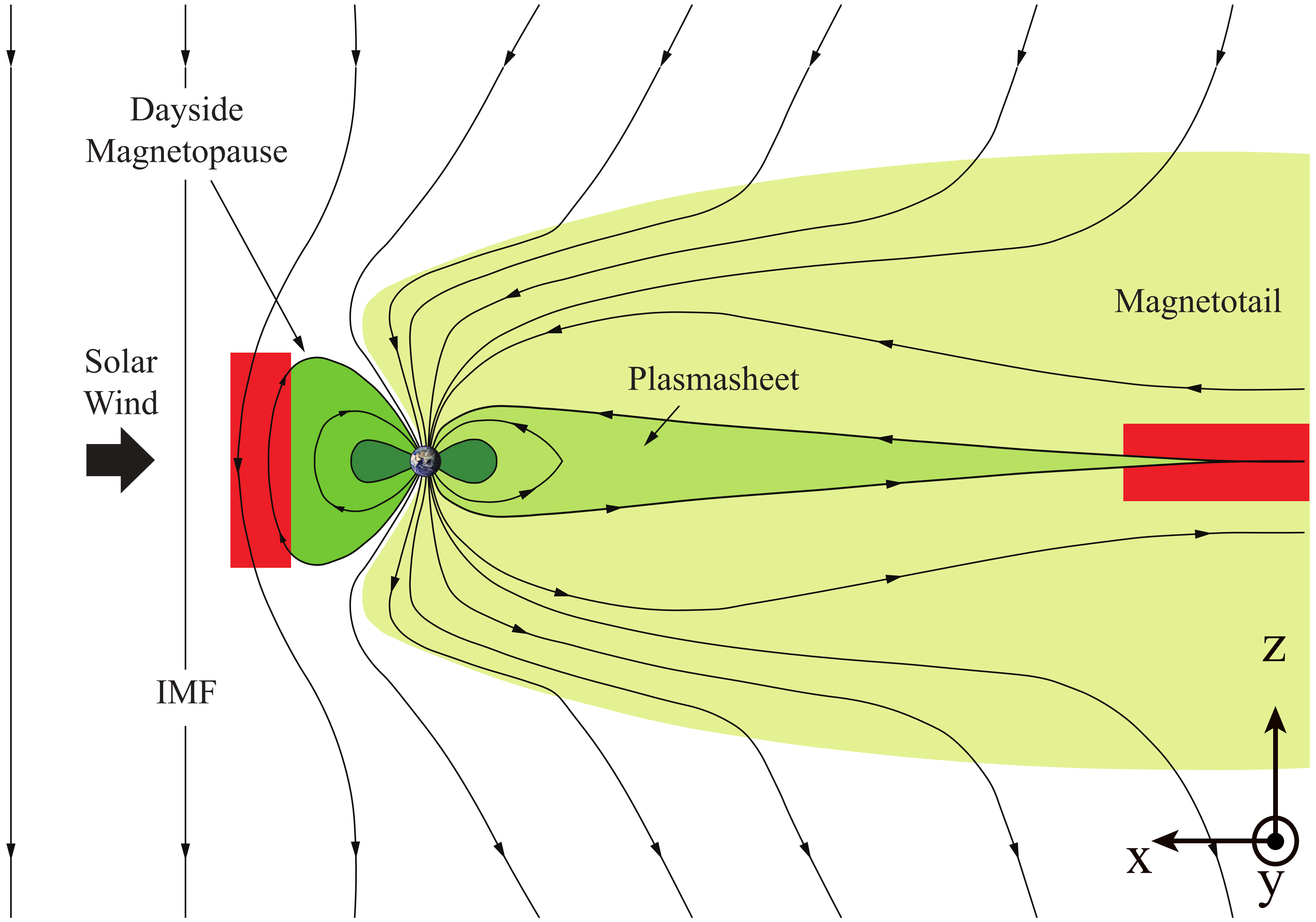


Ions with $\rho_i > R_{jet}$ accelerated and ions with $\rho_i < R_{jet}$ are convected with the jet.

[Richard, Khotyaintsev et al., JGR, 2022]

