Particle energisation and energy transport in Multiscale MHD - Hybrid - Kinetic PIC models of magnetospheres

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Abstract

- Reconnection in the Earth's magnetotail releases energy stored in magnetic fields (and in their sources, magnetic currents) and converts it to plasma flows, propagating both earthward and tailward, and particle energization. The energy released by reconnection is carried by the particle species, in terms of bulk energy, enthalpy and heat flux, and by the electromagnetic fields in terms of Poynting flux.

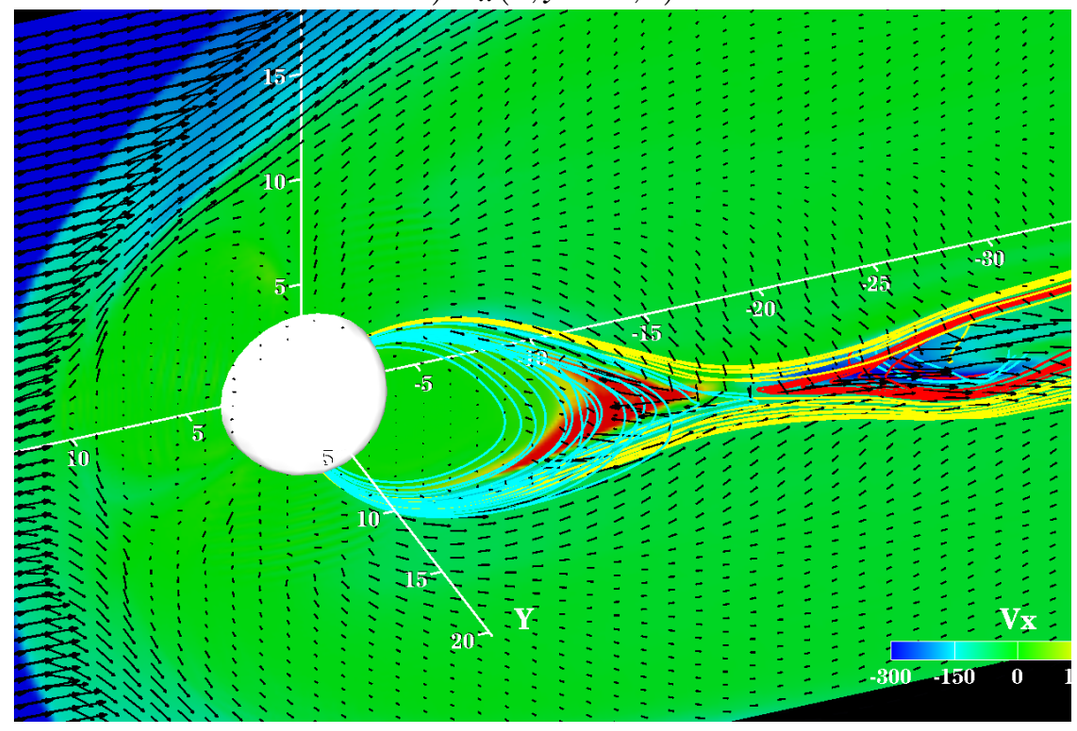
- Space missions can observe locally the different forms of energy flow and from many observations over several events can provide a statistical picture of the spatial correlations between fluxes in different regions around reconnection. However, space missions with one or few spacecraft cannot provide an overall view of the conditions of energy fluxes for a specific event at different times.
- Global MHD models can provide the picture of the energy flows around a specific reconnection event but are limited in what fluxes they can investigate: MHD misses heat fluxes and cannot distinguish electrons from ions. For this reason, we have developed a technique that allows us to launch a kinetic simulation spawned from an MHD state. With this approach we consider the specific event of 7th of February 2009 and follow for 1 minute the full kinetic evolution of a large portion of the magnetotail encompassing all the energy flows generated by reconnection.
- The results provide a detailed view of the energy fluxes and inform us about the extra features missed by MHD, in terms of species contribution, heat fluxes and processes caused by kinetic instabilities not present in MHD global models.

Lapenta, G., El Alaoui, M., Berchem, J., & Walker, R. (2020). Multiscale MHD-Kinetic PIC Study of Energy Fluxes Caused by Reconnection. *Journal of Geophysical Research: Space Physics*.

