

Multi-scale magnetic reconnection in Earth's magnetotail: from interaction with kink instabilities to electron-scale signatures of reconnection growth phase

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LE STUDIUM

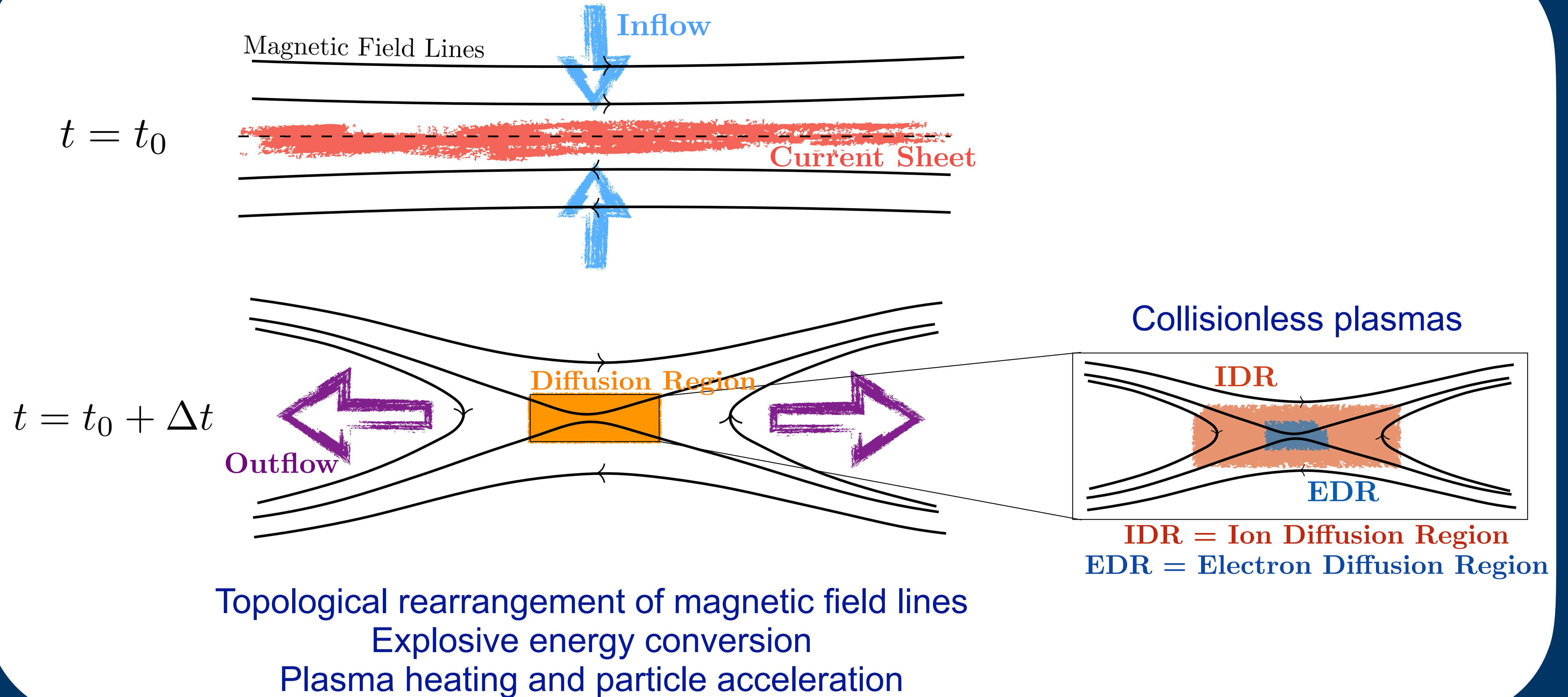
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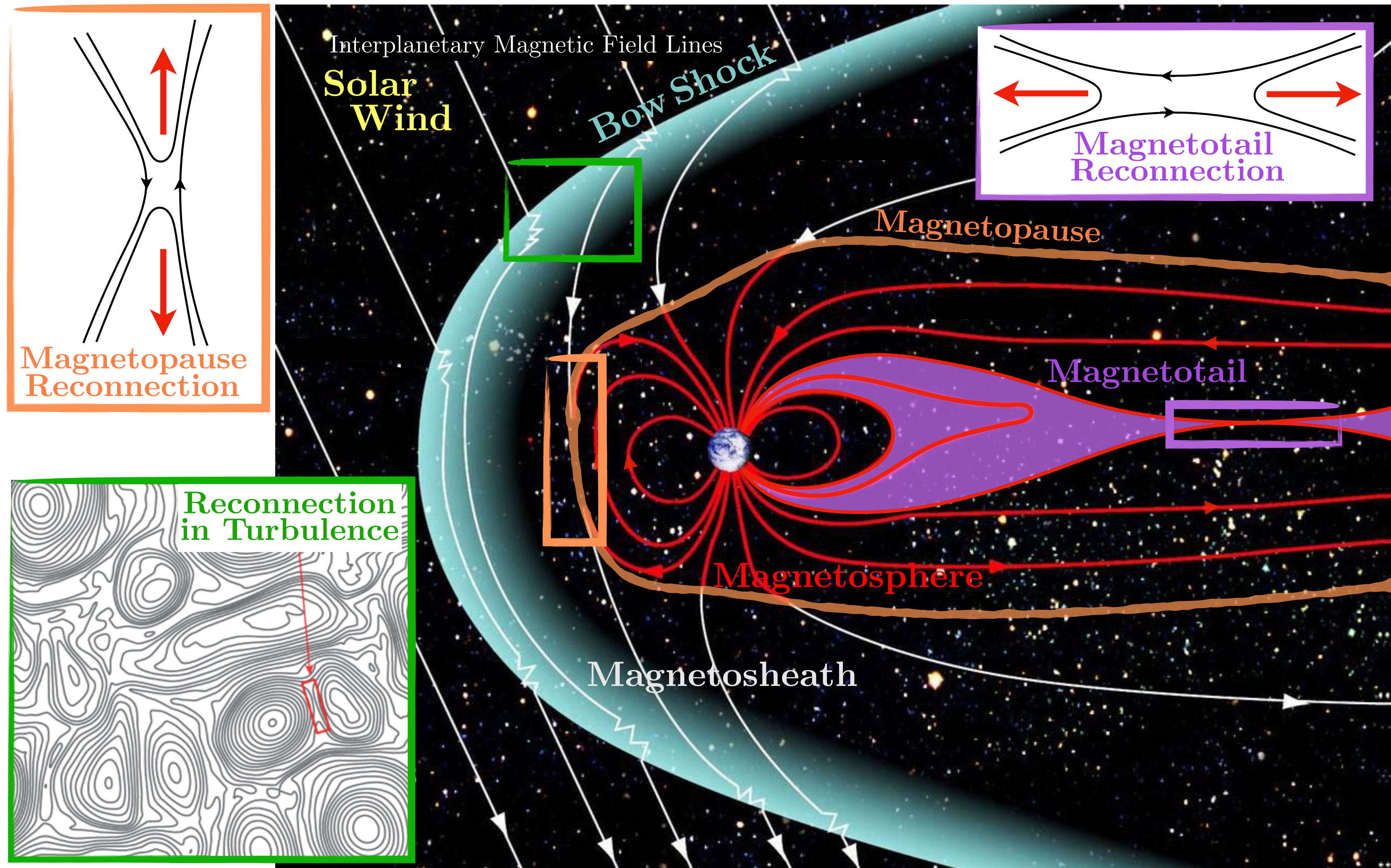
NORDITA Science Programme: Synergies!
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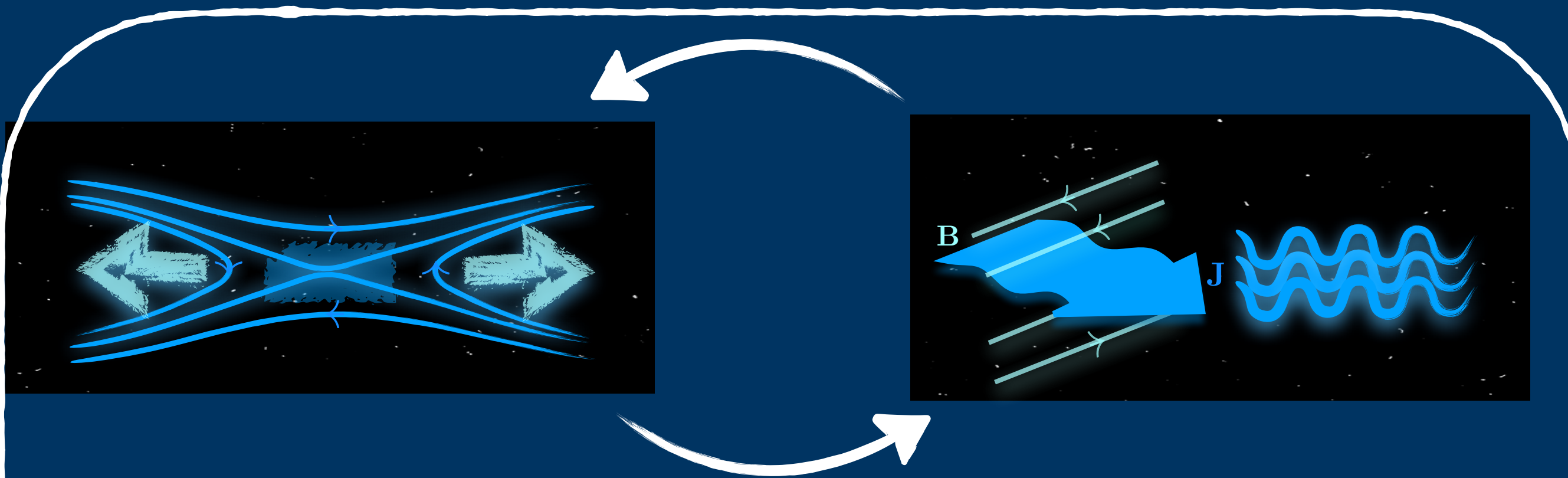
Magnetic reconnection in near-Earth plasmas



Magnetic reconnection in near-Earth plasmas



Interplay of reconnection and instabilities and waves



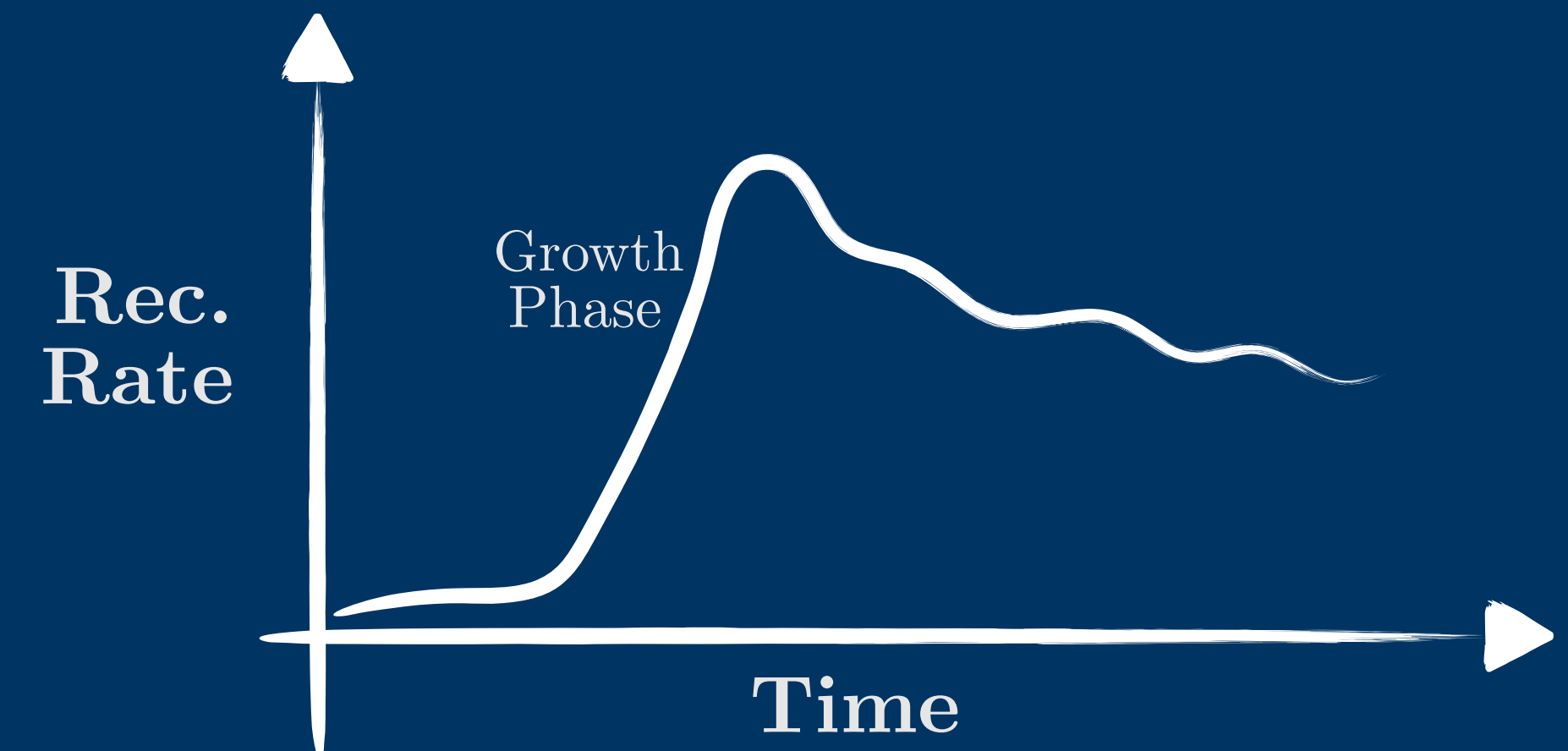
Space Science Reviews (2025) 221:20
<https://doi.org/10.1007/s11214-024-01133-7>



The Role of Kinetic Instabilities and Waves in Collisionless Magnetic Reconnection

D.B. Graham¹ · G. Cozzani² · Yu.V. Khotyaintsev^{1,3} · V.D. Wilder⁴ · J.C. Holmes⁵ · T.K.M. Nakamura⁶ · J. Büchner^{7,8} · K. Dokgo⁹ · L. Richard¹ · K. Steinvall¹⁰ · C. Norgren^{1,11} · L.-J. Chen¹² · H. Ji^{13,14} · J.F. Drake¹⁵ · J.E. Stawarz¹⁶ · S. Eriksson¹⁷

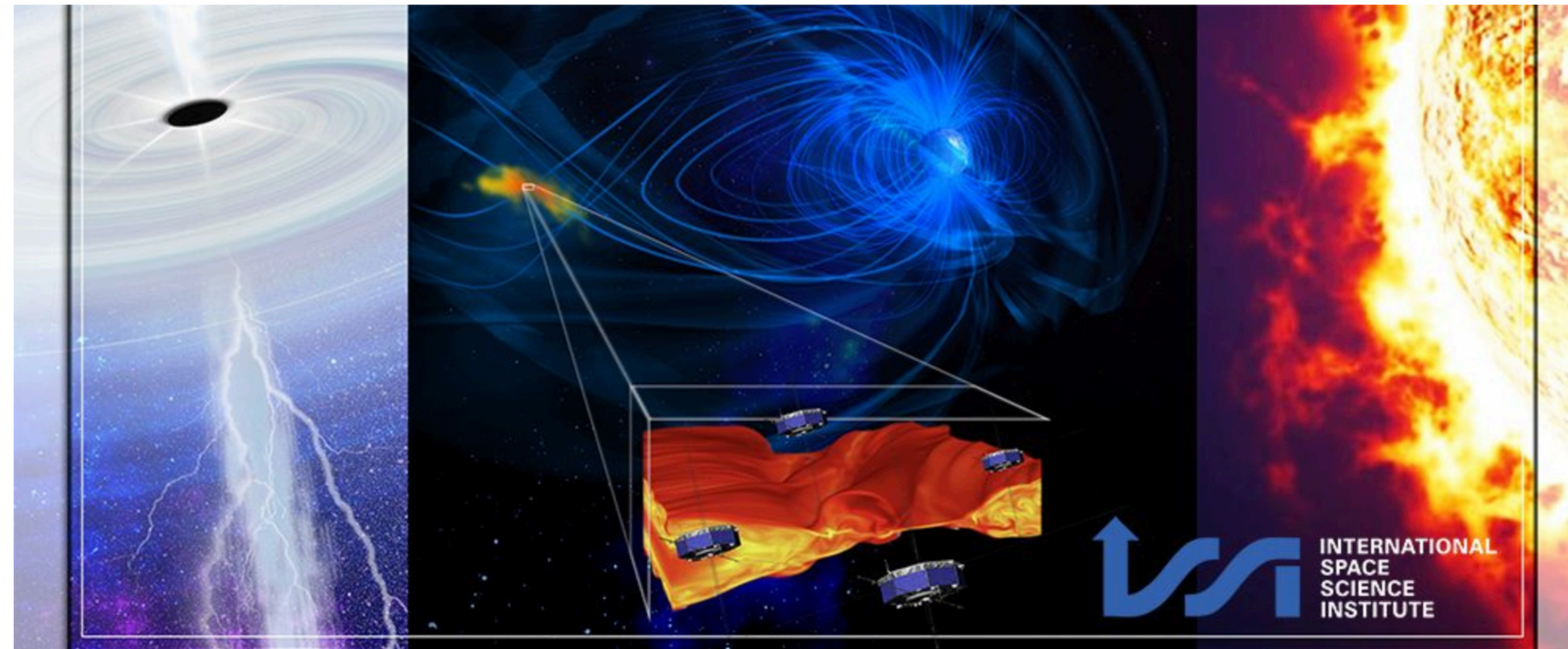
Time evolution of magnetic reconnection



- Is reconnection evolution affected by waves and instabilities?
- How to distinguish different phases, especially in observations?