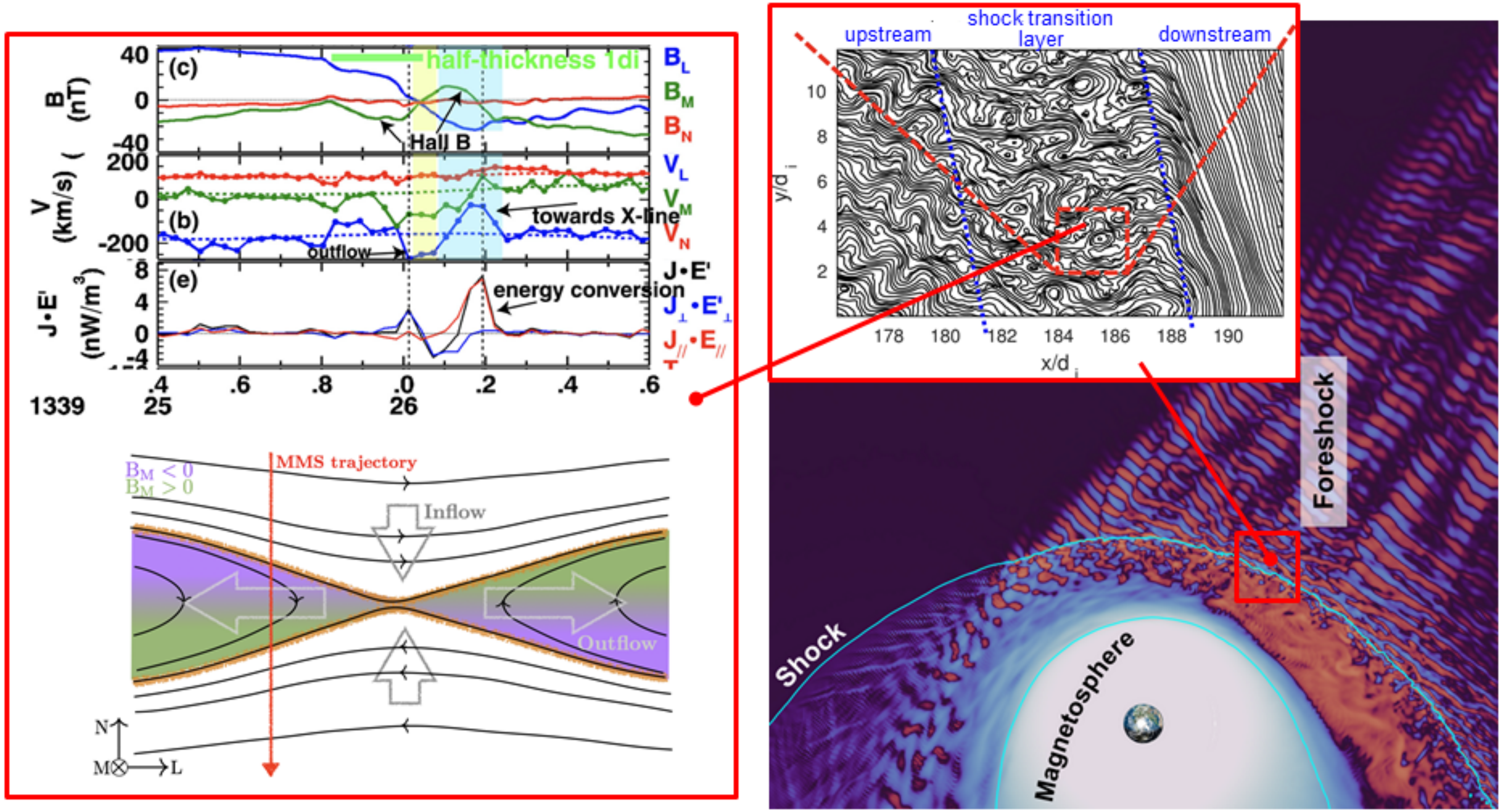
Liminations of magnetospheric observations

- Magnetopause, magnetotail - driven system, small system, both the X-line extent, and outflow are limited by the Earth's dipole
- For larger systems: solar wind reconnection
- High guide-field cases not well developed, can look at the ionosphere