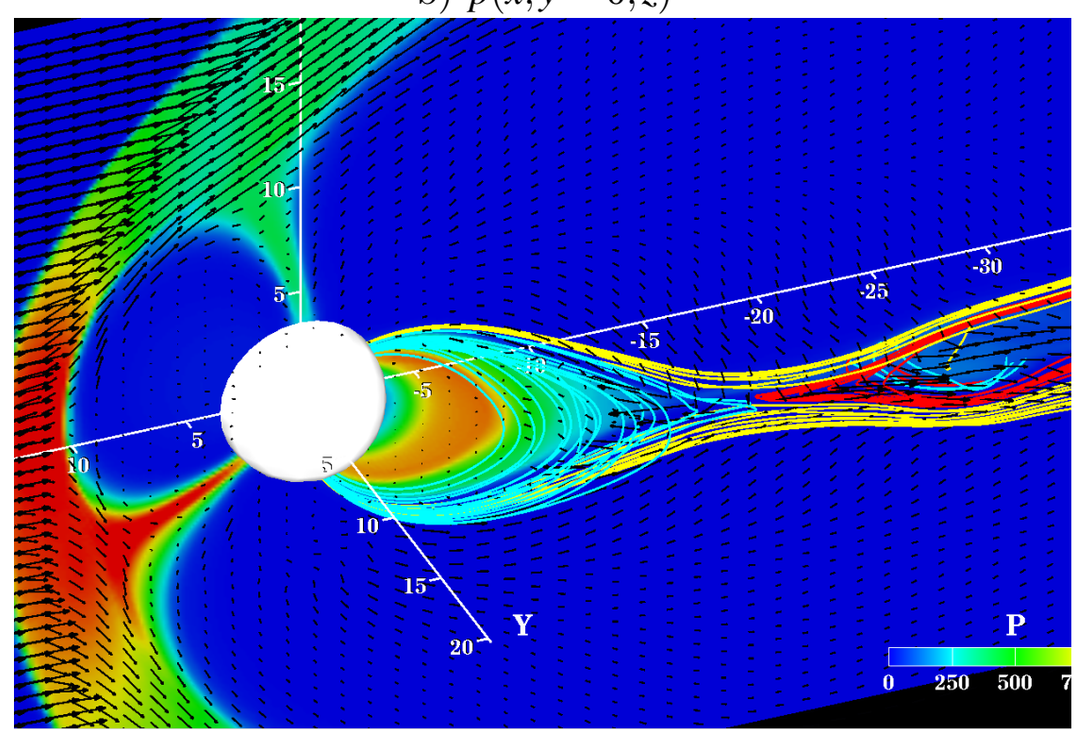
Approach: spawning a PIC simulation from a global MHD model of a specific event

- We consider the substorm of February 7, 2009,
- The event is modeled first with a global MHD model (El-Alaoui et al., 2013)
- Starting at 03:58:00UT we begin a PIC simulation for the subdomain [-7,-38.2]$R_E$in X, [-7.32, 13.48] $R_E$in Yand [-11.25,4.35]R_E in Z in GSM coordinates
- The MHD state provides initial and boundary conditions for a iPic3D simulation.
- iPic3D is a fully kinetic (electrons and ions are particles) implicit PIC code (Markidis, Lapenta, Rizwan-Uddin, 2010)
- See Walker et al: JPP, 2019 for details: DOI: https://doi.org/10.1017/S0022377819000072