Magnetic Reconnection: Explosive Energy Conversion in Space Plasmas

International Space Science Institute : Workshop : 27 June -1 July 2022




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Magnetic Reconnection: Explosive Energy Conversion in Space Plasmas

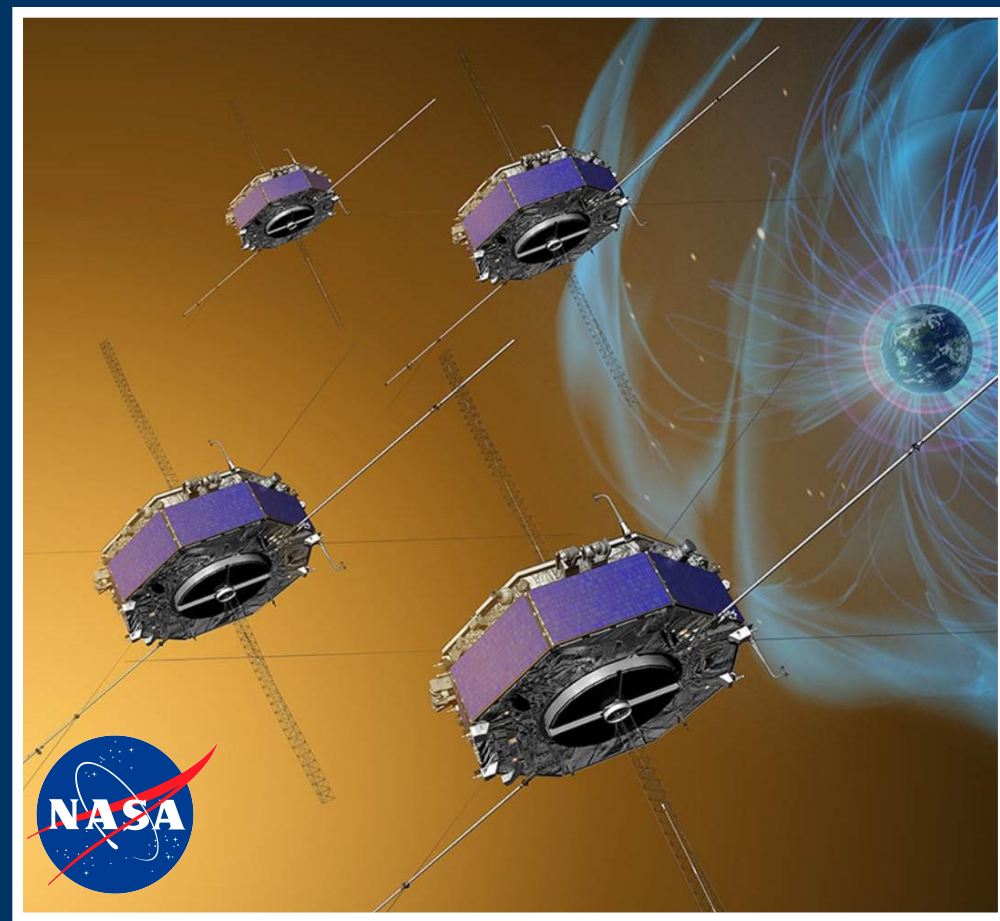
 Participating journal: [Space Science Reviews](#)

 Open for submissions

 Submission deadline
Ongoing

This collection presents results from the [ISSI Workshop "Magnetic Reconnection: Explosive Energy Conversion in Space Plasmas"](#), held 27 June–1 July 2022, which aims to review progress in research of magnetic reconnection and relevant processes in space plasma, based on recent in-situ multipoint observations and theoretical simulations, and to discuss its astrophysical context.

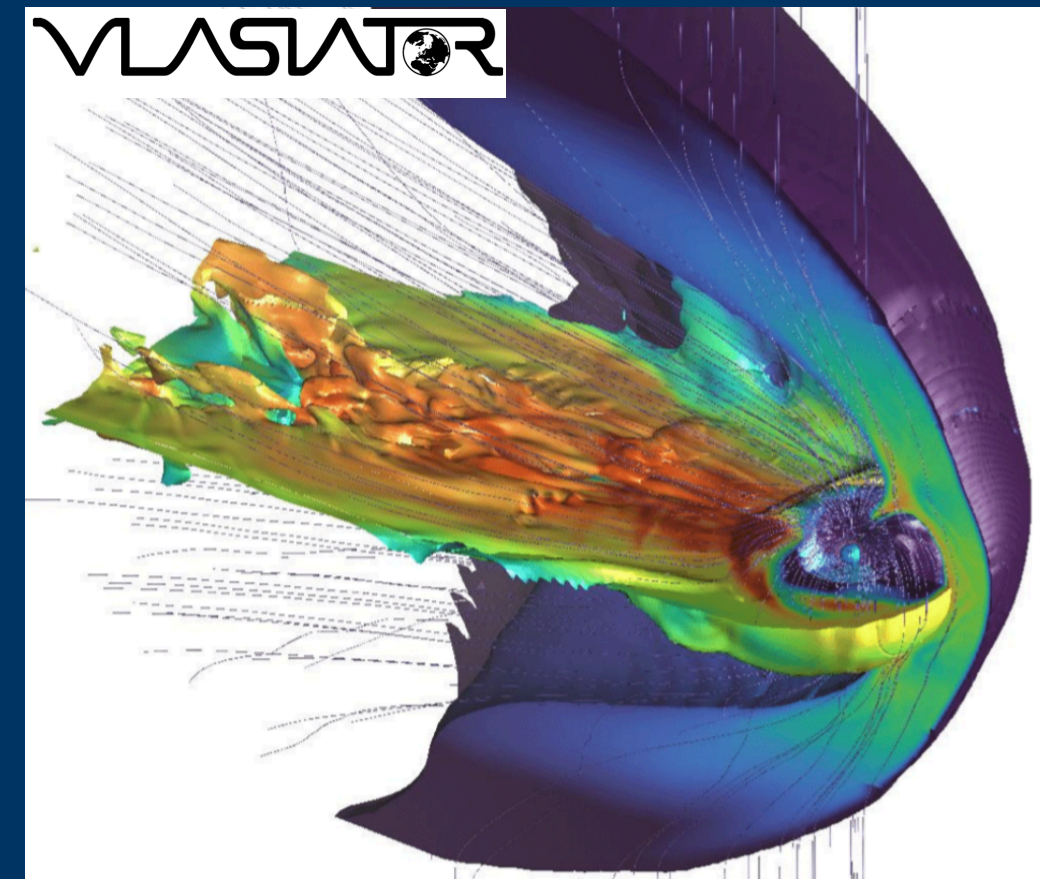
In situ observations and numerical simulations



Magnetospheric MultiScale
(MMS, 2015 —)

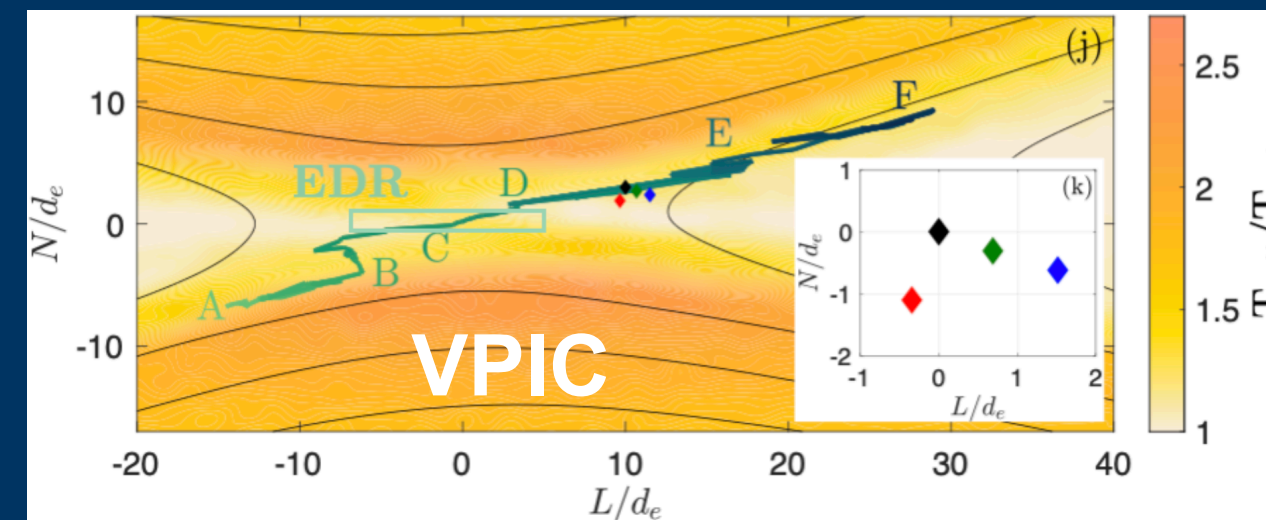
Ion and electron kinetic
scales

Global
Hybrid-Vlasov



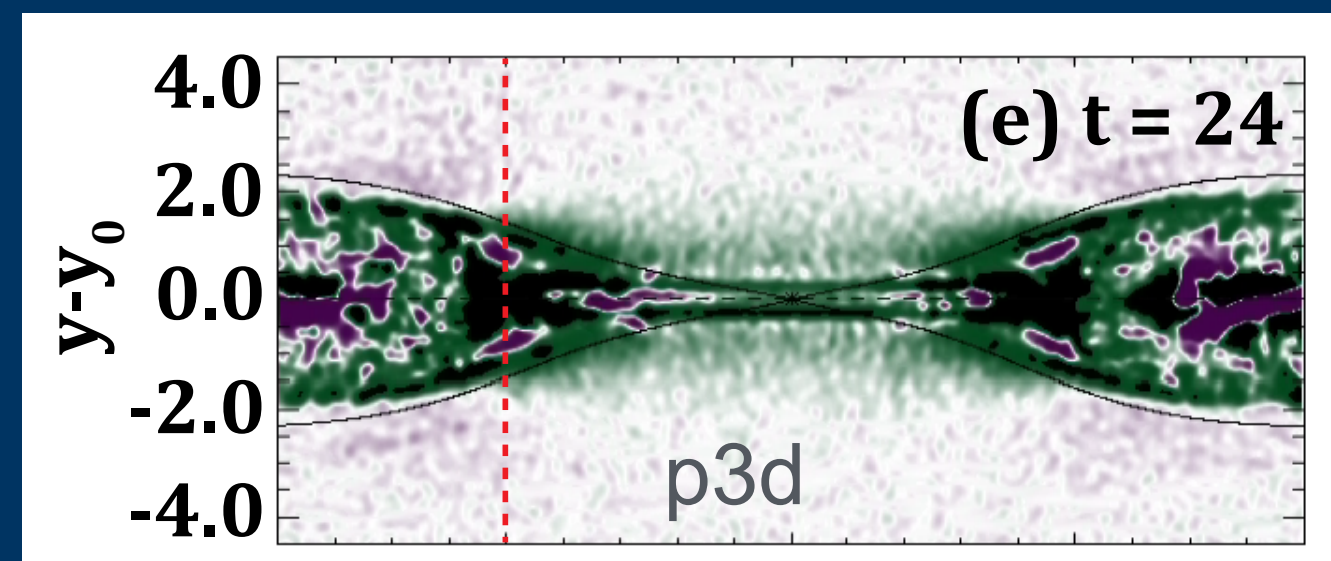
[Ganse et al., Phys. Plasmas, 2023]

Local
Fully-kinetic
PIC



[Bowers et al., Phys. Plasmas, 2008] [Cozzani et al., PRL, 2011]

Local
Fully-kinetic
PIC



[Zeiler et al., JGR, 2002] [Barbhuiya et al., JGR, 2025]

MHD
ion

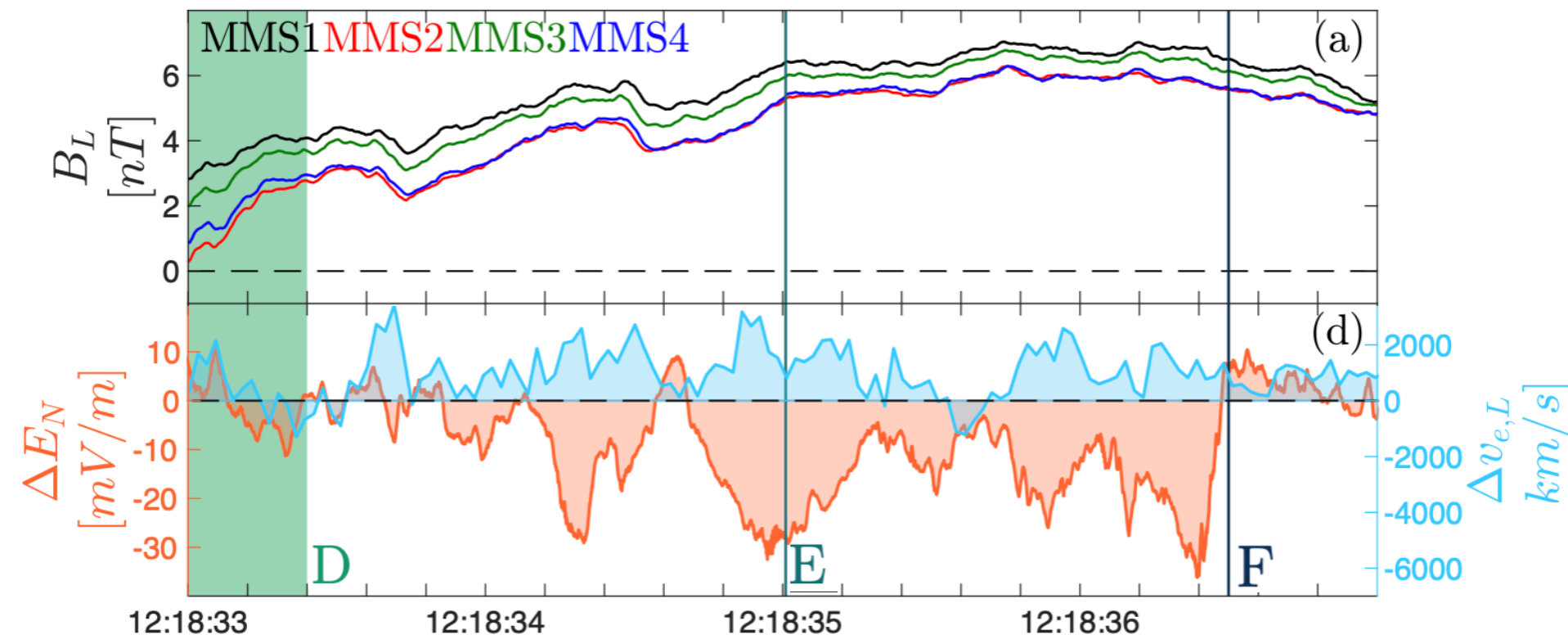
Scales

ion
elec-
tron

Review papers:
[Shay et al., Space Sci. Rev., 2025]
[Palmroth et al., LRCA, 2025]