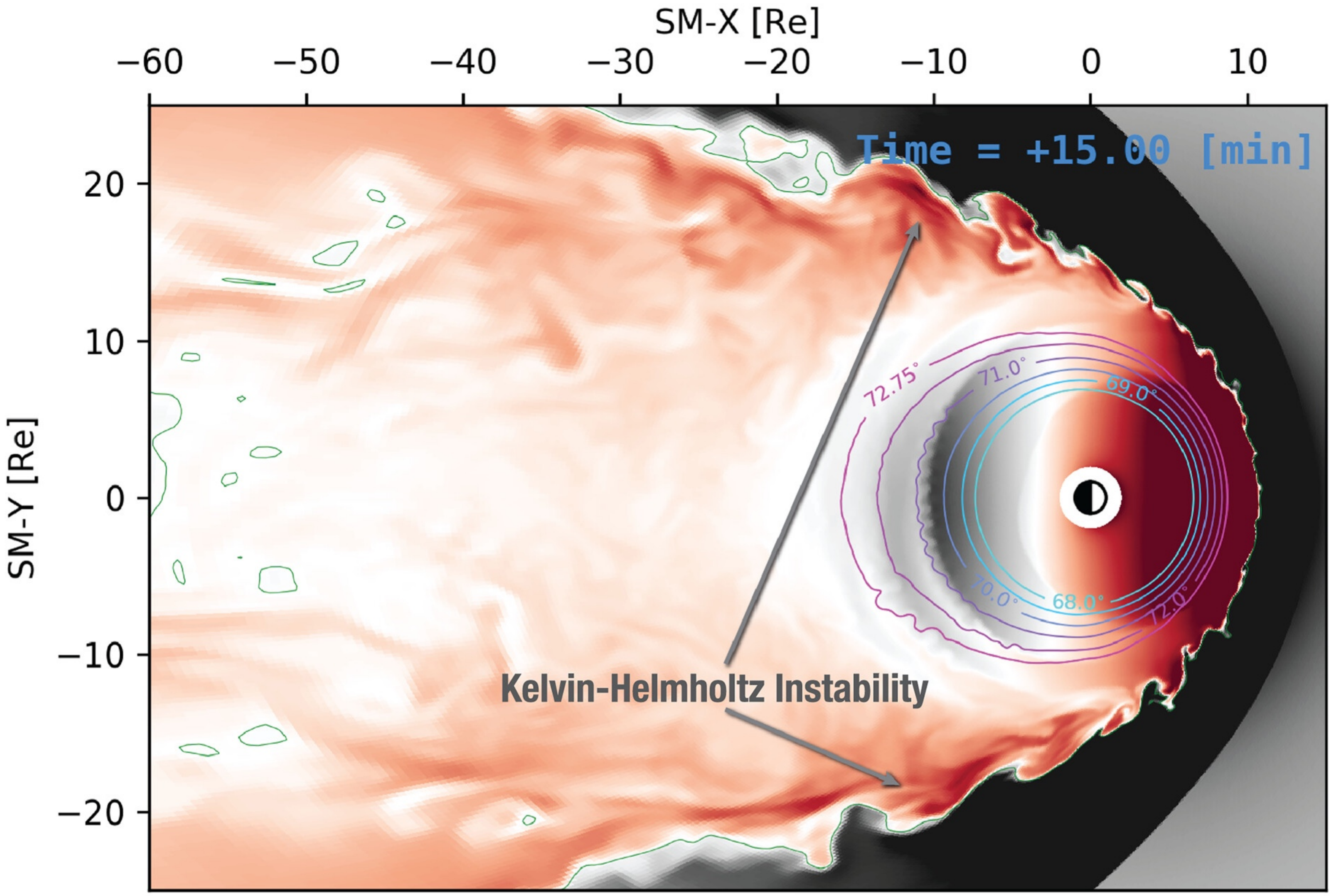
Reconnection is never alone

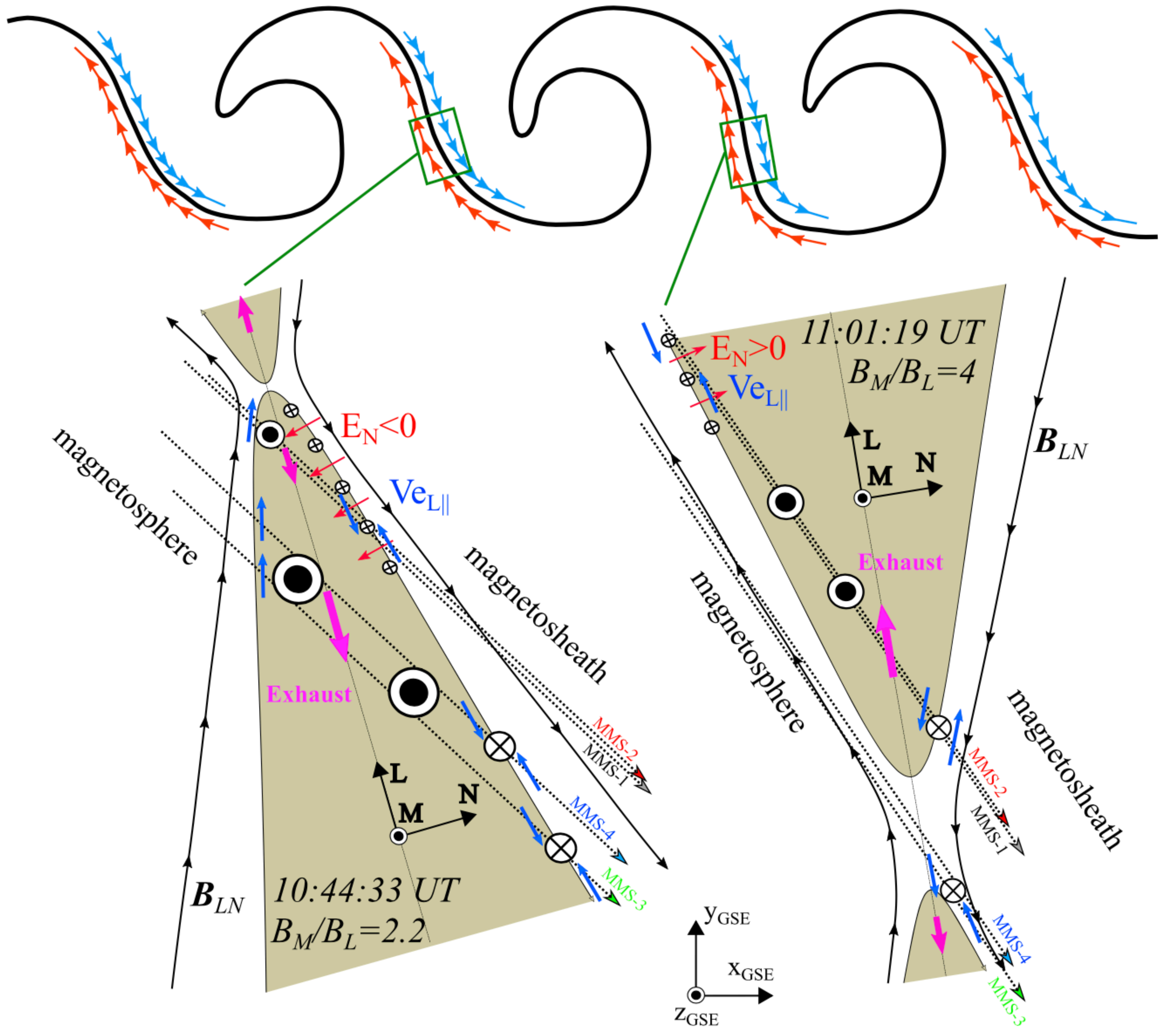
Reconnection + shocks + turbulence



Gingell et al., 2019; Wang et al., 2019; L. Turc

Reconnection + KHI + turbulence





[Sorathia et al, JGR, 2020]