a) $V_x(x, y = 0, z)$

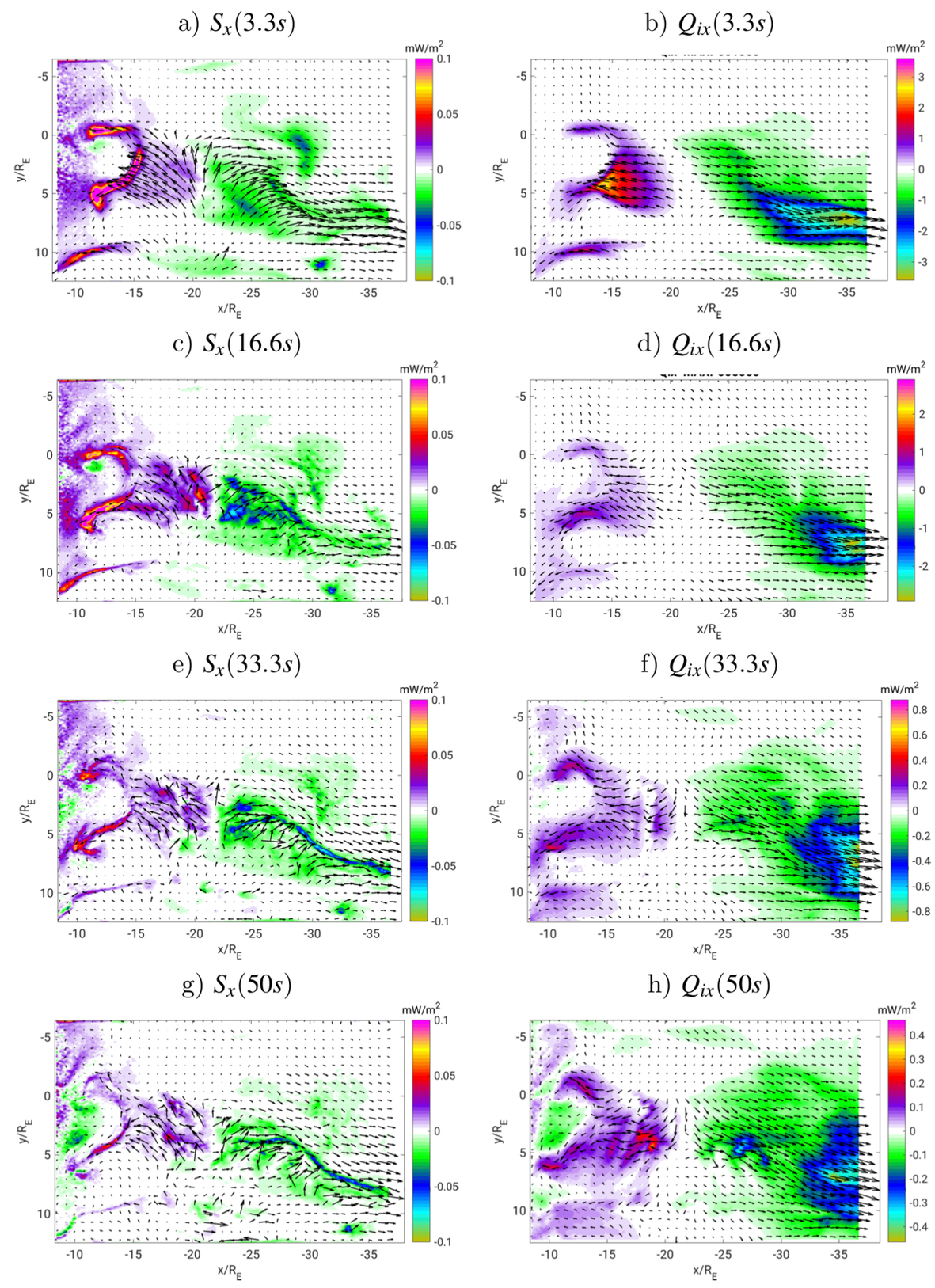


b) $p(x, y = 0, z)$



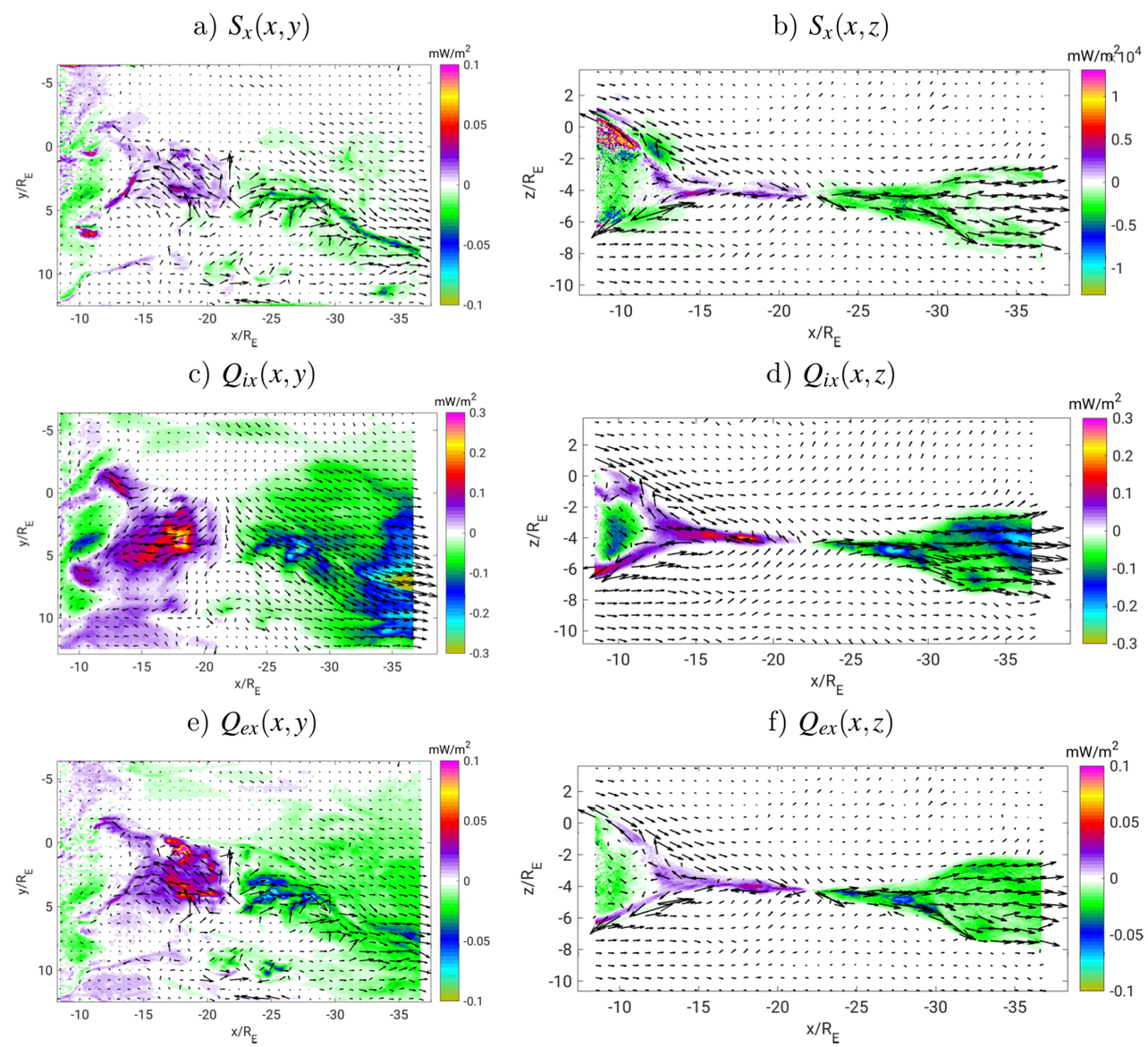
Energy fluxes at different times: Poynting Flux S and ion energy flux Qi