Interplay of instabilities and reconnection at the electron/lower hybrid scales

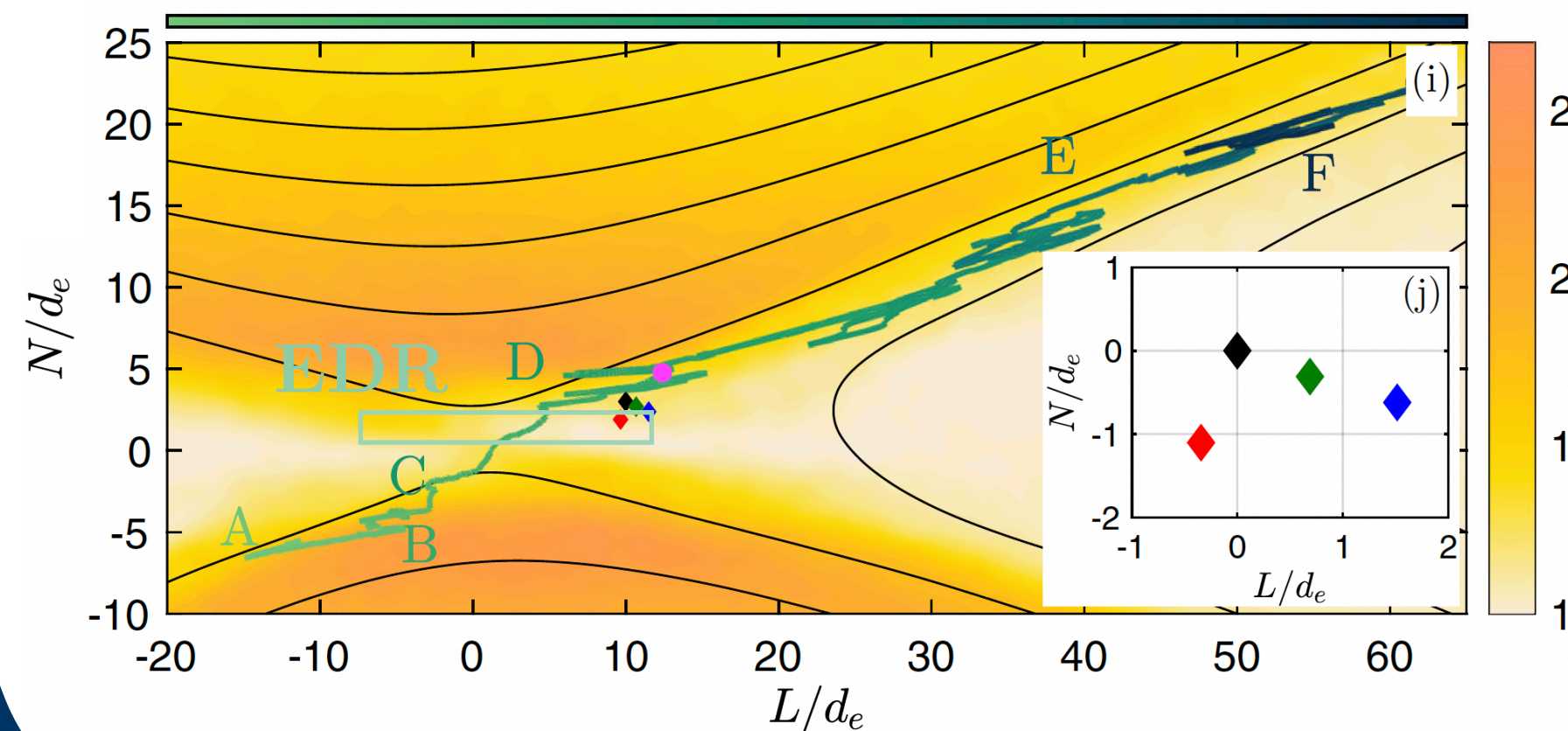
Multi-spacecraft MMS data



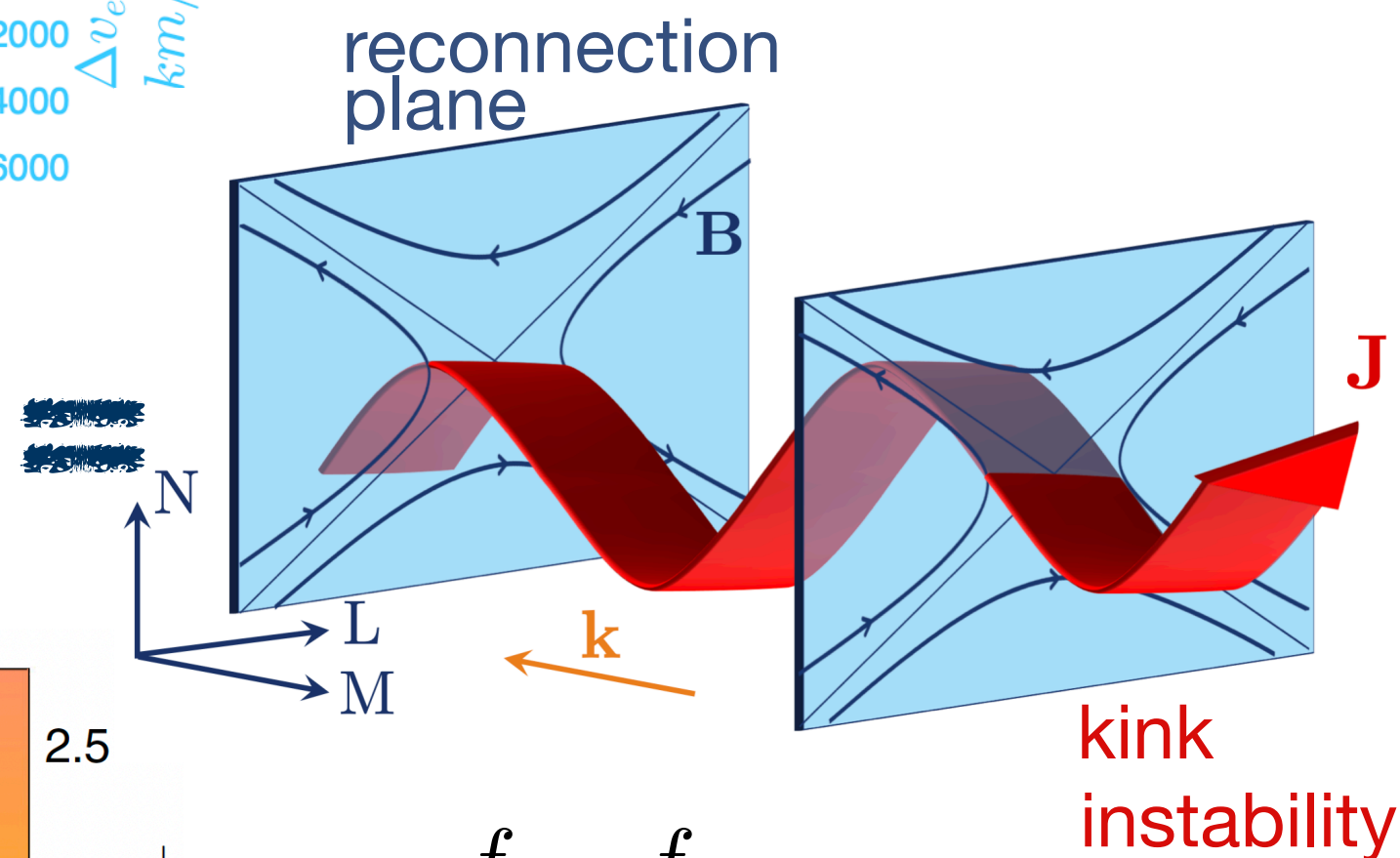
EDR crossing in the magnetotail



PIC simulations



[Cozzani et al., PRL, 2021]



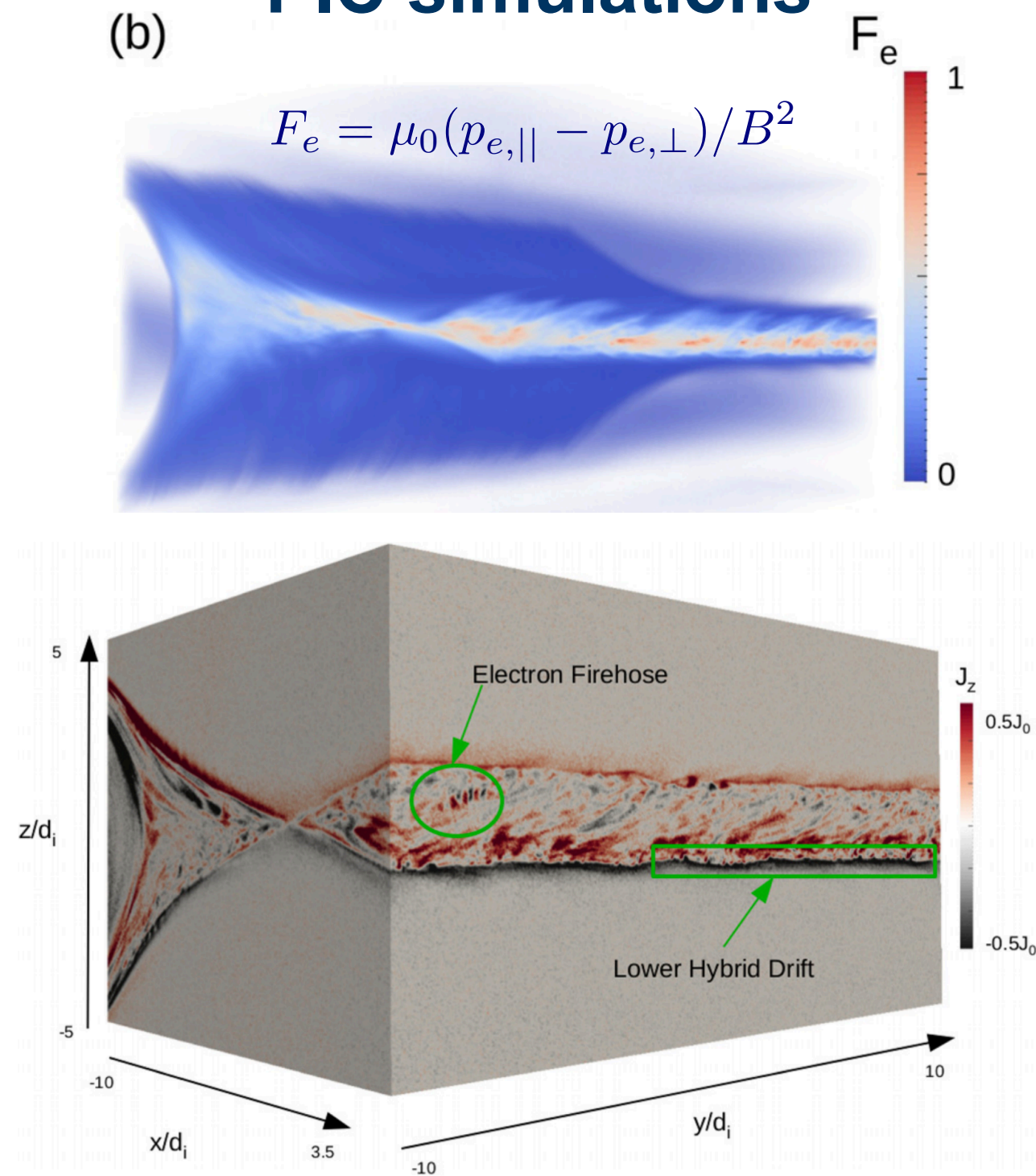
$$f \sim f_{LH}$$

$$|\mathbf{k}| \sqrt{\rho_e \rho_i} \sim 2.2$$

- Large, non-constant differences between spacecraft observations can be explained with a complex trajectory along the separatrix
- Kink modes at center of the thin electron-scale current sheet perturb the EDR
- 3D effects are important. 2D reconnection description is not sufficient to understand the observations

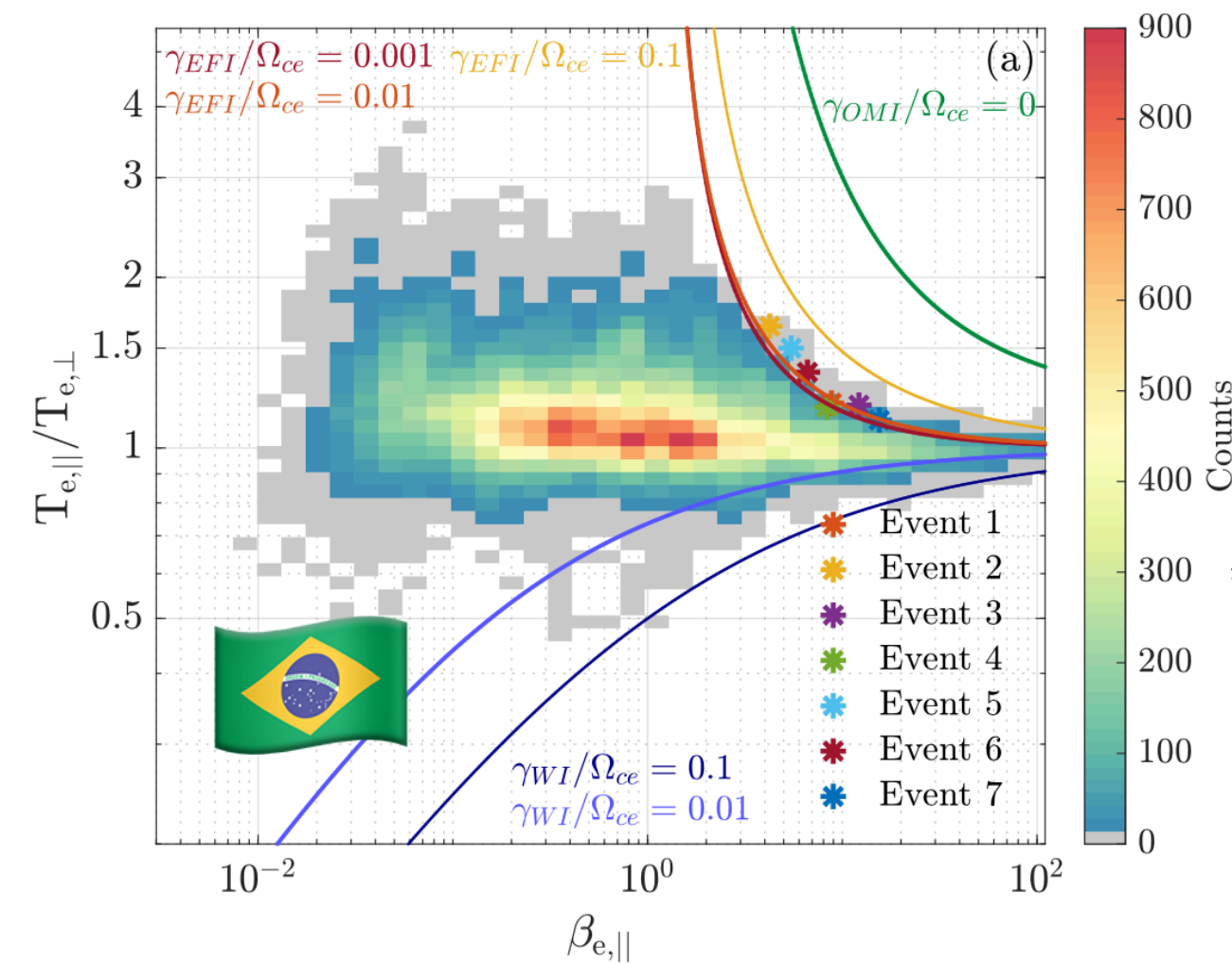
Interplay of instabilities and reconnection at the electron scales: the electron firehose instability (EFI)

(b) PIC simulations



[Le et al., Phys. Plasmas, 2019]

MMS data - indirect evidence

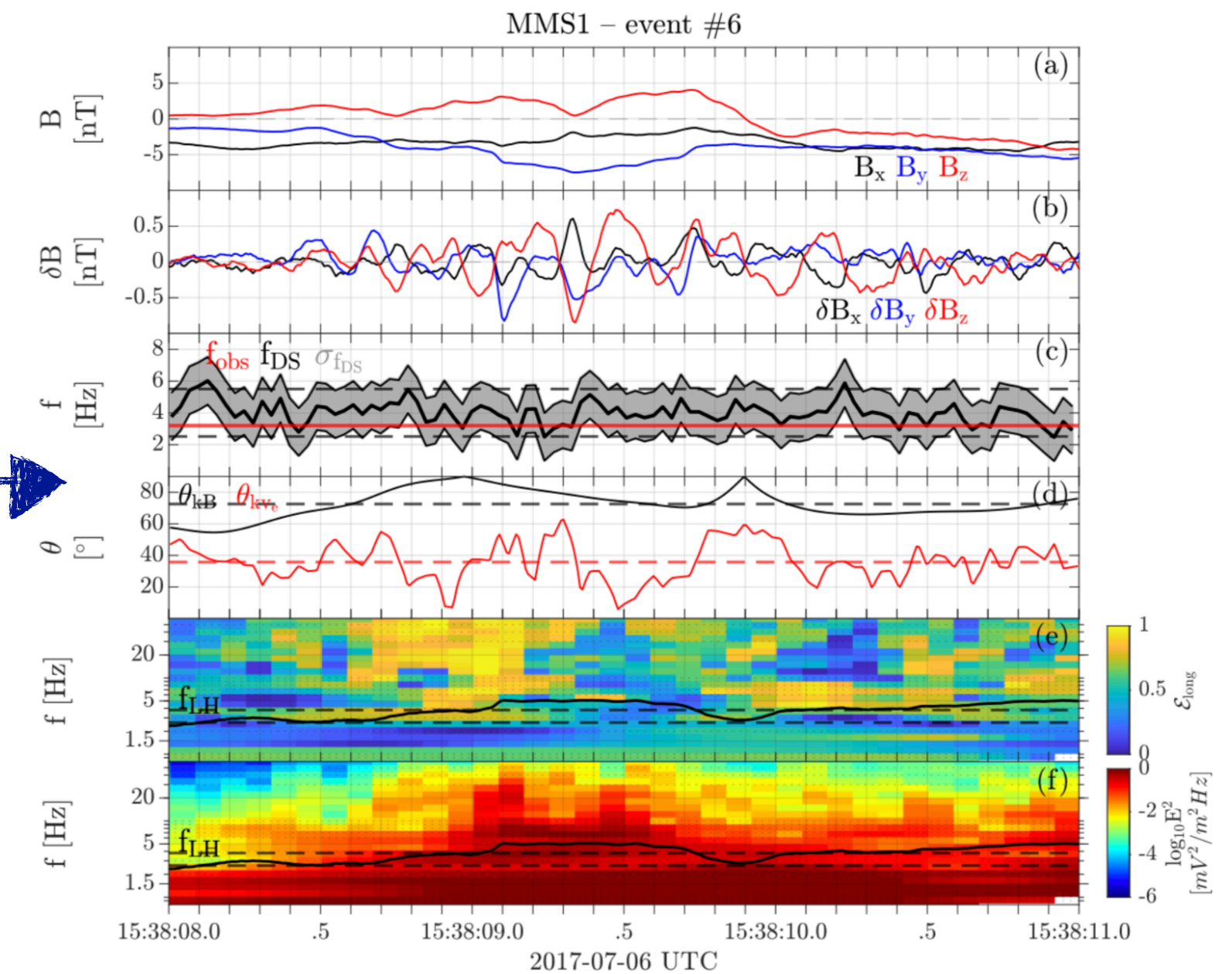


[Cozzani et al., JGR, 2023]

[Štverák et al., JGR, 2008]

[Zhang et al., GRL, 2018]