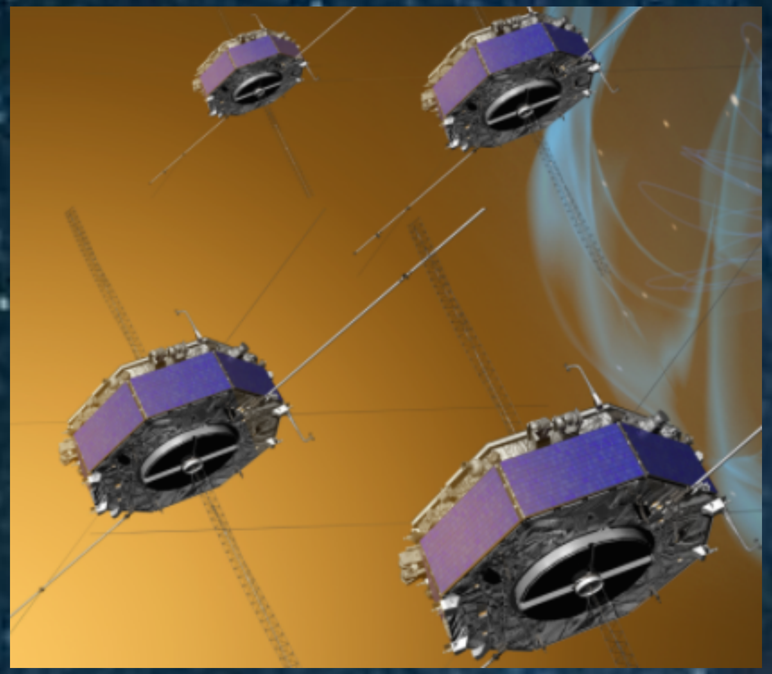
[Eriksson et al, GRL, 2016]

Plasma Observatory - what do we need from the future observations?