- The initial state of MHD is not revolutionized but important features develop
- Finer-scale structures develop, as a consequence os waves and instabilities captured by the kinetic model but absent in MHD.
- The ion energy flux dominates over the Poynting flux (check the color scale, different for S and Qi)
- The contribution of the Poynting flux is minority but not negligible.



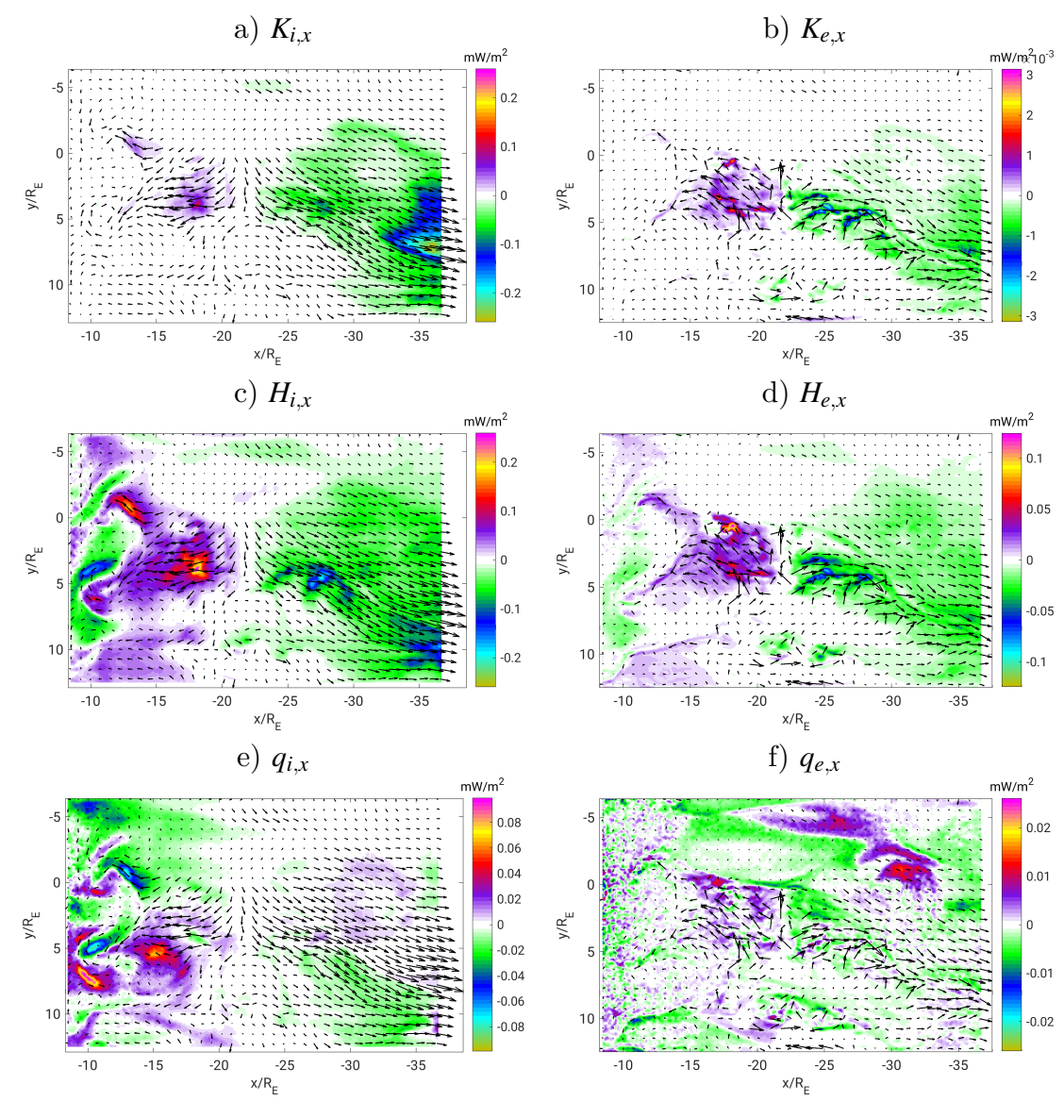
Electron Contribution:

- Two cuts are provided:
  - Left: plane of maximum pressure, this is a warped plane that at each x,y determines where the pressure is maximum along z forming a surface where quantities are represented
  - Right: meridional plane
- The ion again is seen to dominate the energy flow but the contribution of electrons and the Poynting flux is not irrelevant.
- The Poynting flux and the electron energy flow are comparable in size.
- Note however that this run uses a reduced mass ratio where ions are physical protons but electrons have a heavier mass: $m_i/m_e = 256$



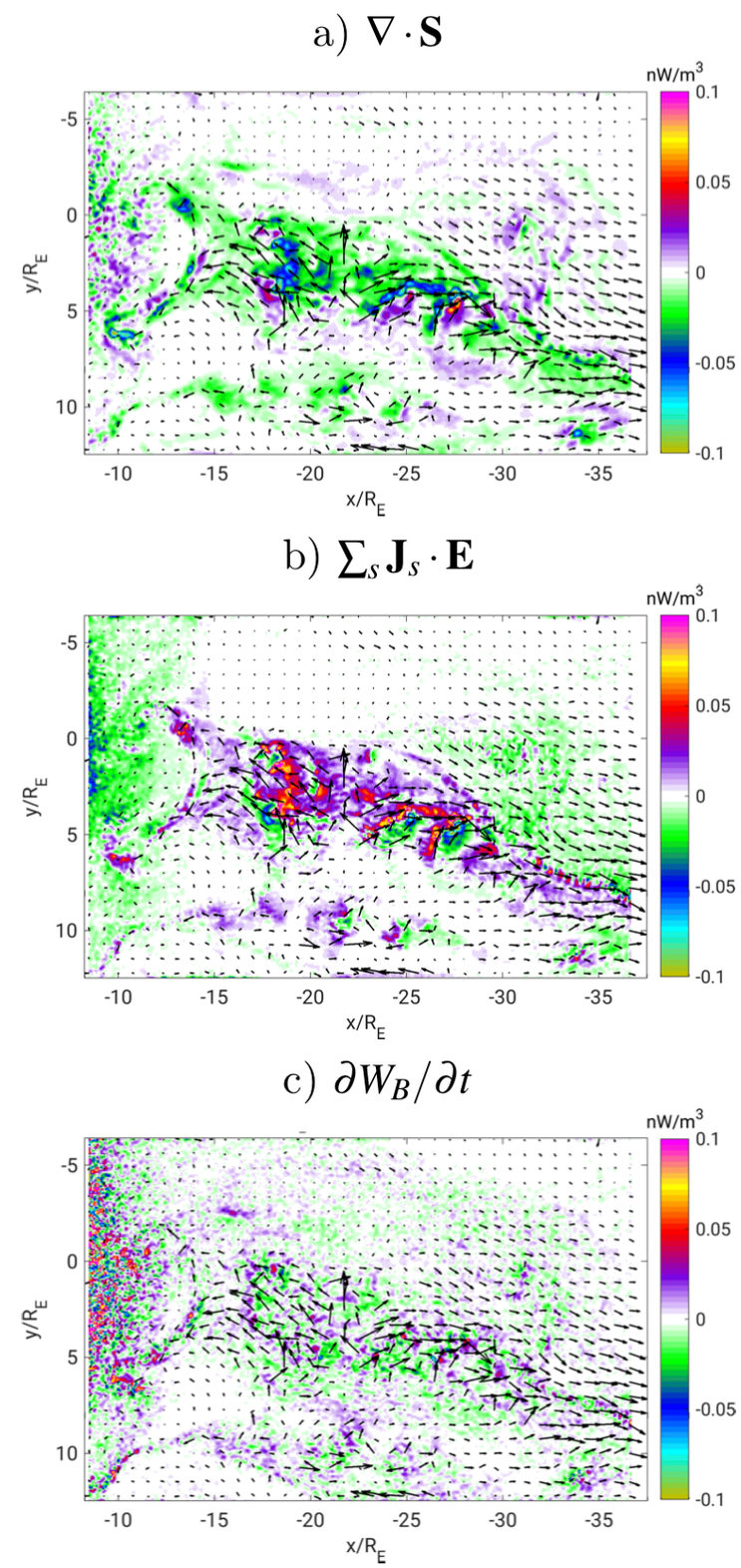
Break up of the energy flux of each species in bulk, enthalpy and heat flux.