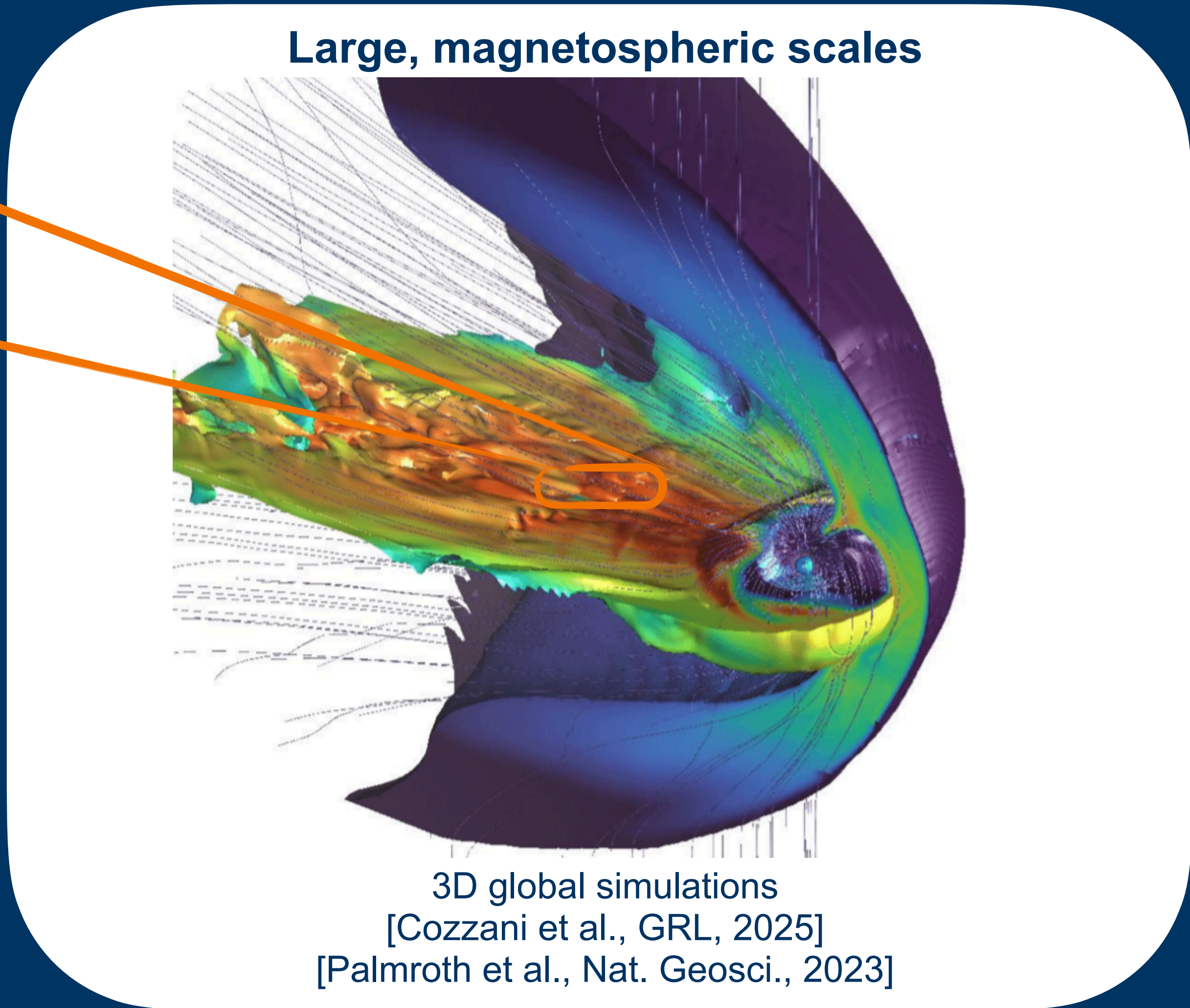
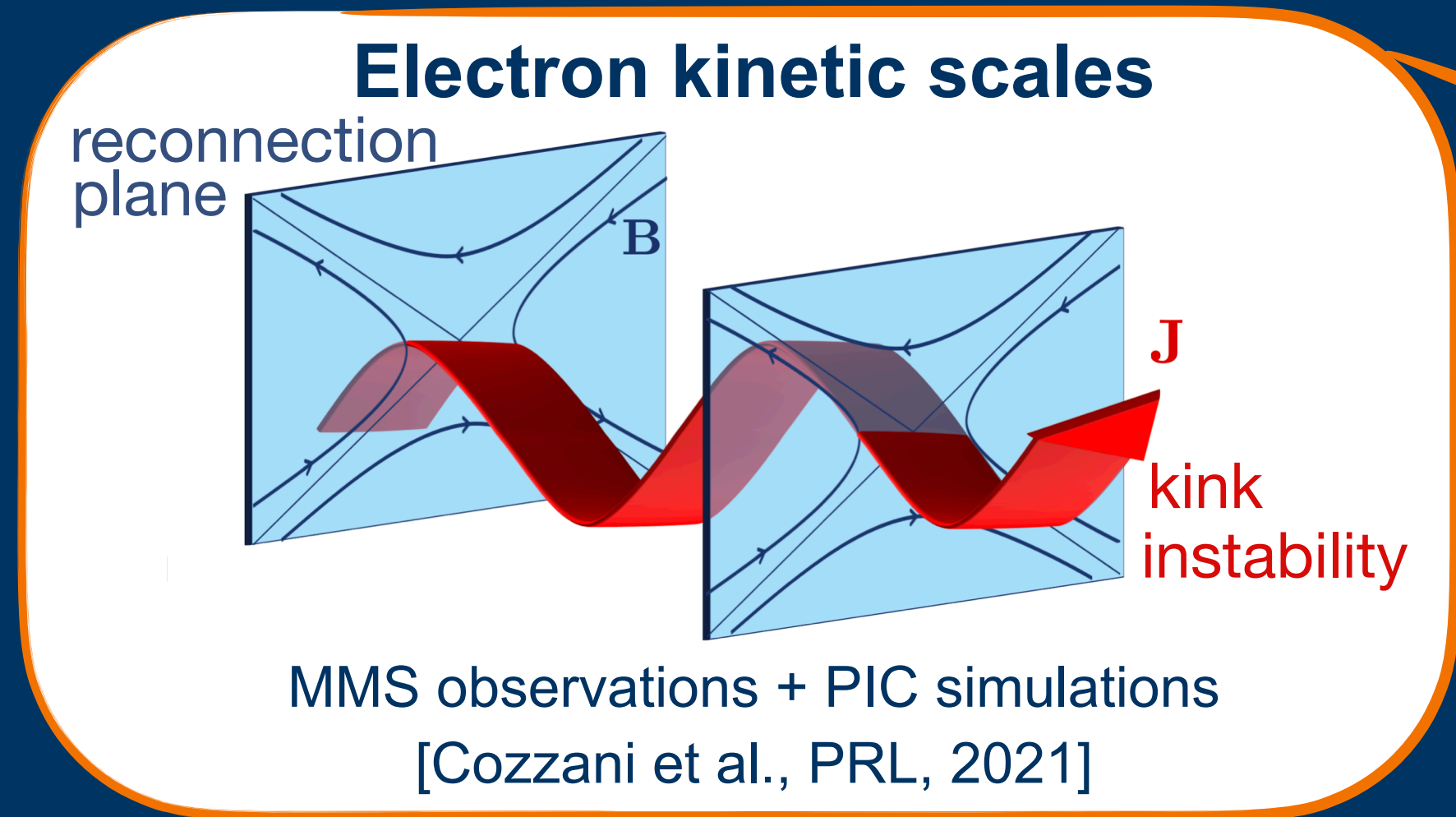
MMS data - direct evidence



[Cozzani et al., JGR, 2023]

- The EFI is a temperature-anisotropy-driven instability that can develop in the reconnection outflow
- We report the first direct in situ observations of the non-propagating electron firehose wave mode in the outflow region in the magnetotail

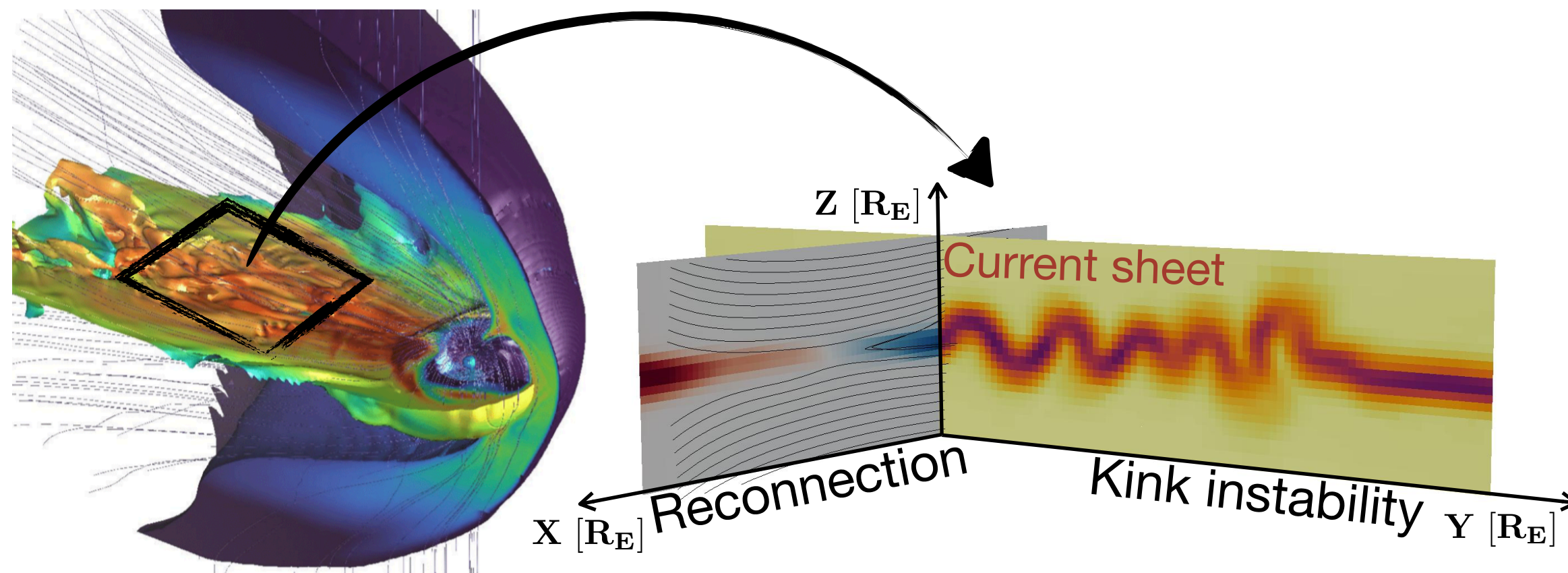
**Magnetic reconnection and instabilities co-exist.
Is the reconnection affected by the presence of the kink instability?**



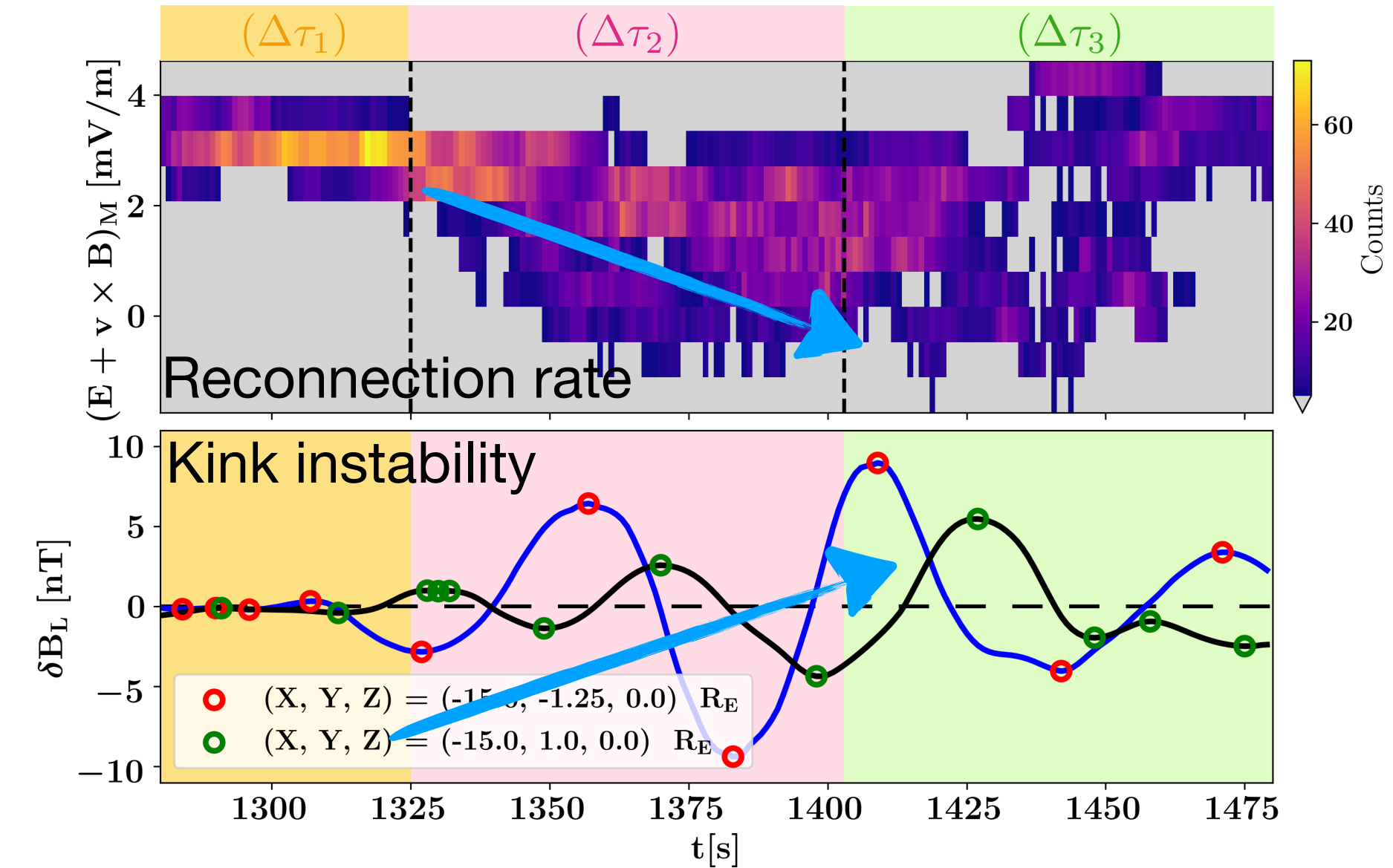
Simulations allow to follow the time evolution of the global system