Reaching for the future from the shoulders of giants

First simultaneous multi-scale measurements

Electron scale | Ion scale | Fluid scale



MMS (2015-):
first 3D electron-scale view

Cluster (2000-2026):
first 3D view of the magnetosphere

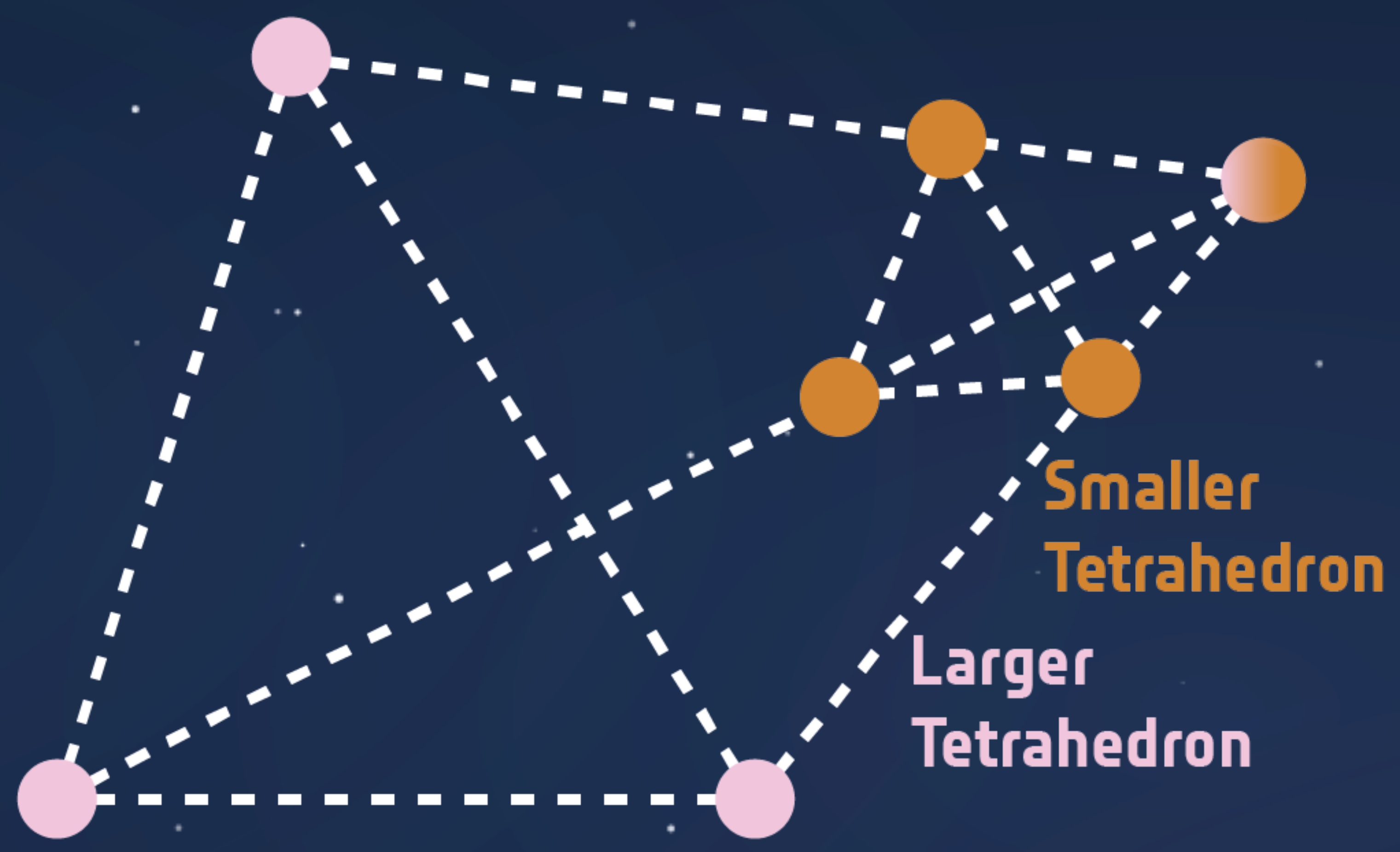
Multi-point has been transformative

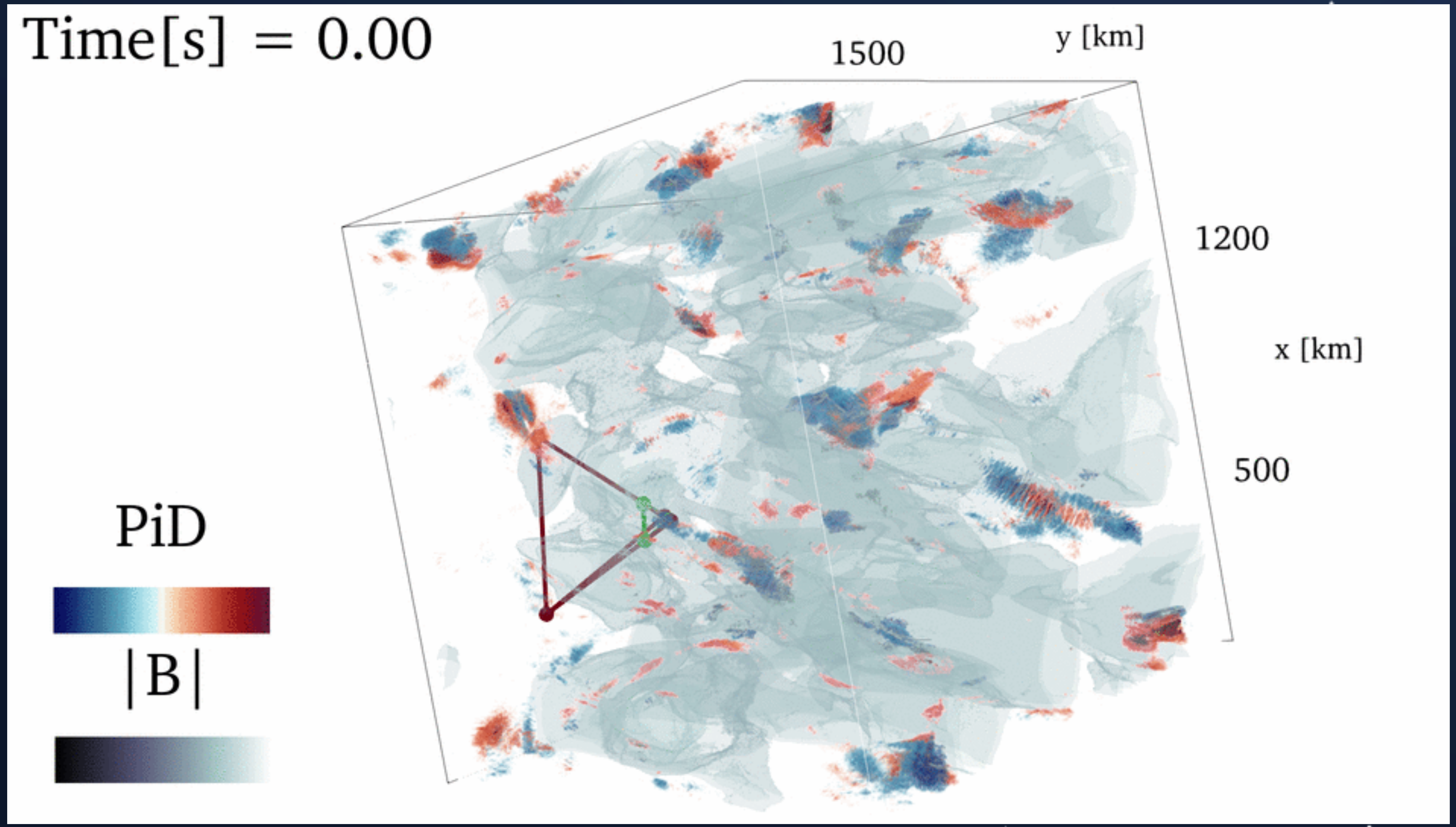
Single-scale limit reached

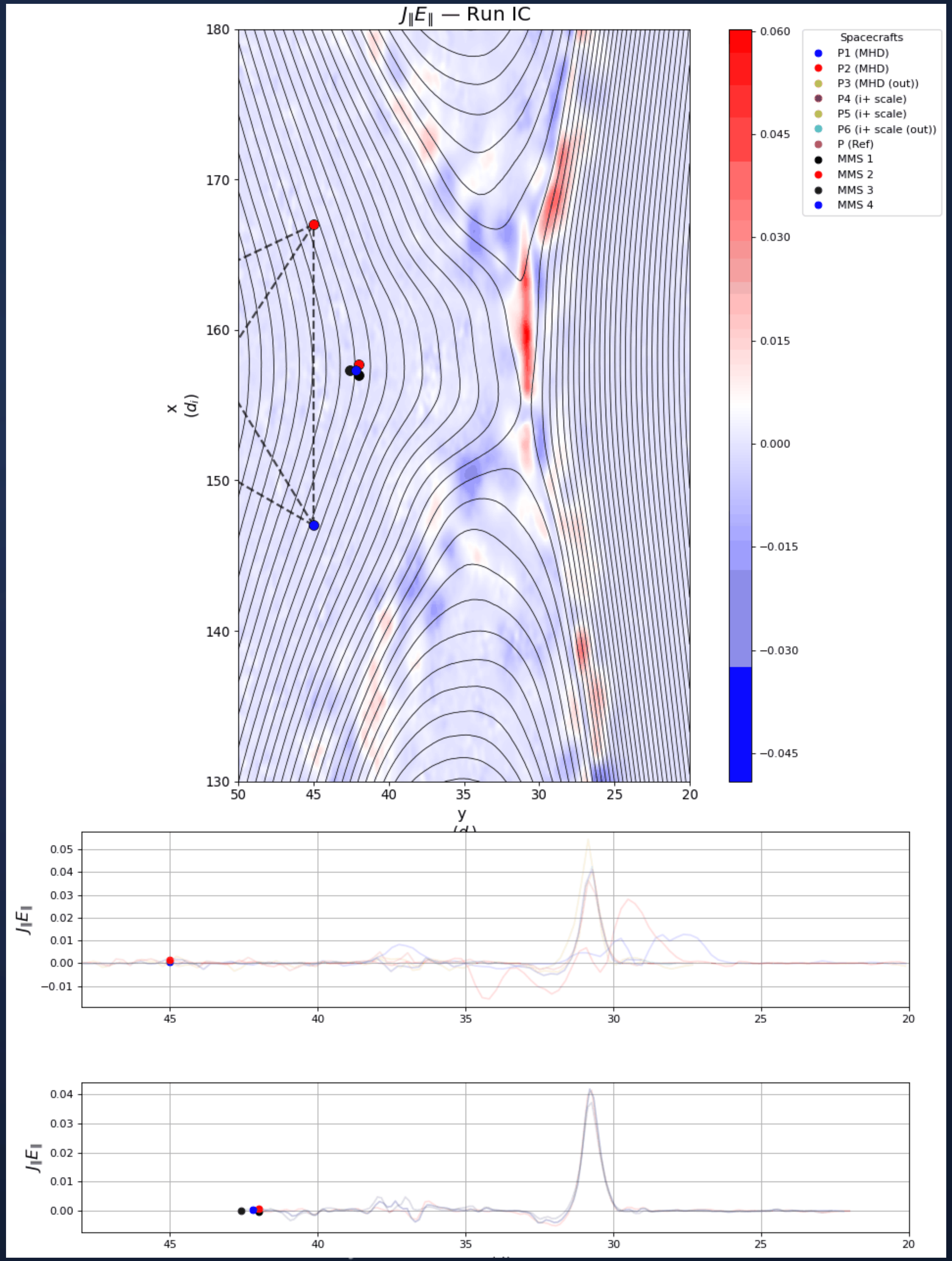
How many points do we need ?