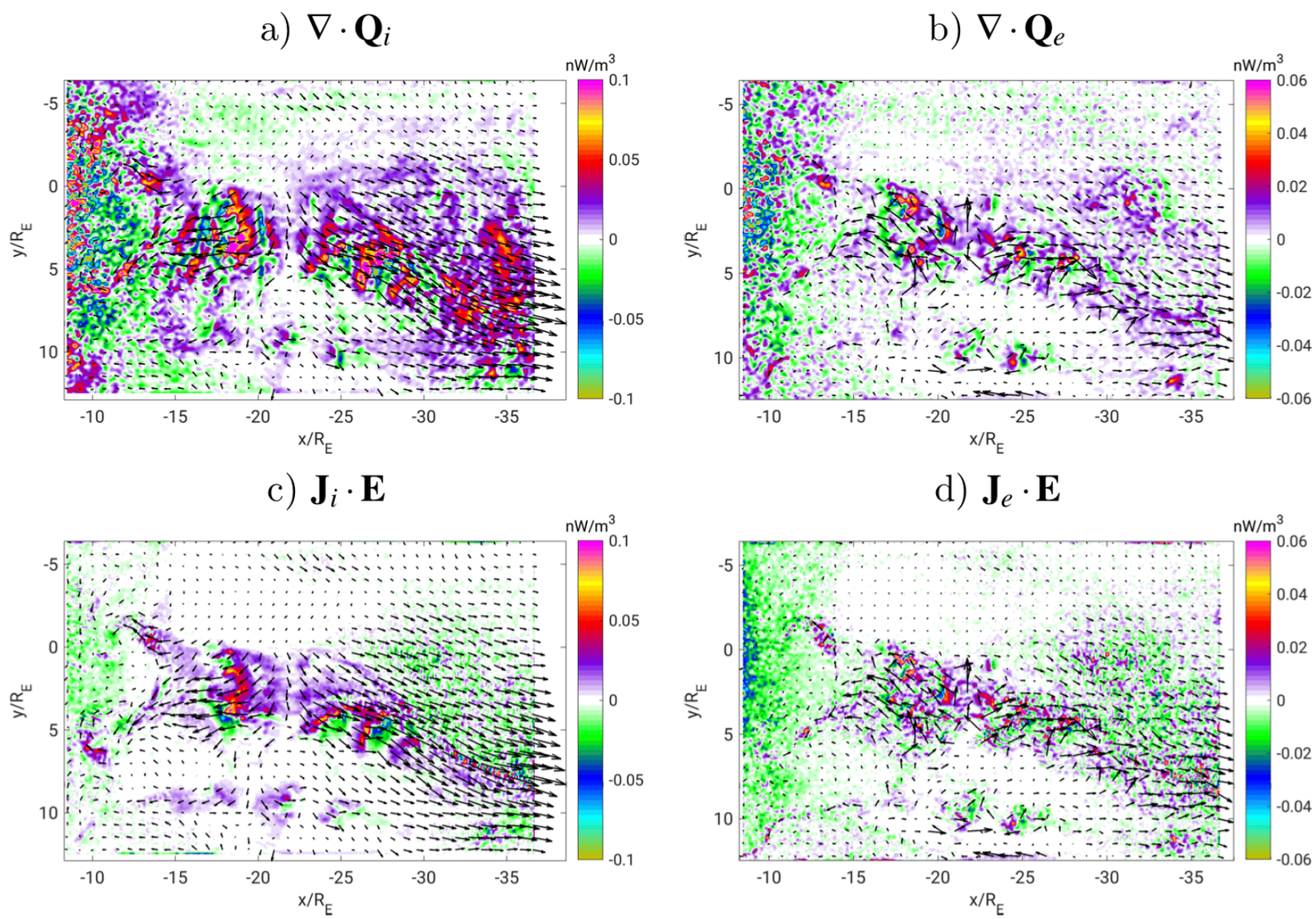
- Left: ions; Right, electrons
- Top: bulk energy flux
- Middle: enthalpy flux
- Bottom: Heat flux
- The ion bulk and enthalpy flux are of similar strength but enthalpy is dominant in the Earthward flow.
- The electron bulk flow is smallest but the electron enthalpy flux is significant.
- The heat flux carries less energy but its structure conveys information on the processes and the non-maxwellian nature of the local distribution