Interplay of instabilities and reconnection at the ion/fluid scale

3D Vlasiator magnetospheric simulations



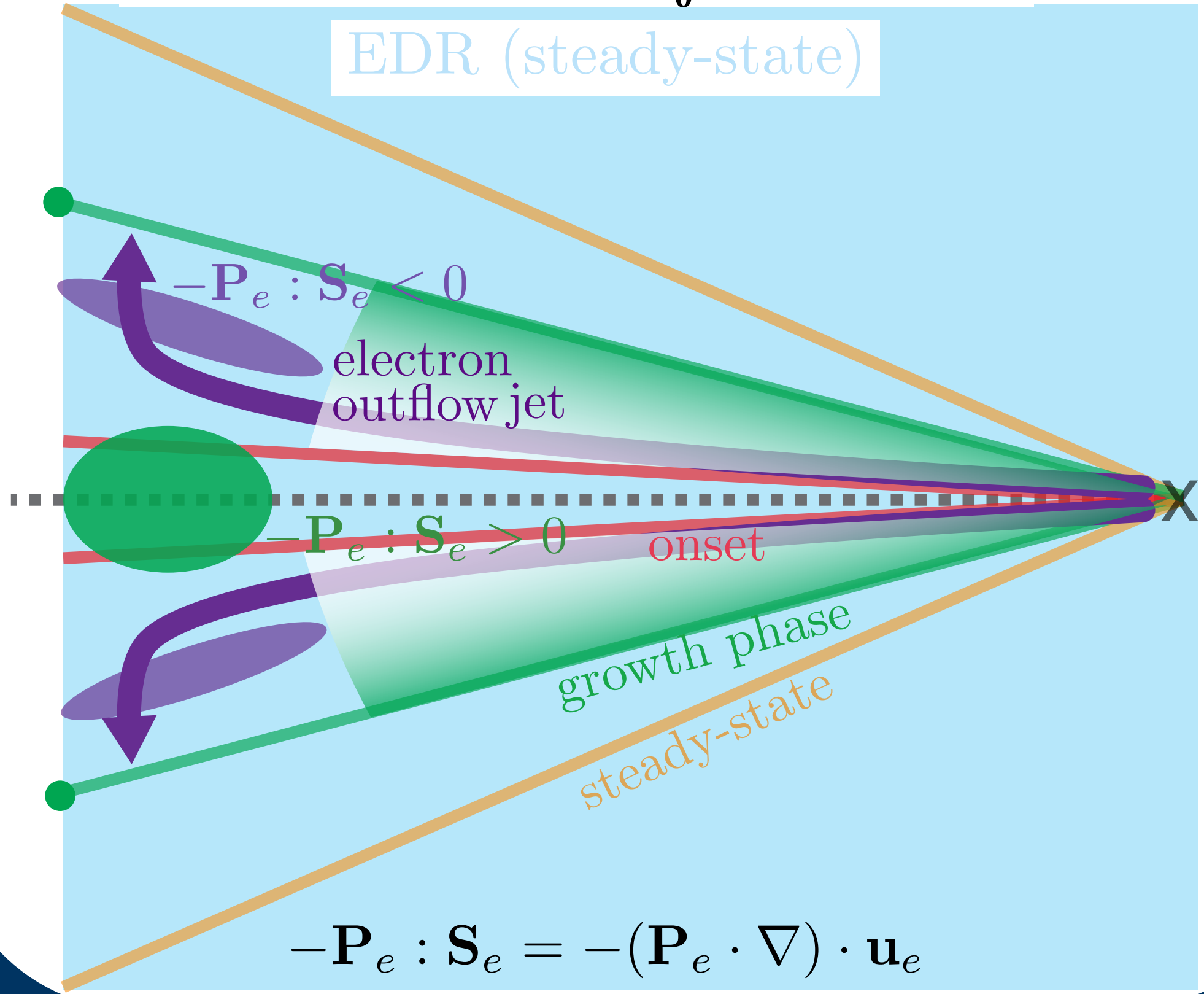
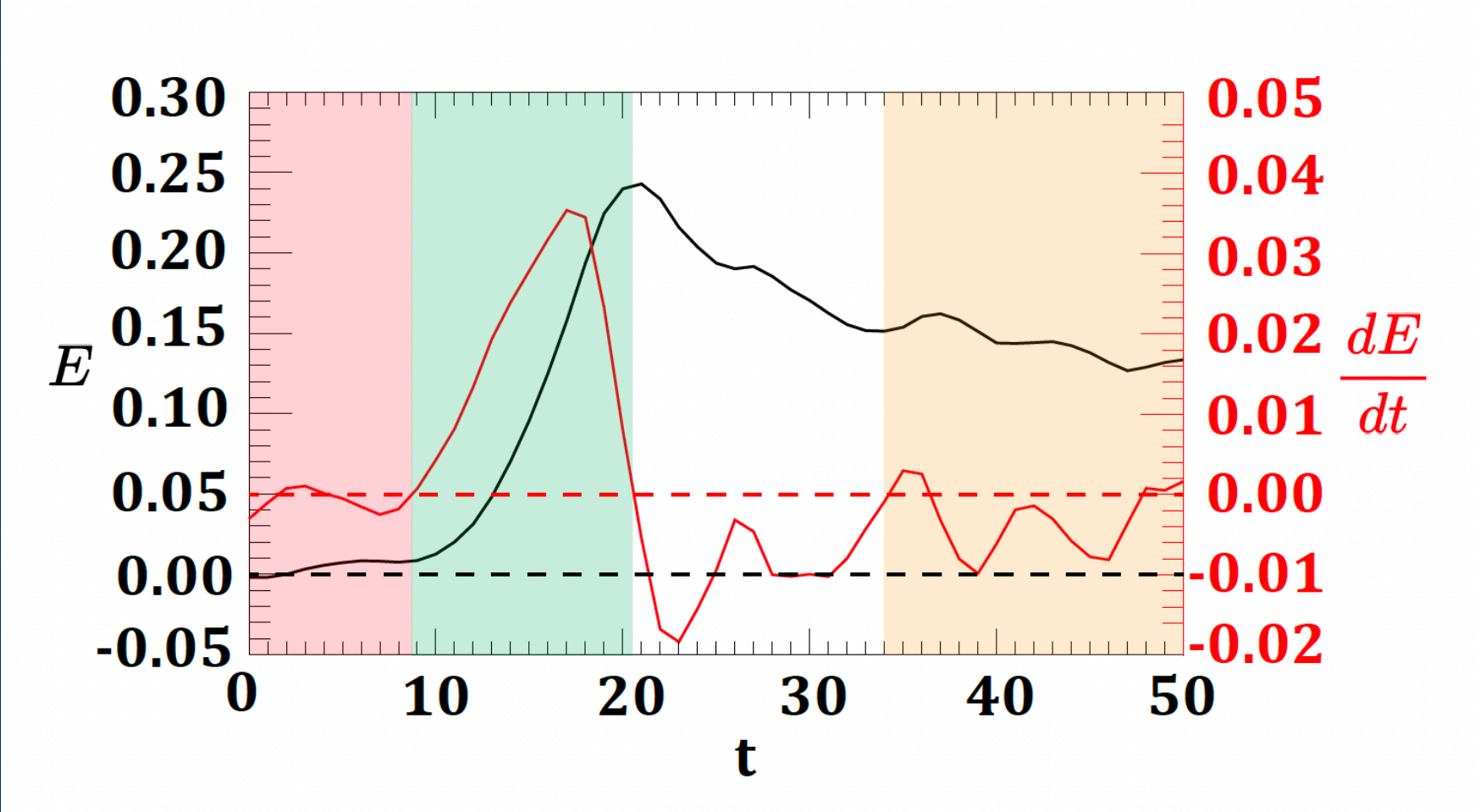
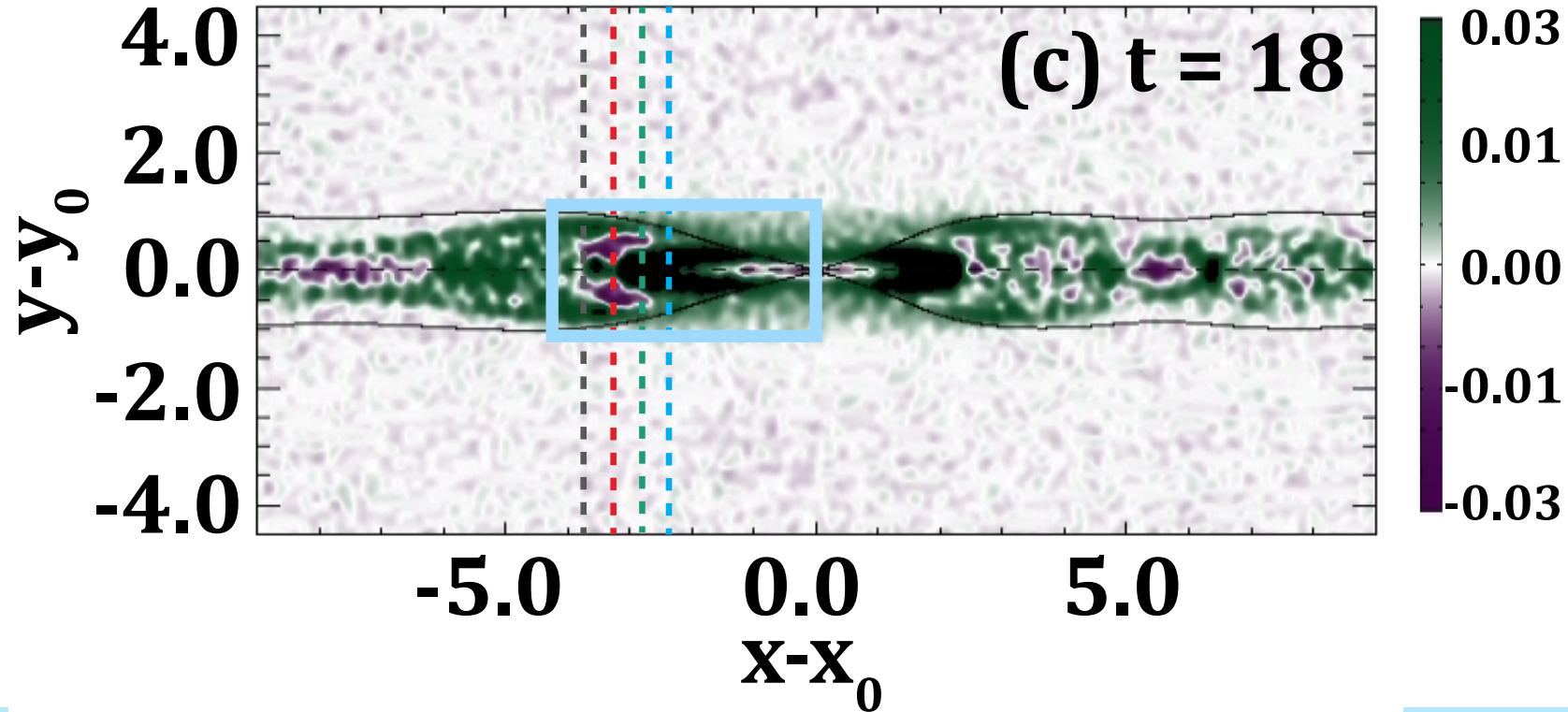
[Cozzani et al., GRL, 2025]
[Palmroth et al., Nat. Geosci., 2023]



Is the reconnection rate evolution influenced by the kink instability?

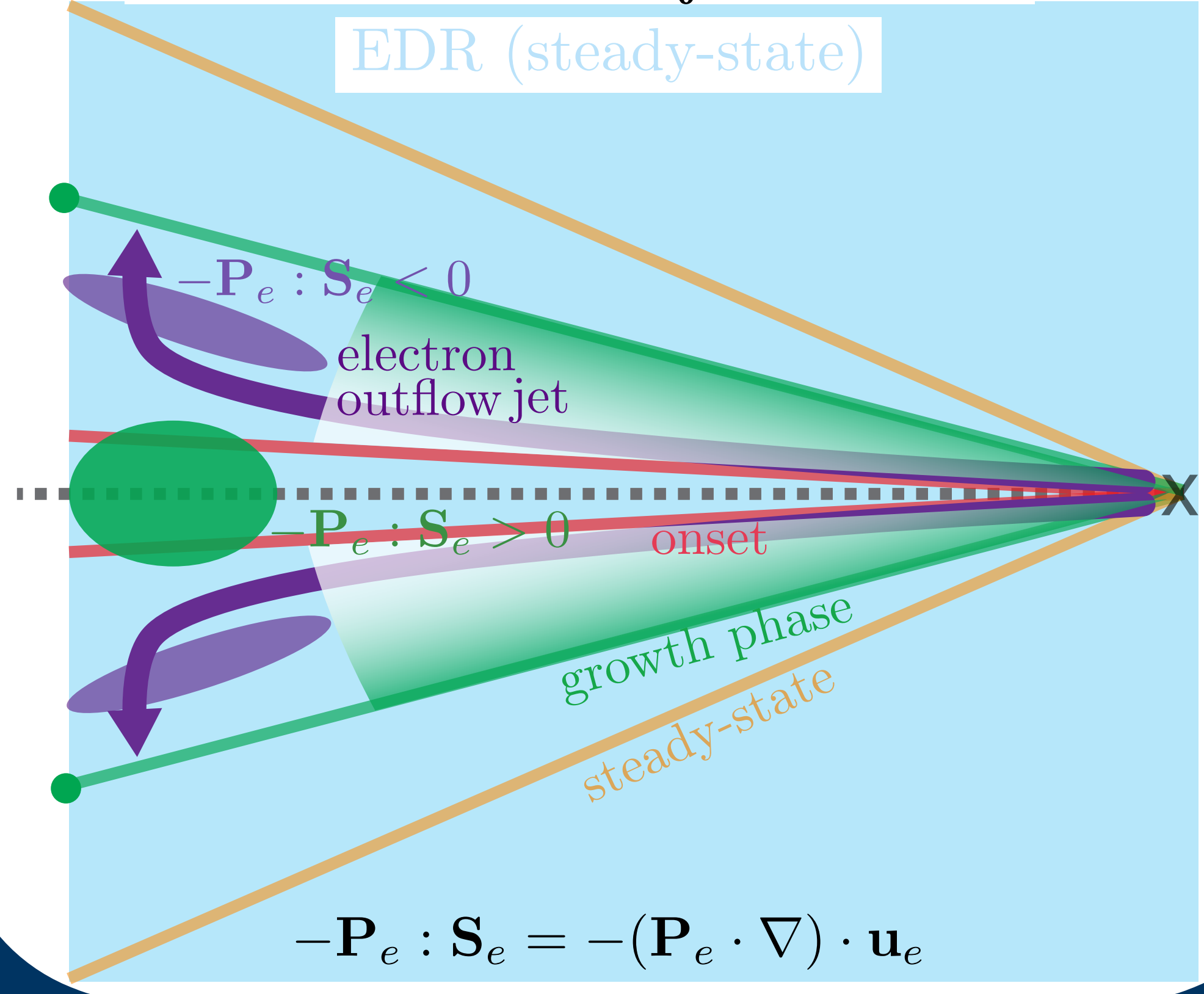
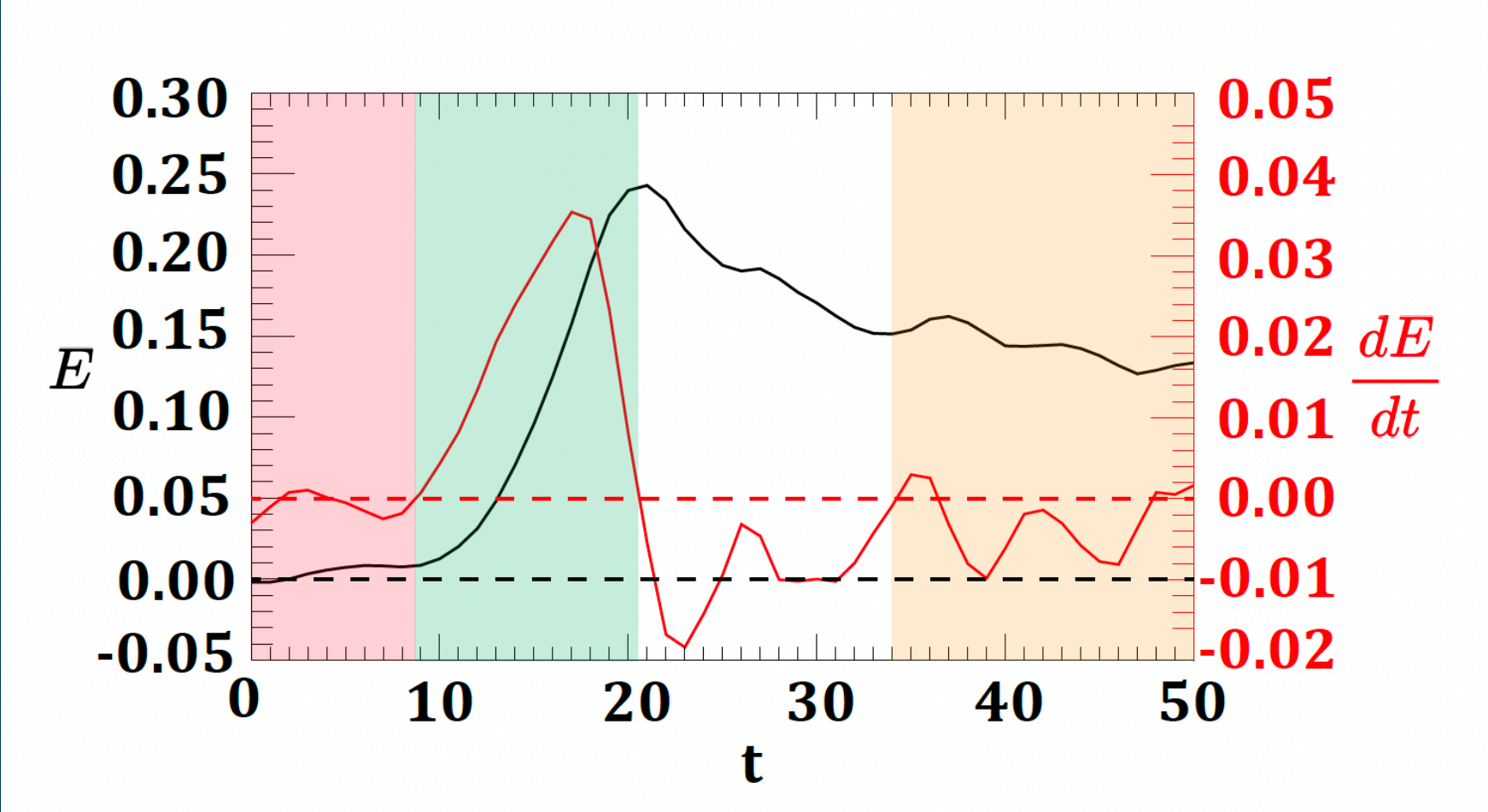
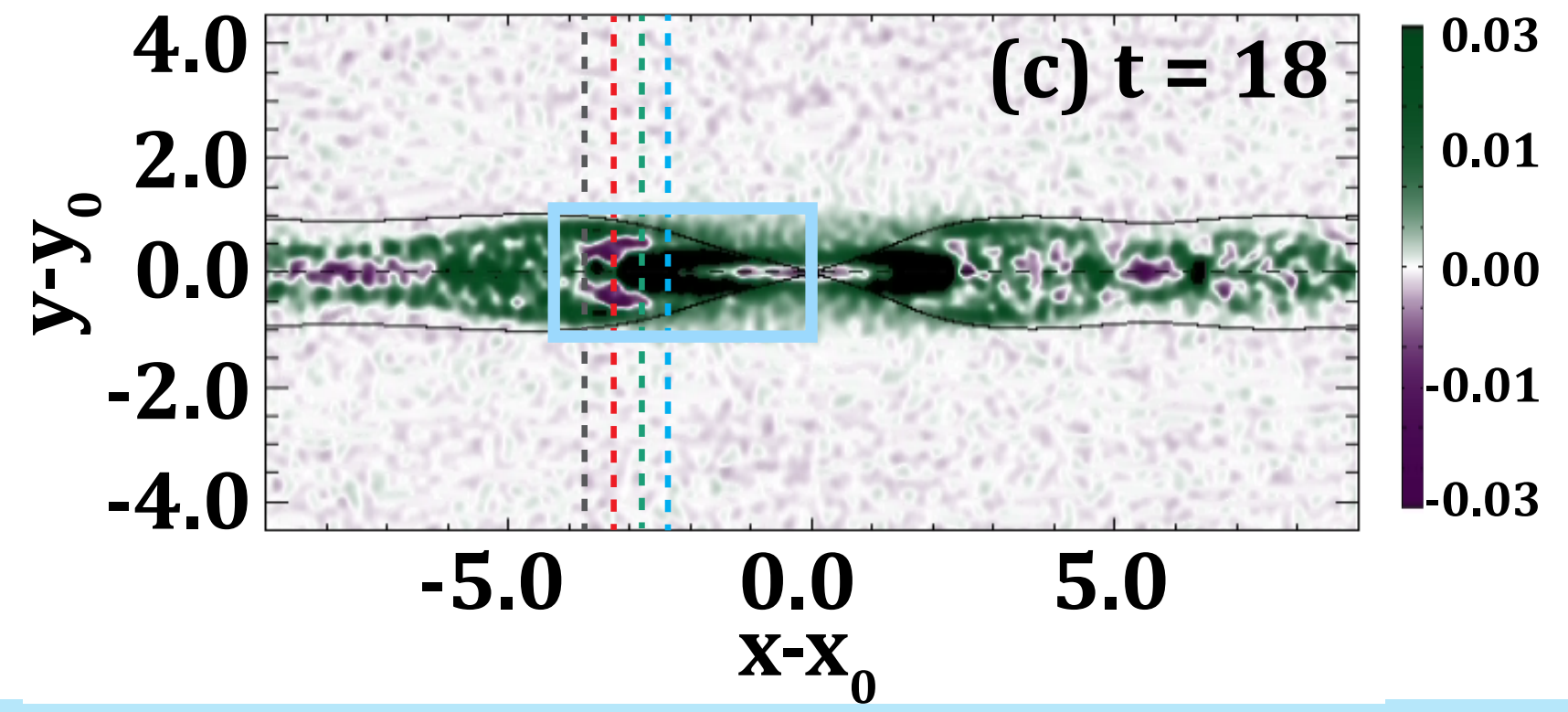
- We study the interaction of magnetic reconnection and the current sheet kink instability in the magnetotail of 3D Vlasiator simulation
- The reconnection rate decreases during the instability growth phase. Strong interplay of the two processes.