4 points: single scale in 3D, simple plasma structures

7 points: two scales in 3D, non-planar & non-stationary structures

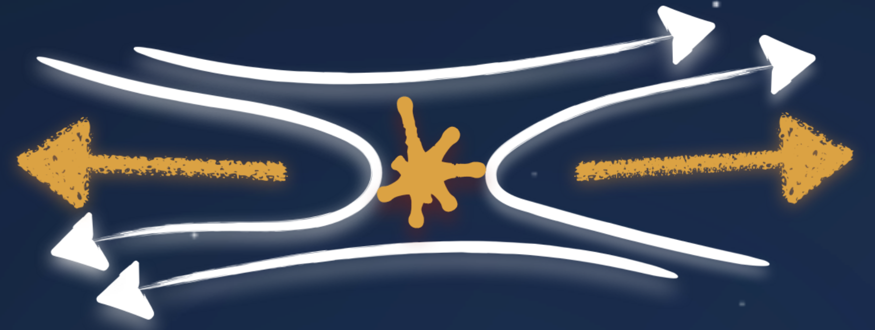






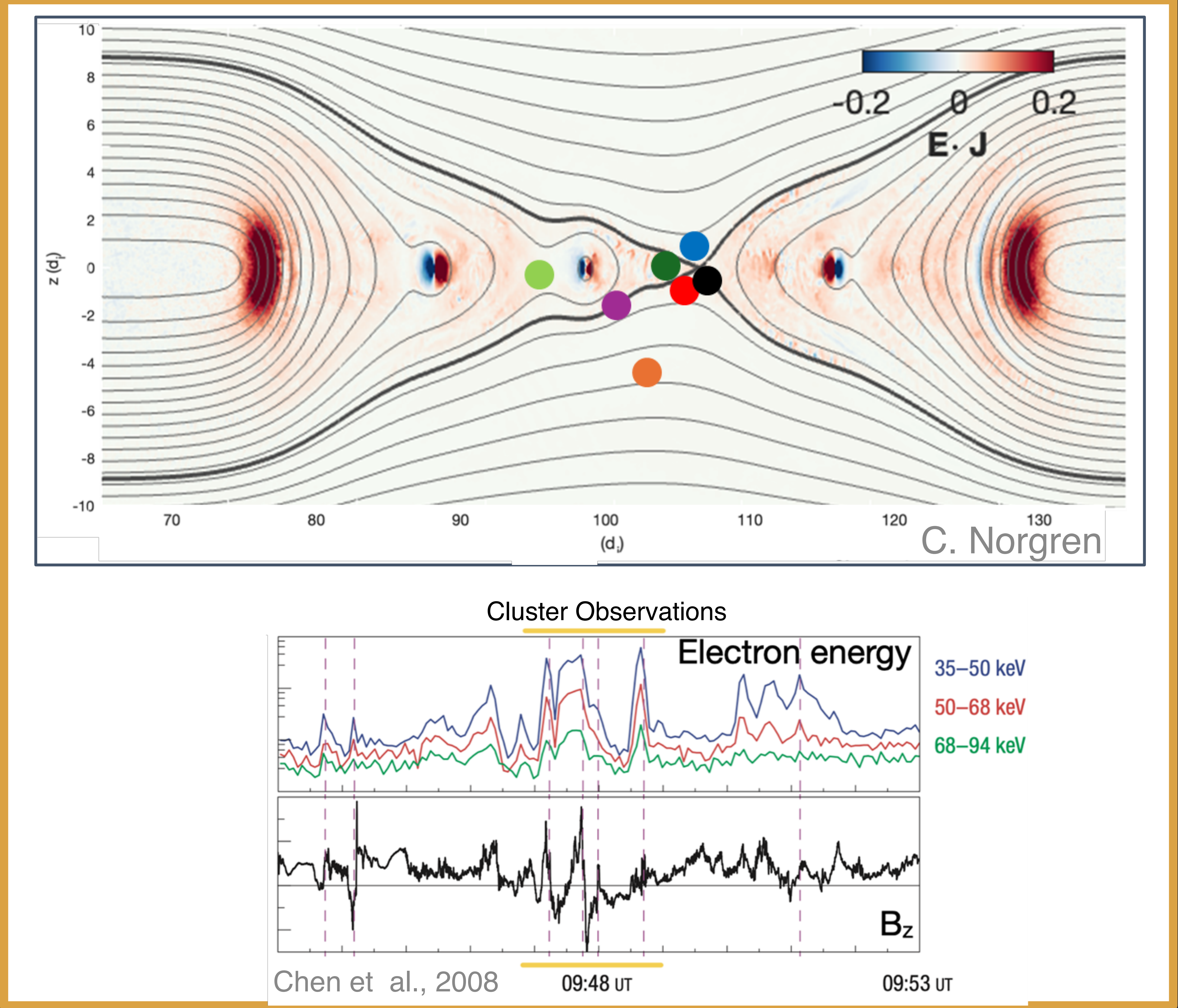
How are particles energized during magnetic reconnection?

SO2



Reconnection regions: inherently multi-scale structures from kinetic to fluid scales.

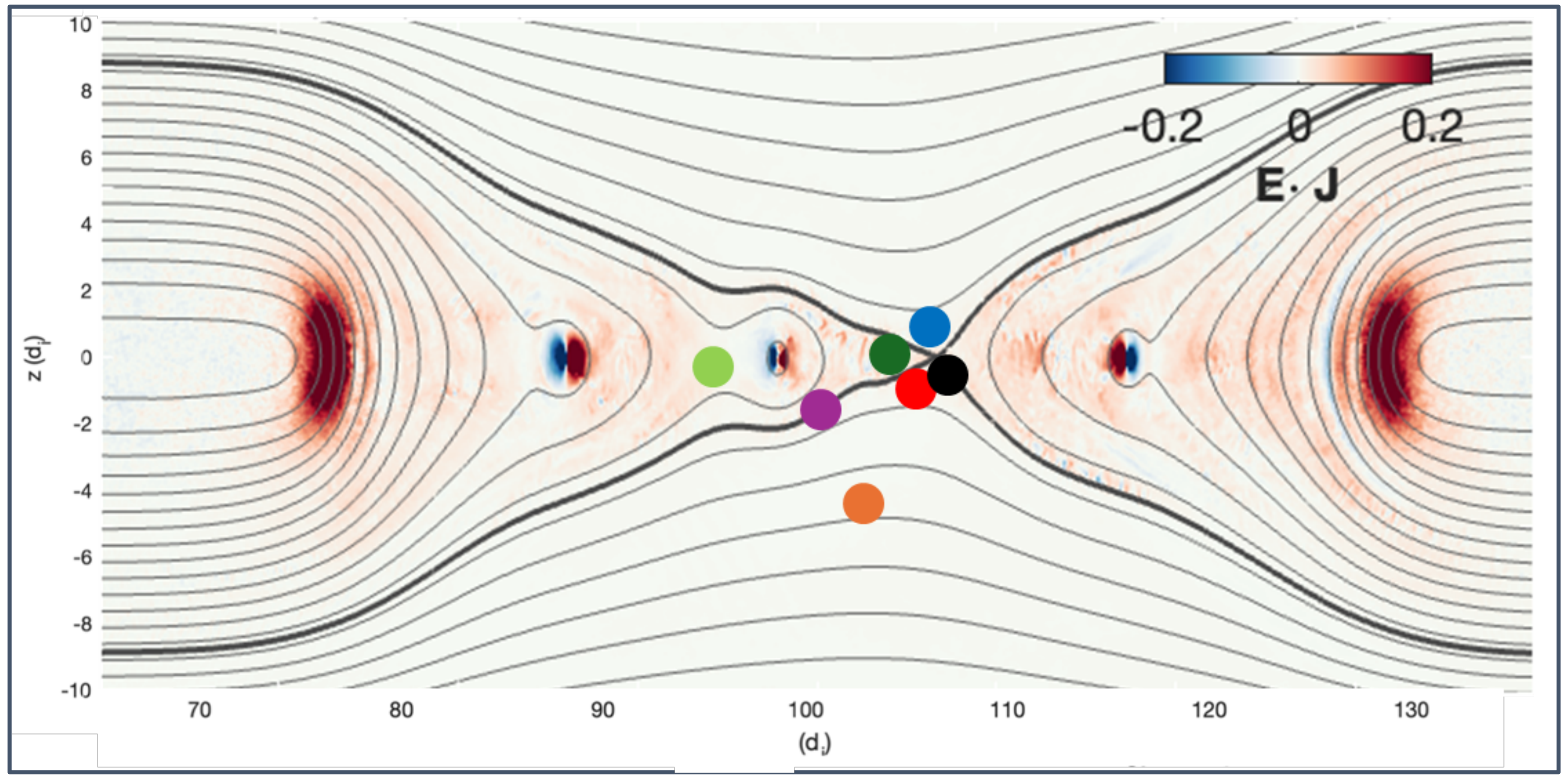
Key unknowns: multi-step particle acceleration