Energy balance: the electromagnetic energy balance equation

- By and large reconnection is fairly steady with only a noisy bubbling of electromagnetic energy net exchange
- But there is a strong conversion of energy between the species and the Poynting flux.
- The divergence of the Poynting flux nearly exactly balances the work done by the species
- When $\mathbf{J}_s \cdot \mathbf{E}$ is positive the power goes to the particles (load, in electrotechnical language). In the reconnection region and the outflow this is mostly the case
- But there are isolated regions of inverse exchange where the energy goes from the particles to the electromagnetic field (generator)



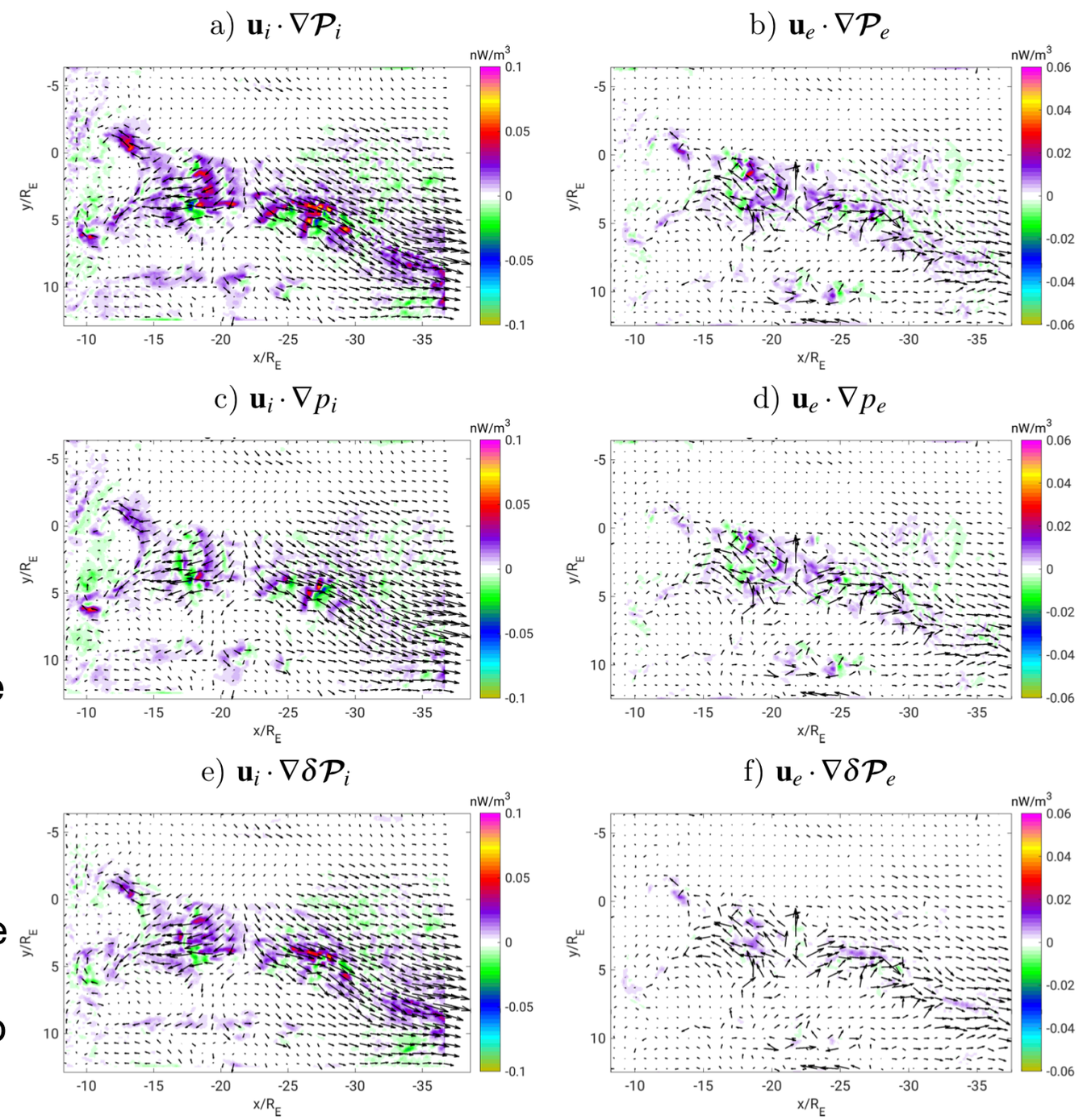


Energy balance for the species: left ions, right electrons

- The ions exchange the largest amount of power but the electron contribution is not negligible.
- For both species the process is becoming turbulent