Identifying the growth phase of reconnection using pressure-strain interaction: PIC simulations

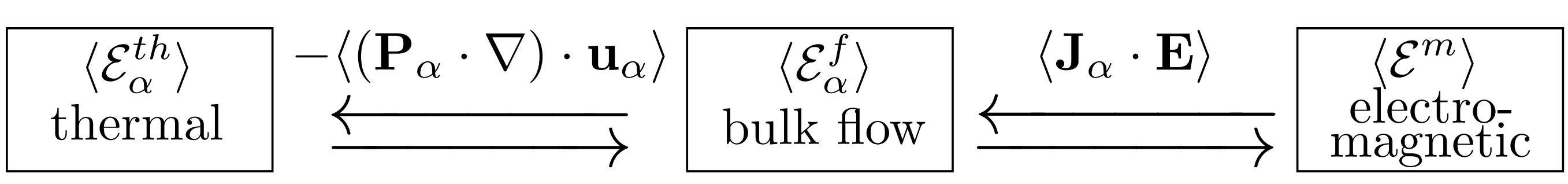


[Barbhuiya & Cassak, PoP, 2022] [Barbhuiya et al., JGR, 2025]

Identifying the growth phase of reconnection using pressure-strain interaction: PIC simulations



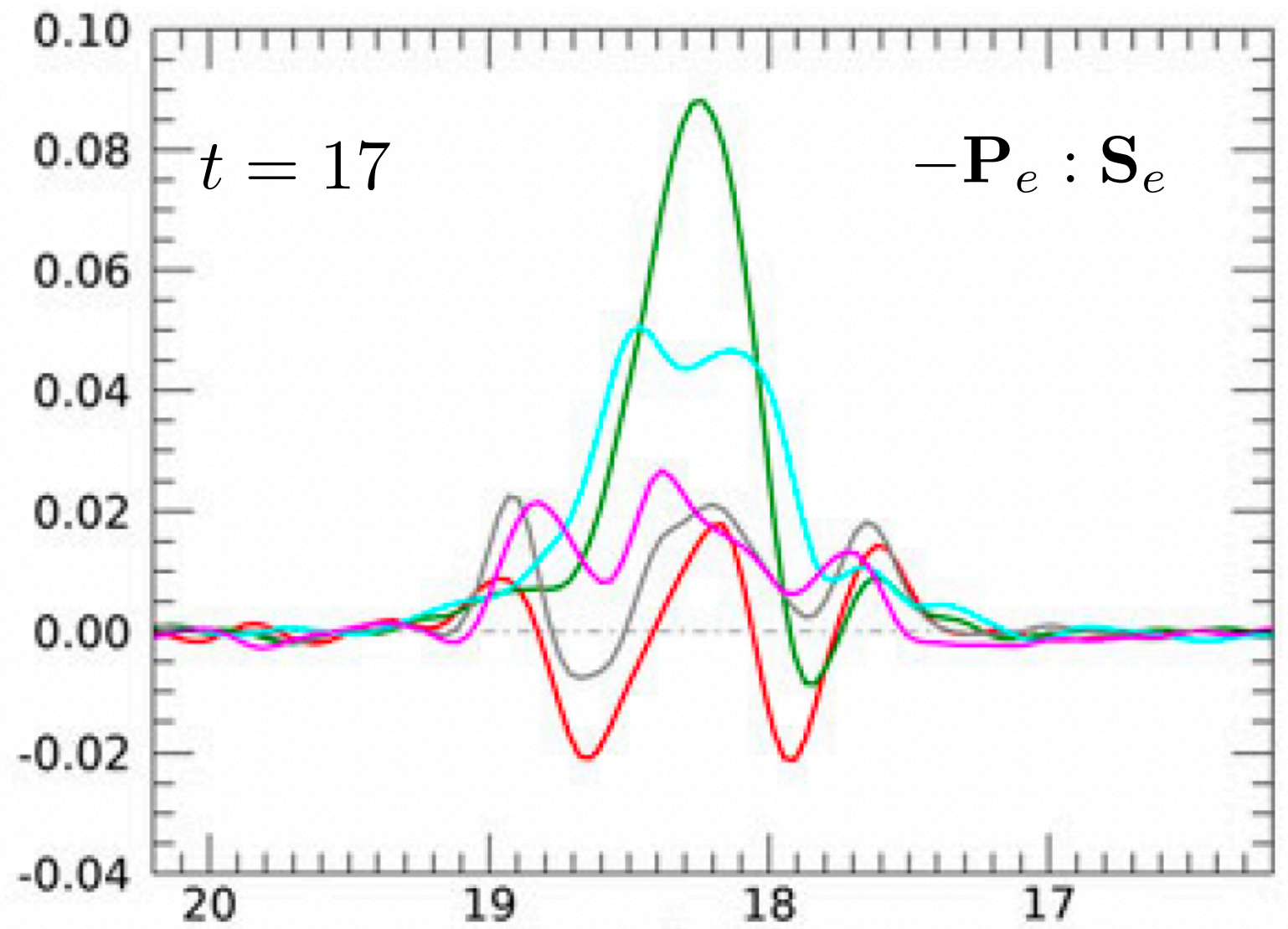
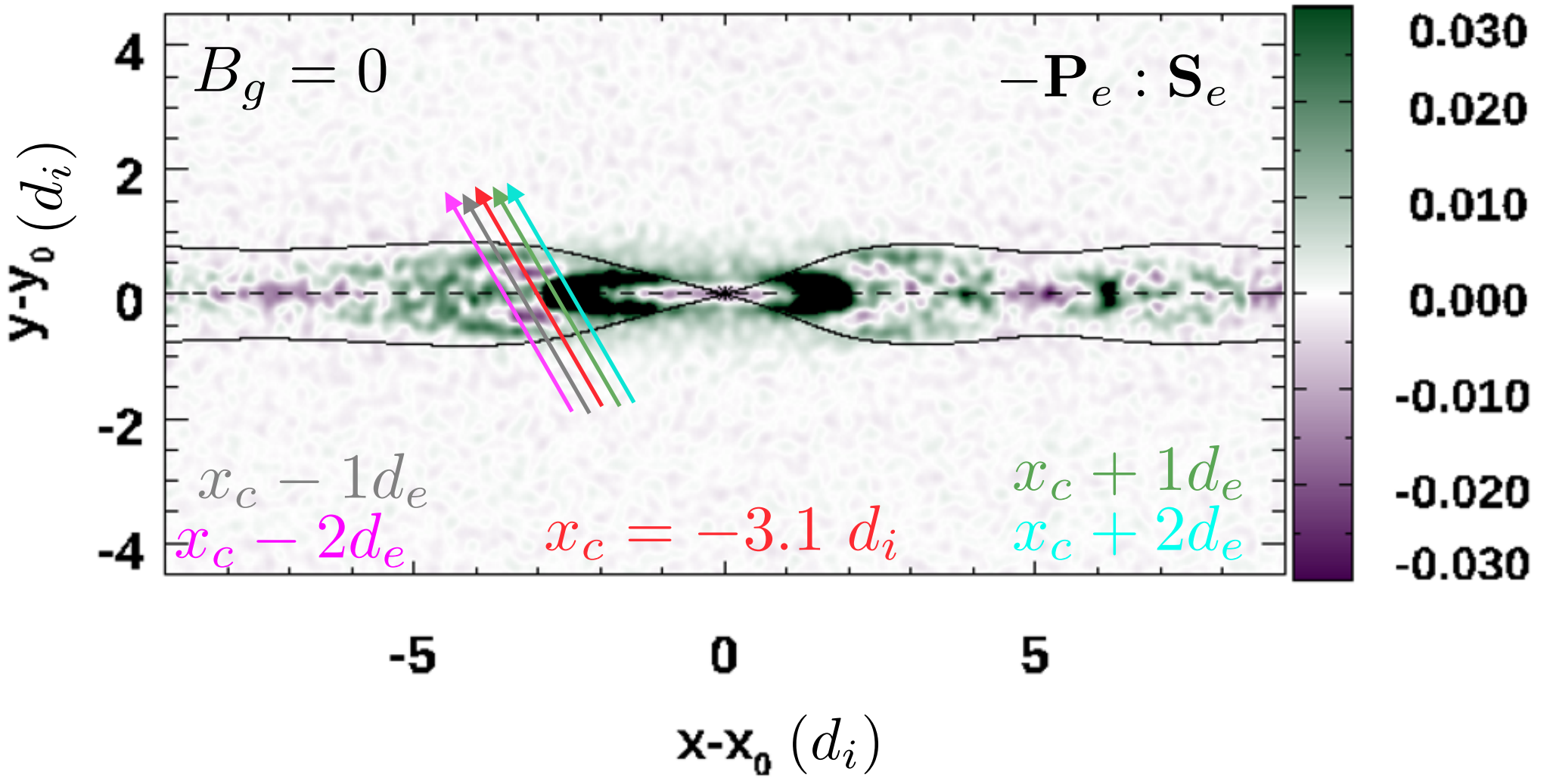
- Characteristic spatial structures in the electron pressure-strain interaction at the EDR edge during growth phase only
- Structures associated with opening of separatrices and formation of the outflow (dilation/compression)



Pressure-strain interaction term

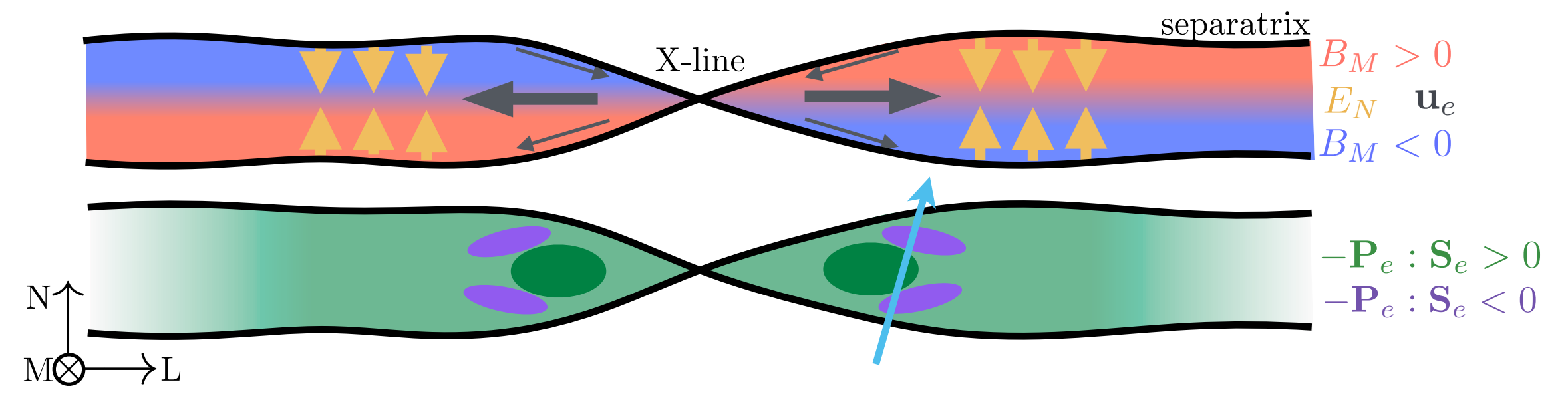
Identifying the growth phase of reconnection using pressure-strain interaction: MMS observations