*PO first: Provide **quantitative, cross-scale description** of the drivers and processes of electron, proton and heavy ion energization.*

Open questions

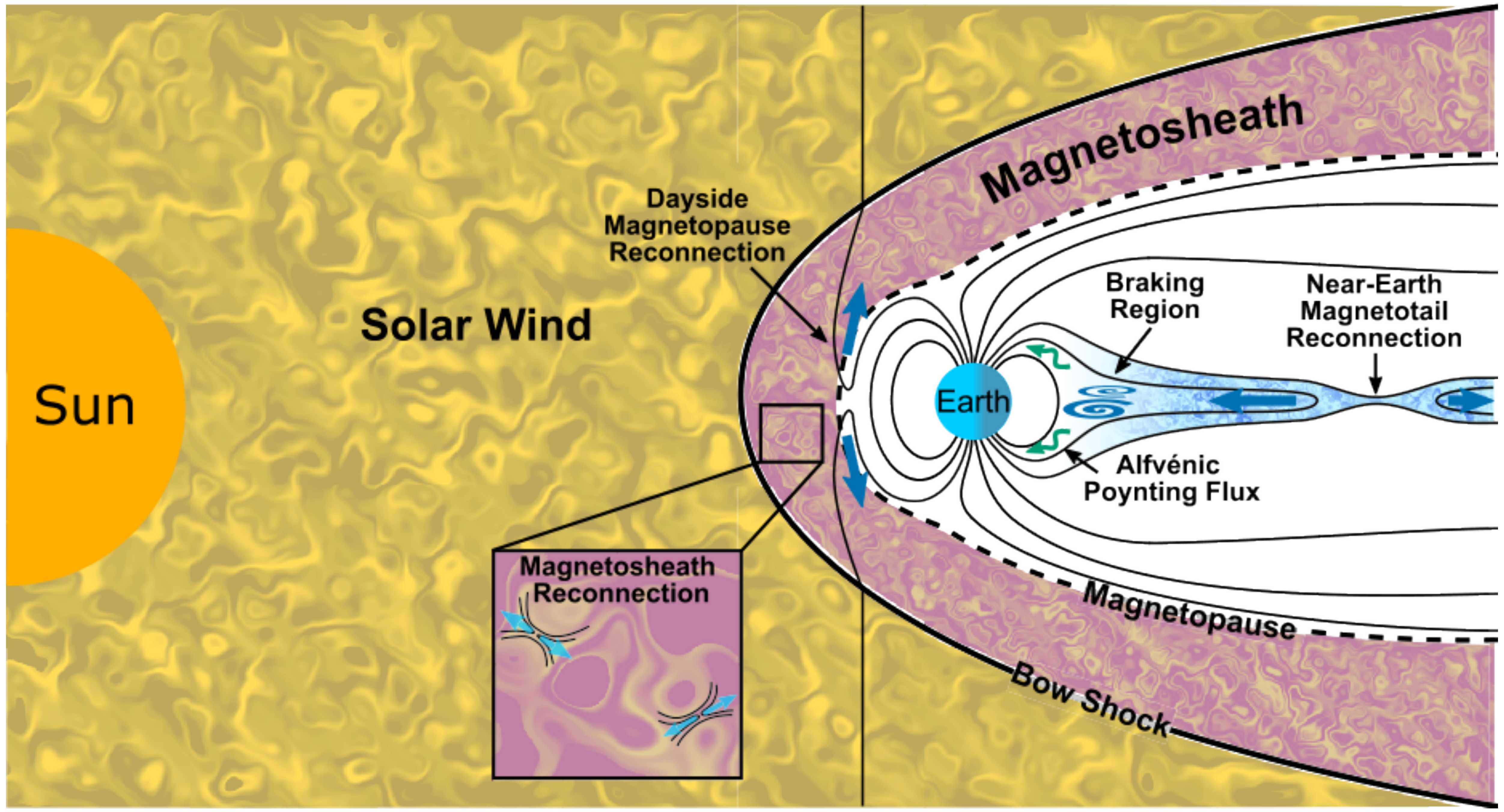
- Islands, mesoscales
- Guide field, i.e., contribution of waves, electron inertia
- 3D, X-line spreading, fragmentation
- Onset, cessation
- Partition electrons-ions
- Energy partition (thermal vs tail)



Summary

- Pressure tensor importance established: EDR is agyrotropy-driven. There is additional physics at even smaller scales, but the pressure-agyrotropy is robust.
- Anomalous resistivity is weak, but there is an anomalous transport
- Distributed energization in outflows is increasingly evident
- Strong 3D at different scales
- Reconnection is never alone (+turbulence, + KHI, +shocks)

Reconnection is everywhere



Stawarz et al., SSR, 2024