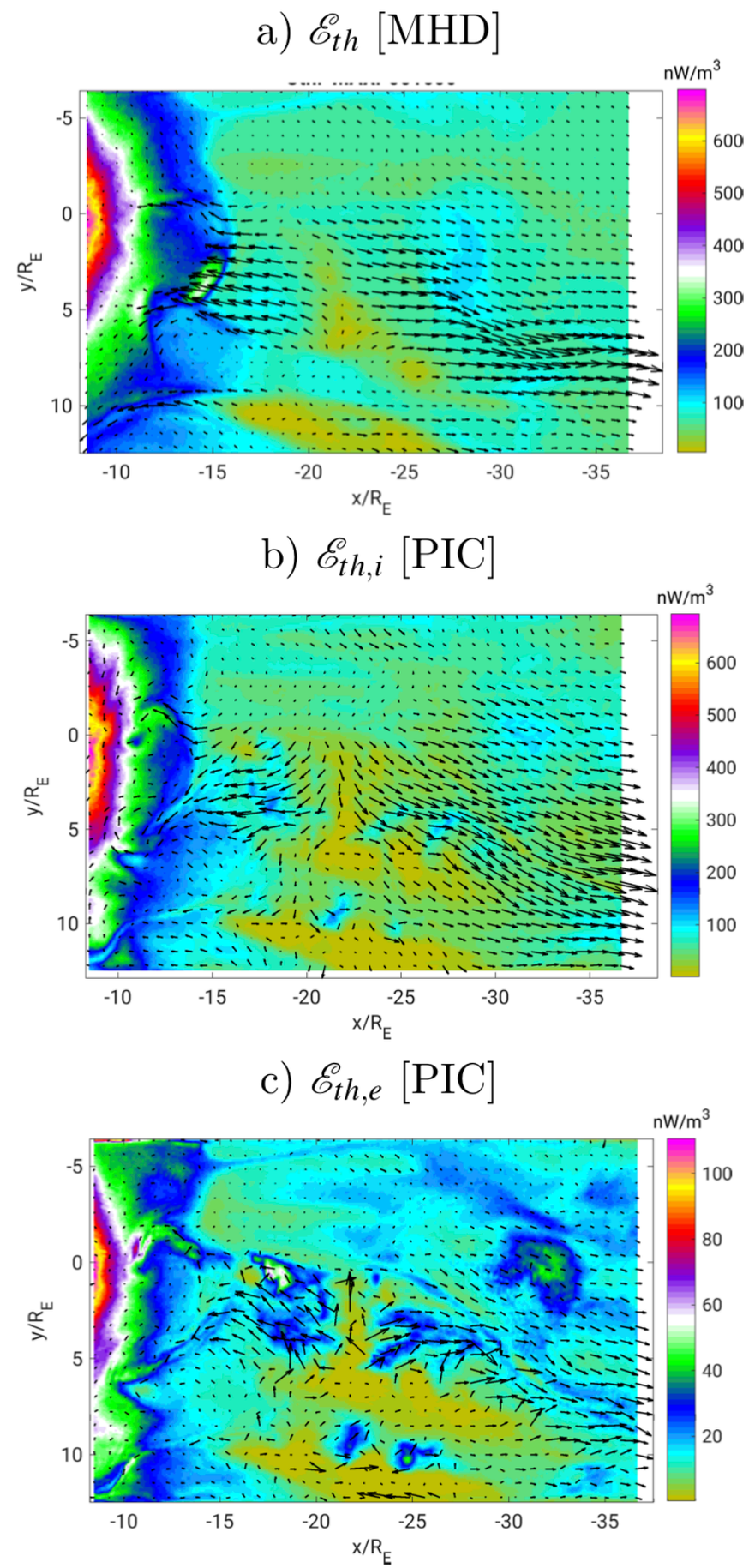
Role of the pressure tensor and its off-diagonal components

- Left: ions; Right:electrons
- Top: Full pressure tensor contribution to the energy exchange
- Middle: contribution from the trace of the pressure tensor
- Bottom: contribution from only the deviator terms
- For both electrons and ions the deviator contribution is as important as that of the trace.
- In both species the outflow develops into a turbulent state



Thermal energy of the species compared with the single MHD internal energy

- The ion thermal energy remains fairly similar to the MHD state we start from
- The electrons thermal energy, initially set identical to the ion thermal energy (except for $T_i/T_e = 5$) becomes much more structured
- Results are shown on the maximum pressure plane
- The presence of instabilities in the outflow produces striations and fronts in both species, more pronounced for the electrons.



Key Points

★ A multi-scale approach provides information about kinetic processes missed by MHD in the description of the energy fluxes from reconnection.

★ Ion bulk energy and enthalpy flows carry the greatest fraction of the energy, a feature common to MHD and kinetic models.

★ A significant contribution to the energy budget comes from the electron enthalpy flux, an effect missed by MHD models.

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