PIC simulations

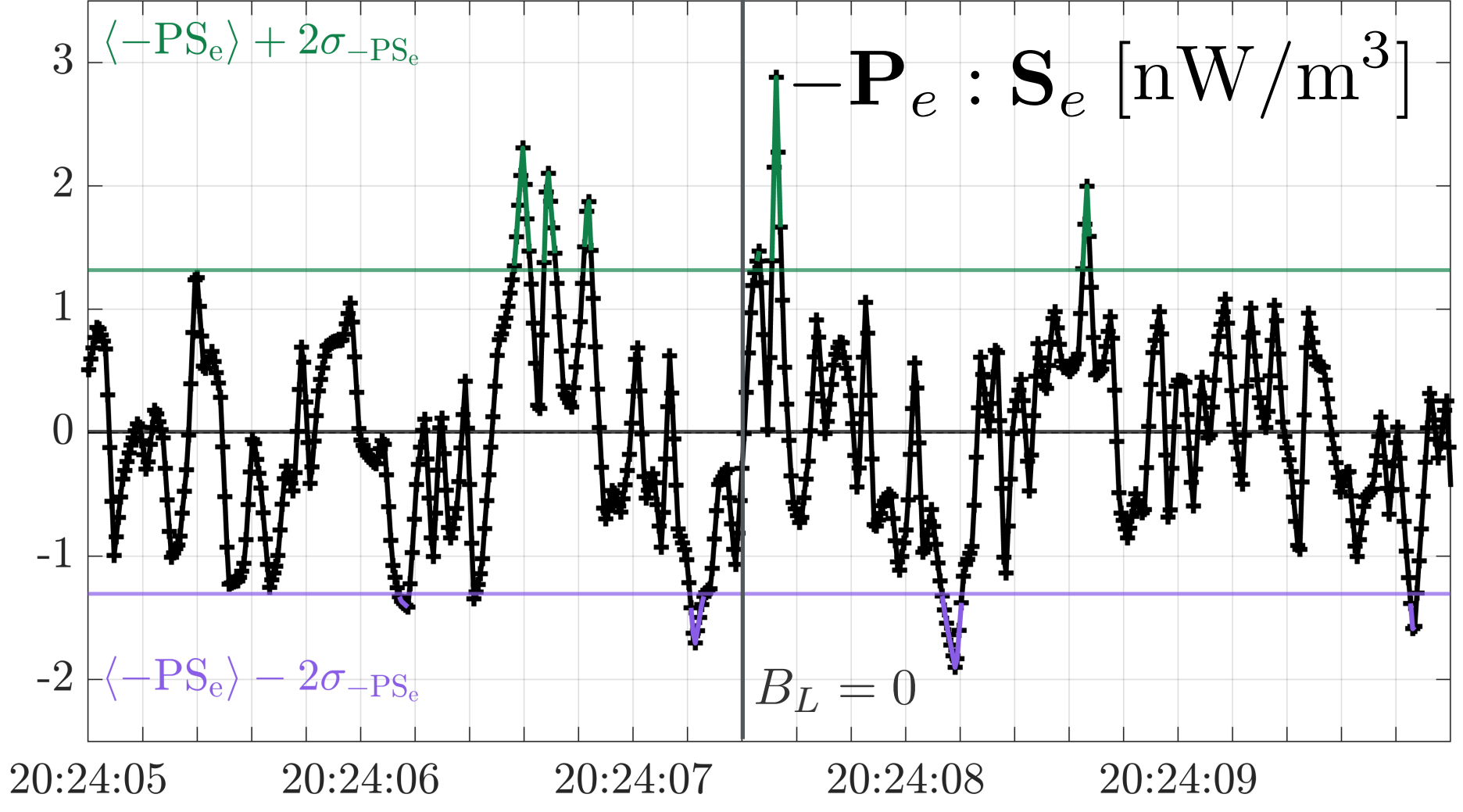


M. H. Barbhuiya

MMS observations

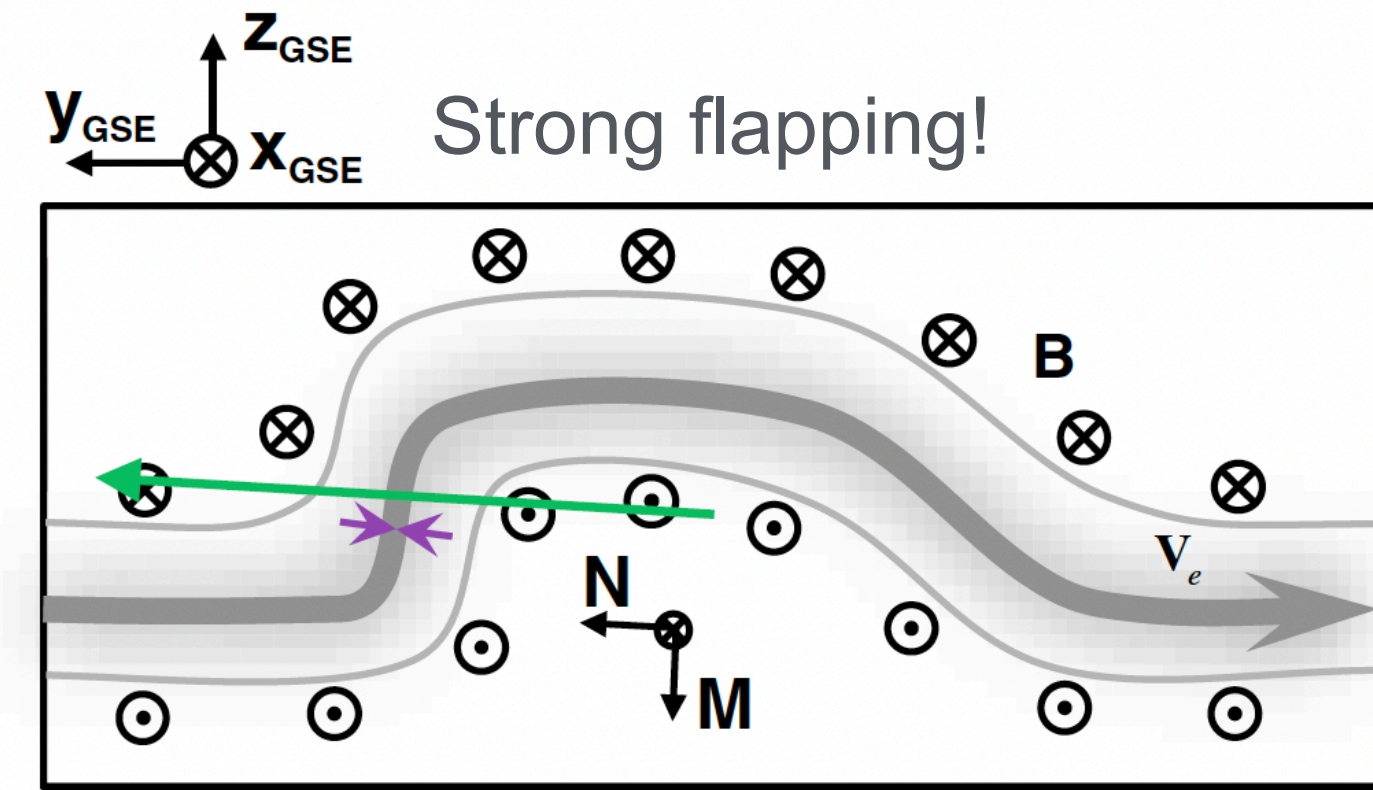
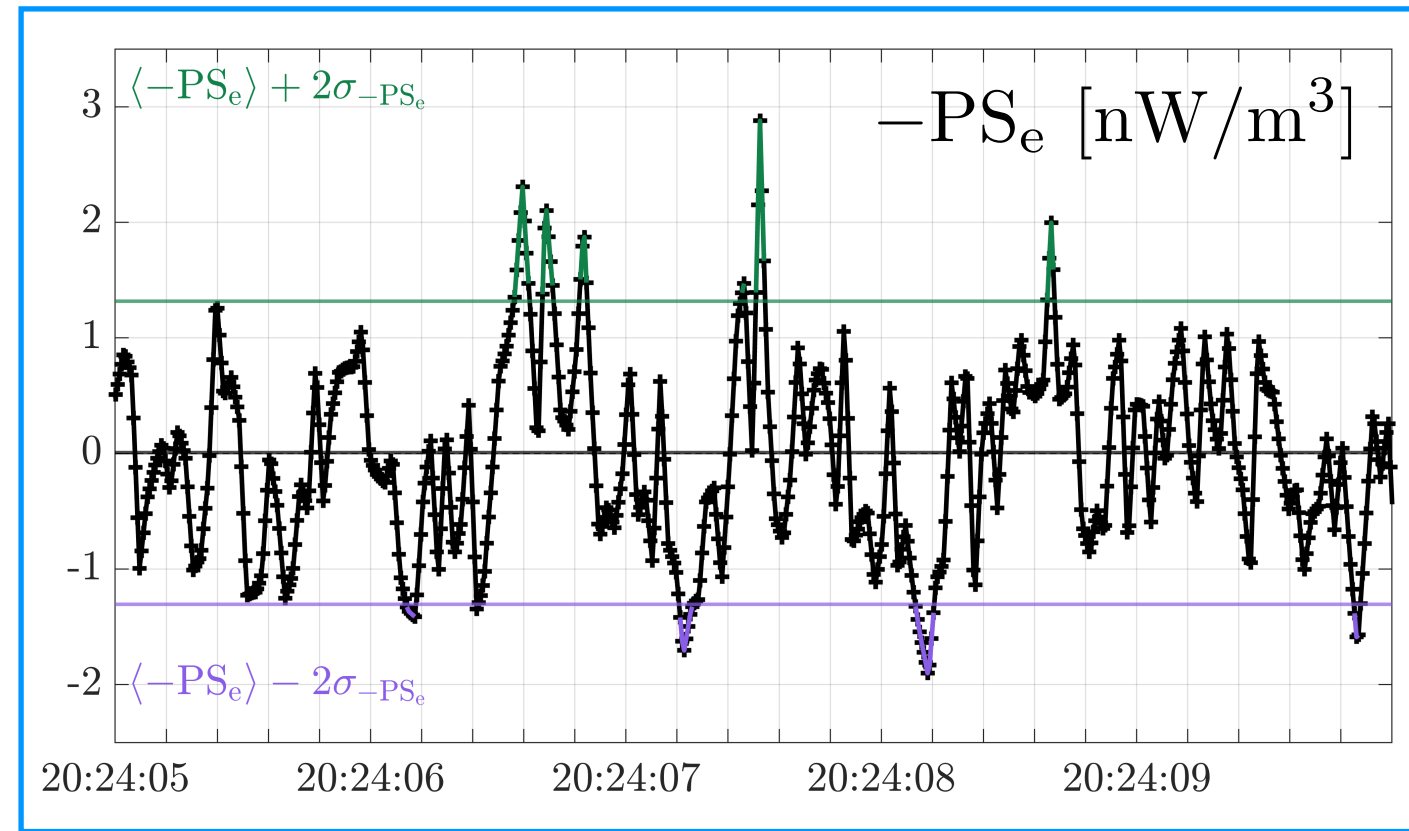
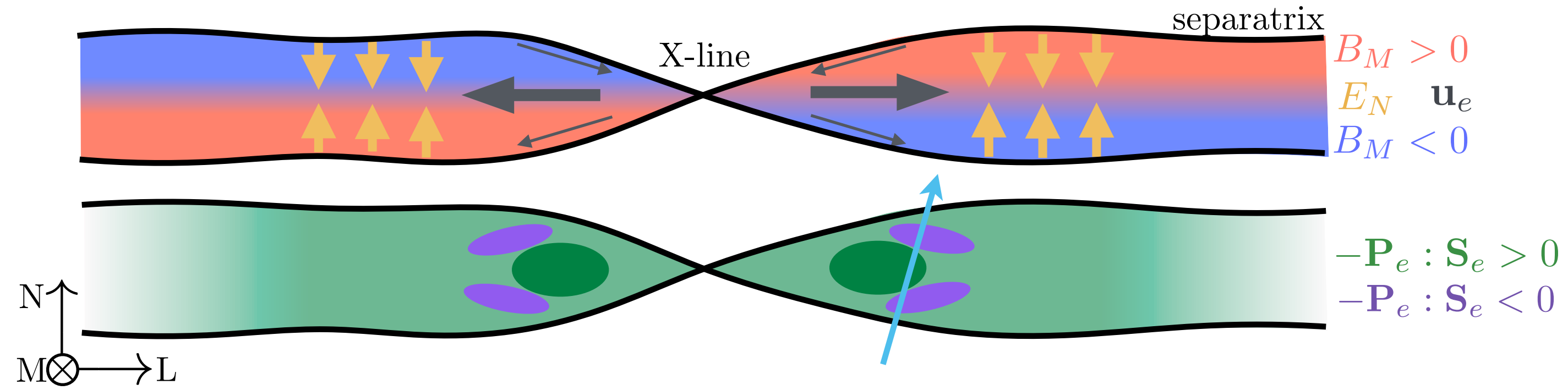
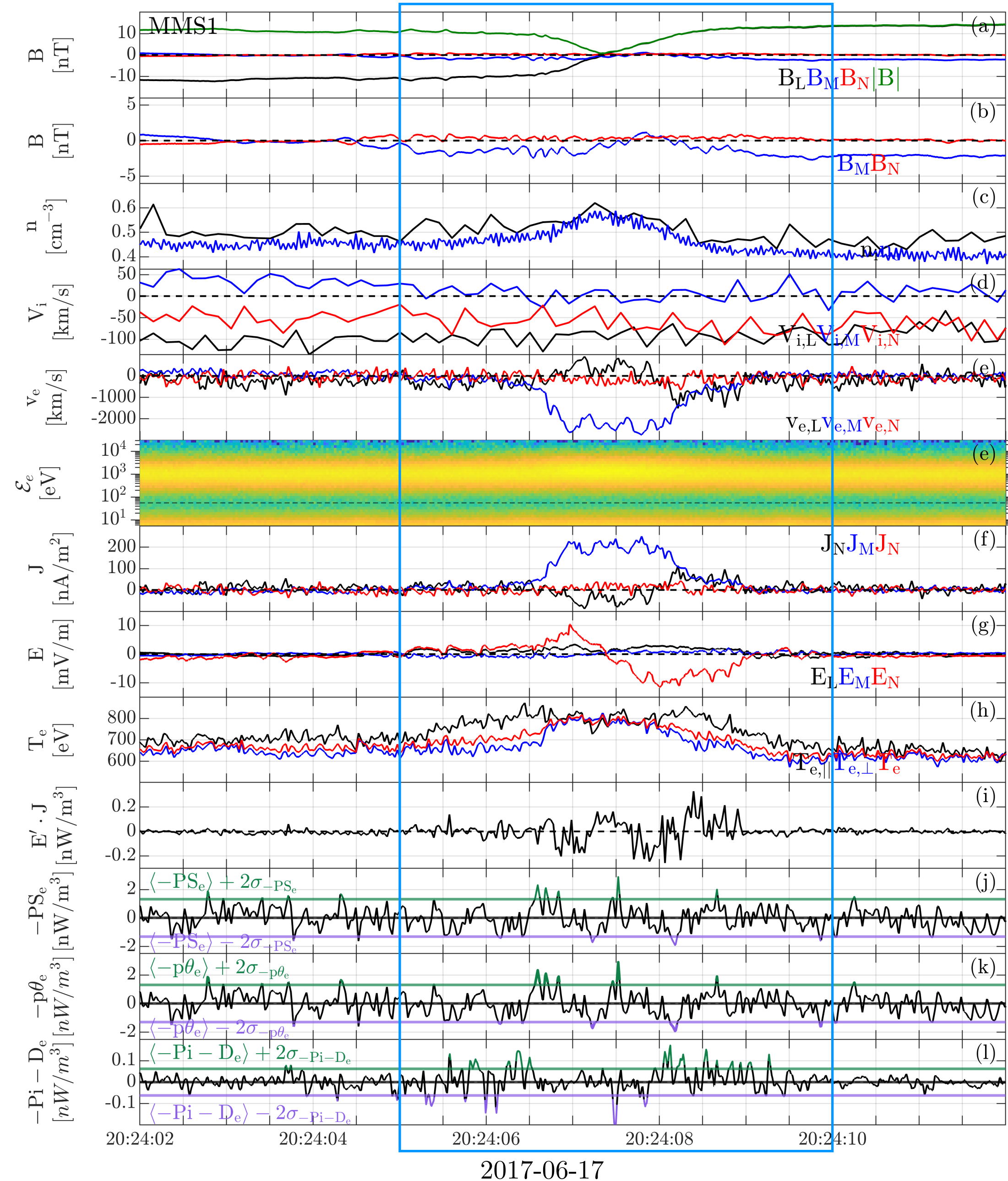


Pressure-strain variations during an EDR crossing in the magnetotail



[Cozzani et al., in preparation]

Event #3 – EDR crossing along N – Possible growth phase

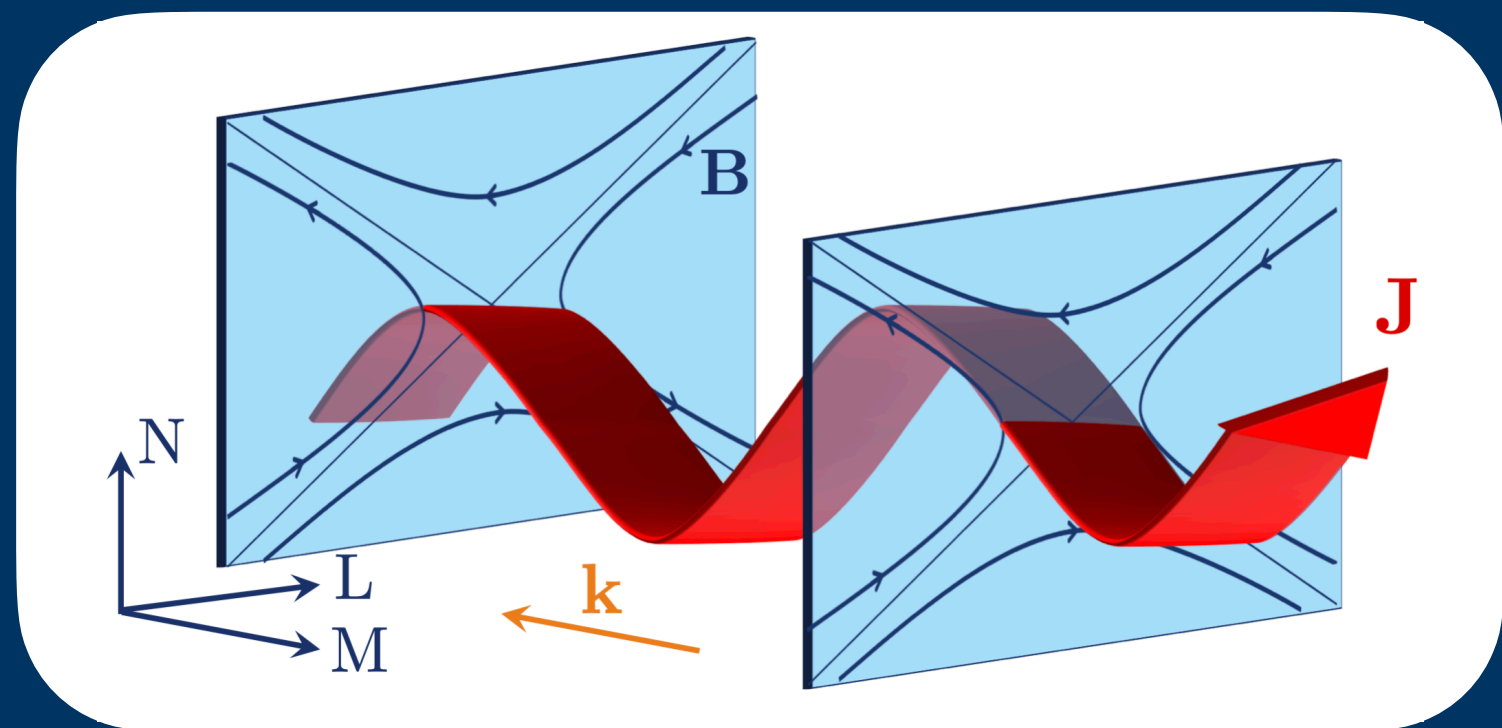


[Wang et al., GRL, 2018]

Event #3
 $d_{SC} \sim 26$ km; $d_e \sim 7$ km; $B_g \sim 0$;
 $d_{CS} \sim 7 d_e$; $V_{CS,N} \sim -70$ km/s

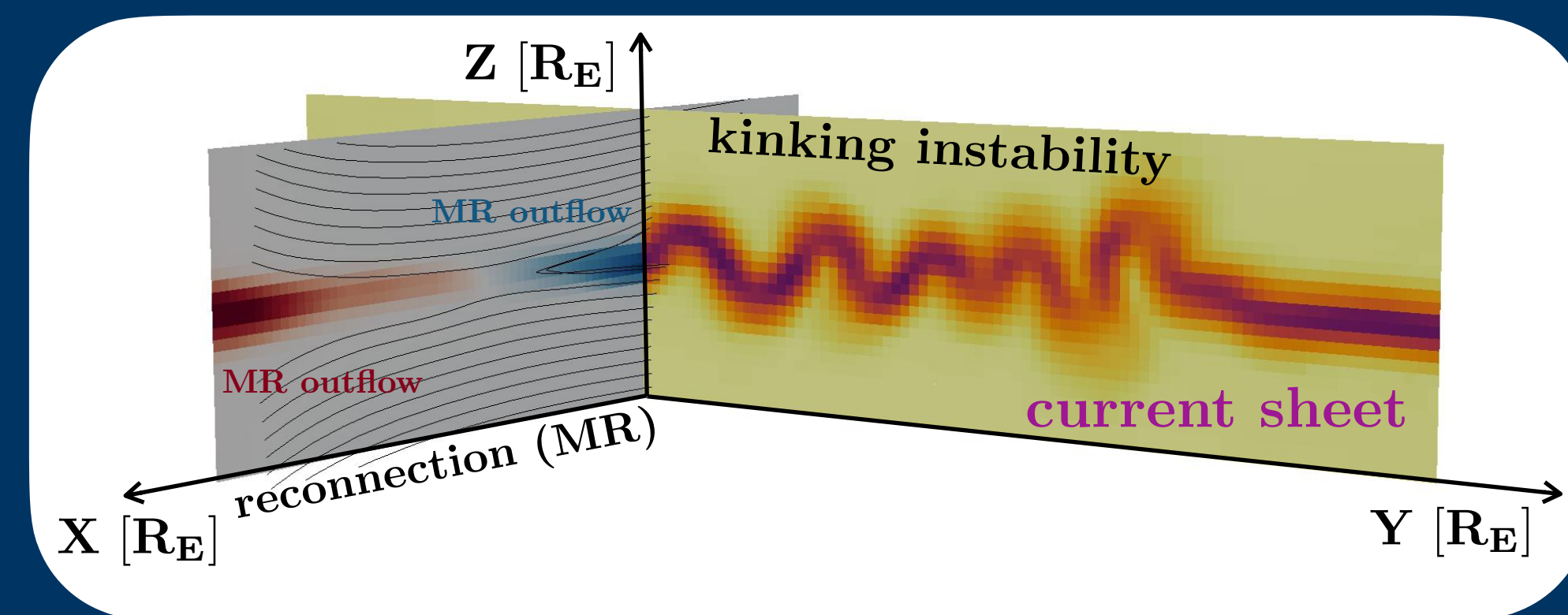
[Lu et al., Nat. Comm., 2020]
 [Farrugia et al., JGR, 2021]

Take home messages

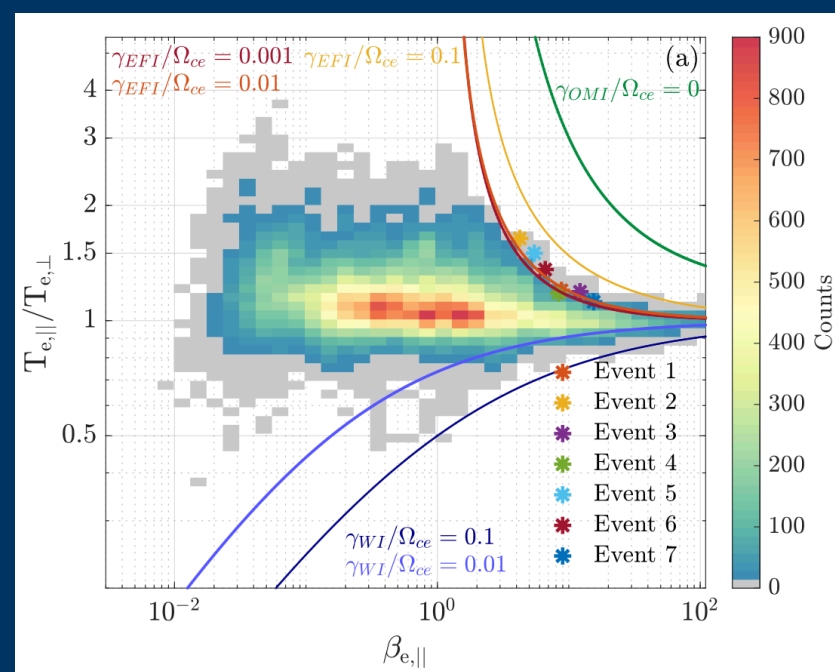


Kink instabilities at the lower-hybrid scale can affect electron dynamics and perturb the reconnecting current sheet and the EDR.

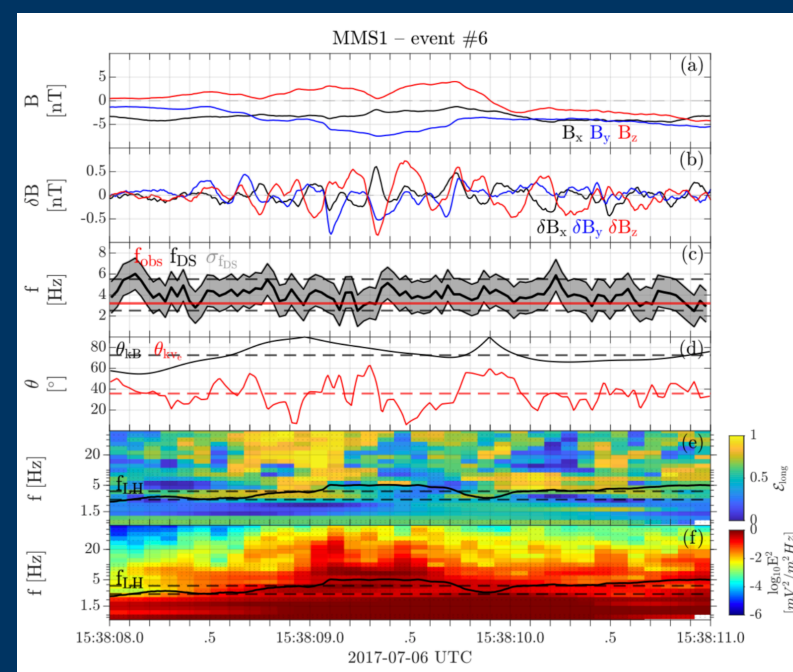
The interaction of reconnection and kink instability is still poorly understood. Global magnetospheric simulations indicate that the reconnection rate decreases during the kink instability growth phase.



Indirect evidence

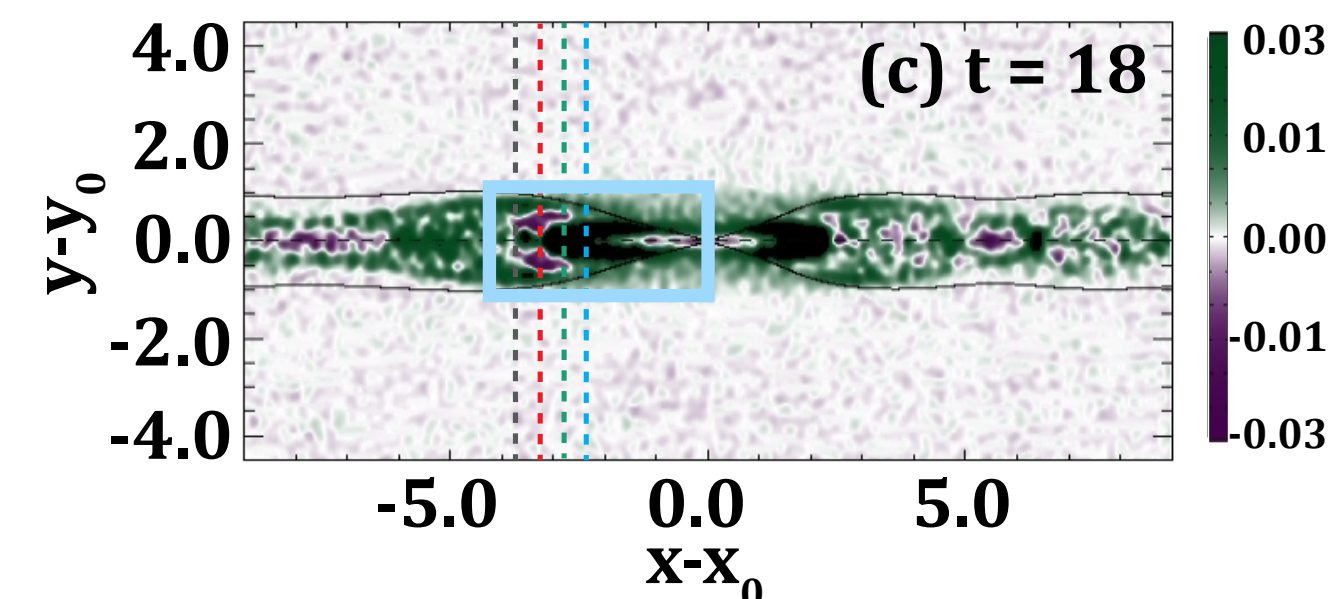


Direct evidence



We report the first direct in situ observations of the non-propagating electron firehose wave mode in the outflow region in the magnetotail. The interaction with reconnection is still not understood.

PIC simulations indicate that spatial structures in pressure-strain interaction at the EDR edge could be a useful indicator for the reconnection growth phase. We suggest that these signatures can be observed by MMS.



References

Review Papers

- Space Science Review ISSI collection Magnetic Reconnection: Explosive Energy Conversion in Space Plasmas <https://link.springer.com/collections/jebbbdaeda>
- D. B. Graham, G. Cozzani, et al., The role of kinetic instabilities and waves in collisionless magnetic reconnection, Space Sci. Rev. 221, 20 (2025). <https://doi.org/10.1007/s11214-024-01133-7>
- M. Shay, et al., Simulation models for exploring magnetic reconnection, Space Sci. Rev. 221, 81 (2025). <https://doi.org/10.1007/s11214-025-01210-5>
- M. Palmroth, et al., Vlasov methods in space physics and astrophysics, Living Rev. Comput. Astrophys. 4, 1 (2025). <https://link.springer.com/article/10.1007/s41115-025-00024-0>

Papers

- M. H. Barbhuiya, et al., Identifying the growth phase of magnetic reconnection using pressure-strain interaction, J. Geophys. Res. 130, e2024JA033446 (2025). <https://doi.org/10.1029/2024JA033446>
- G. Cozzani et al., , Interplay of magnetic reconnection and current sheet kink instability in the Earth's magnetotail, Geophys. Res. Lett. 52, e2024GL111848 (2025). <https://doi.org/10.1029/2024GL111848>
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- M. Alho, G. Cozzani et al., Finding reconnection lines and flux rope axes via local coordinates in global ion-kinetic magnetospheric simulations, Ann. Geophys. 42, 145 (2024). <https://doi.org/10.5194/angeo-42-145-2024>
- G. Cozzani et al., Direct observations of electron firehose fluctuations in the magnetic reconnection outflow, J. Geophys. Res. 128, e2022JA031128 (2023). <https://doi.org/10.1029/2022JA031128>
- G. Cozzani et al., Structure of a perturbed magnetic reconnection electron diffusion region in the Earth's magnetotail, Phys. Rev. Lett. 127, 215101 (2021). <https://doi.org/10.1103/PhysRevLett.127.215101>

Challenges and open questions

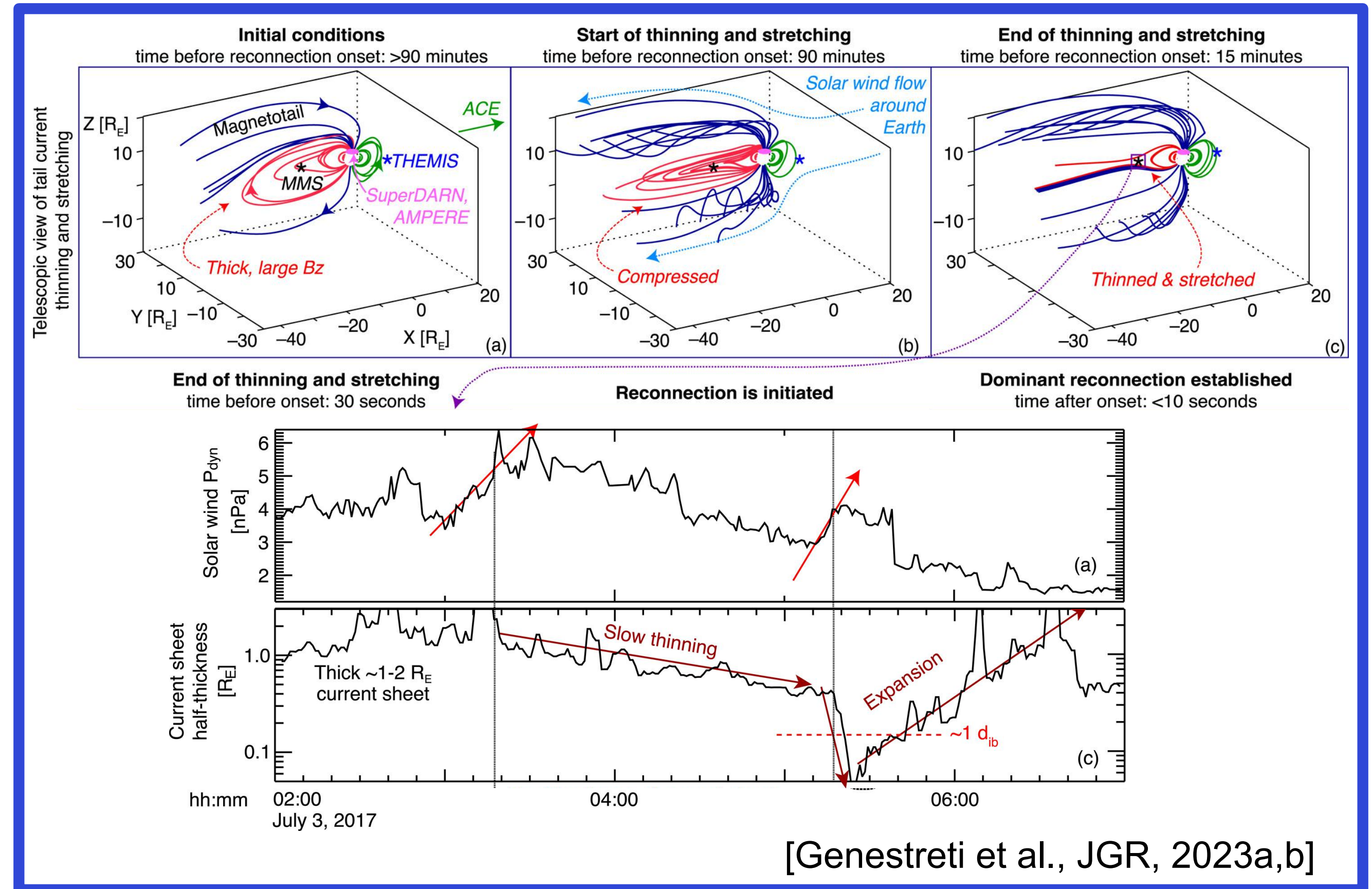
Challenges and open questions

(most of them requiring cross-scale approach)

- **Onset in weakly driven current sheets (e.g. the magnetotail)**

- Interplay with waves (3D effects, anomalous resistivity)

- Large-scale X-line topology (extent of the reconnection line, prime and secondary X-lines)



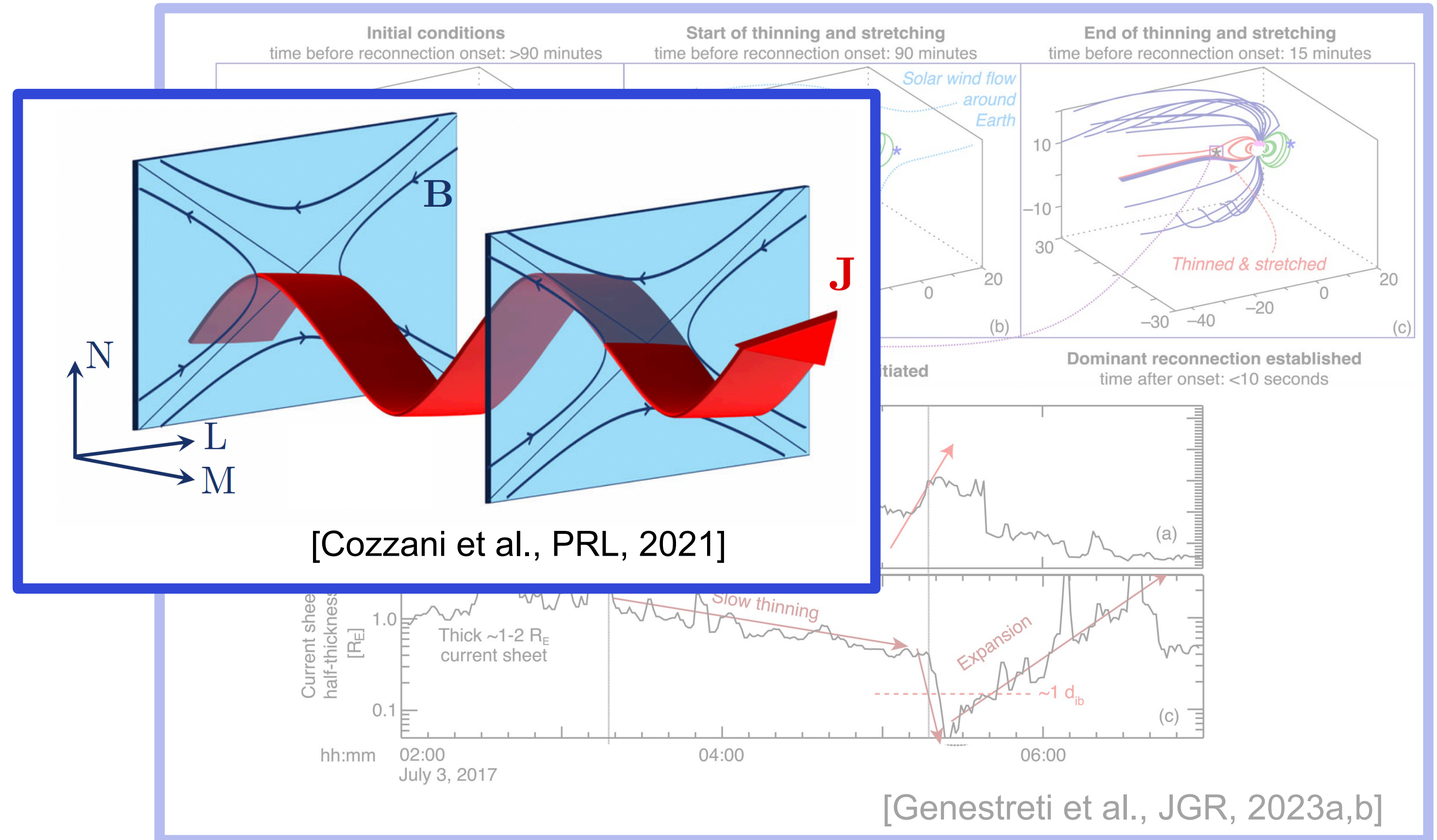
- Role of turbulence

- ... (this is not a comprehensive list!)

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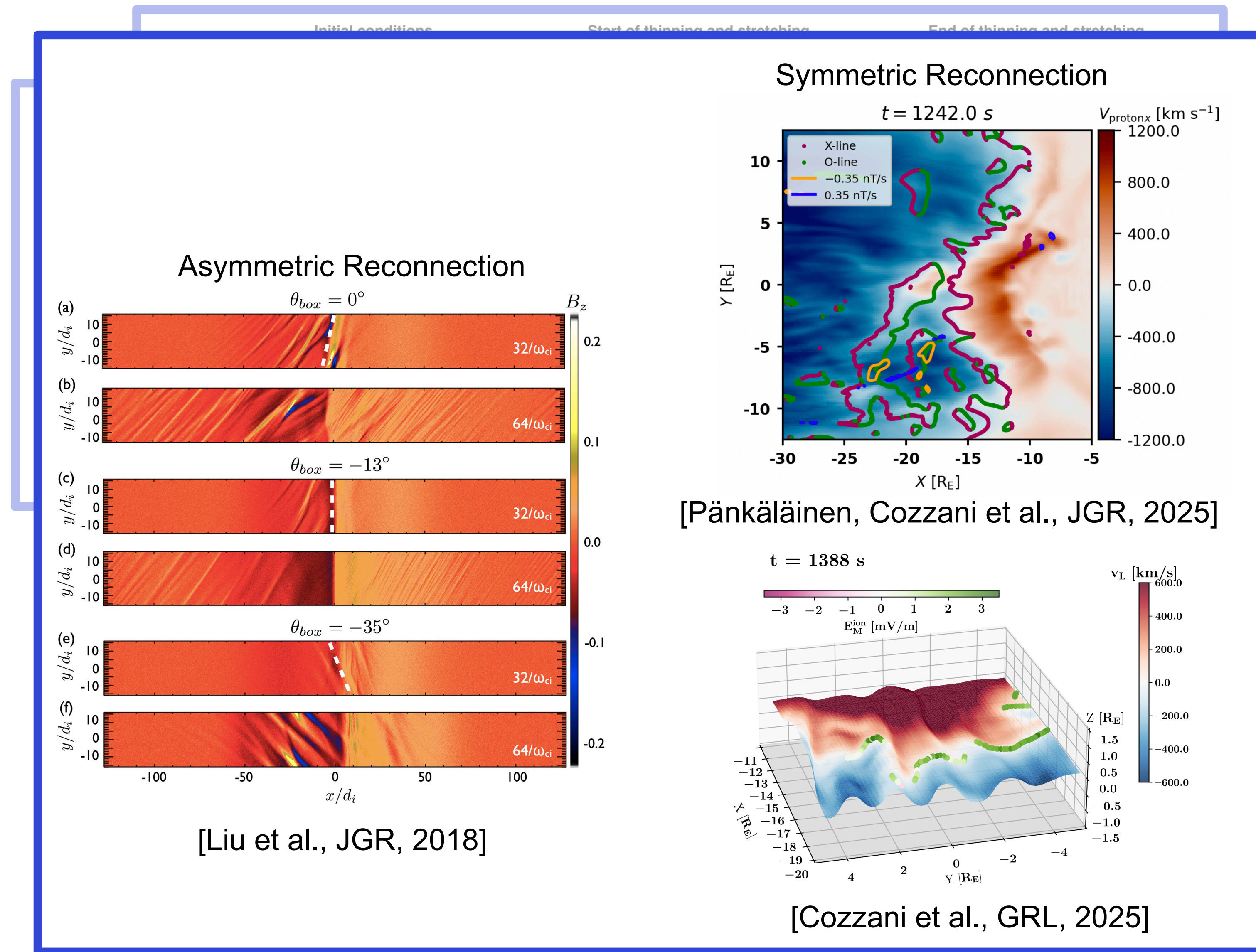
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[Liu et al., JGR, 2018]

[Pänkäläinen, Cozzani et al., JGR, 2025]

[Cozzani et al., GRL, 2025]

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