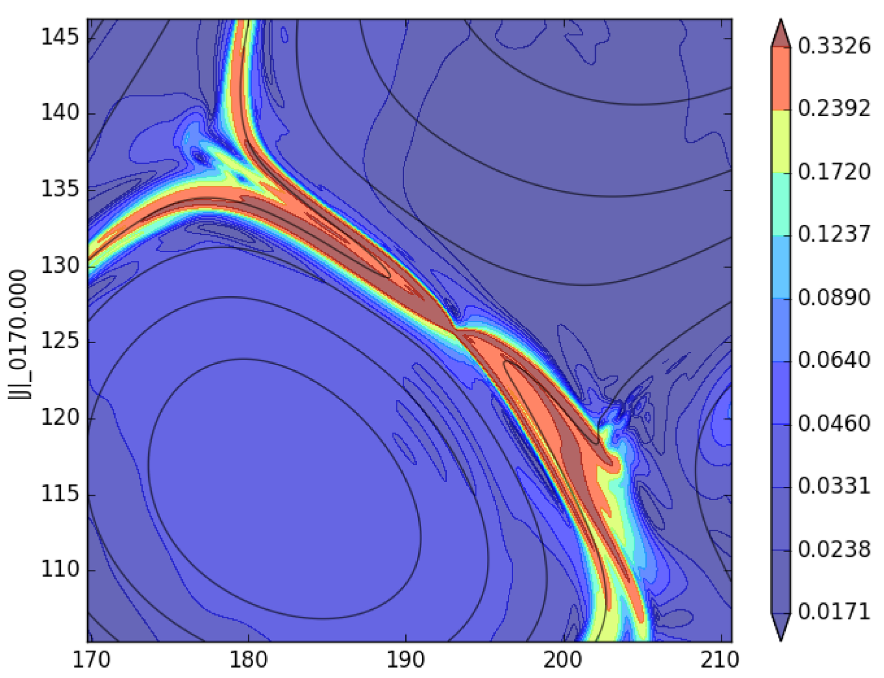
Energy conversion rates in proximity of magnetic reconnection sites

S. Fadanelli[1,2], F. Califano[1], B. Lavraud[2]

Overview:

- our aim is to clarify by which channels does energy get transformed in a reconnecting plasma systems
- our approach is focusing on the evolution of fluid elements, not single particles but rather the whole plasma

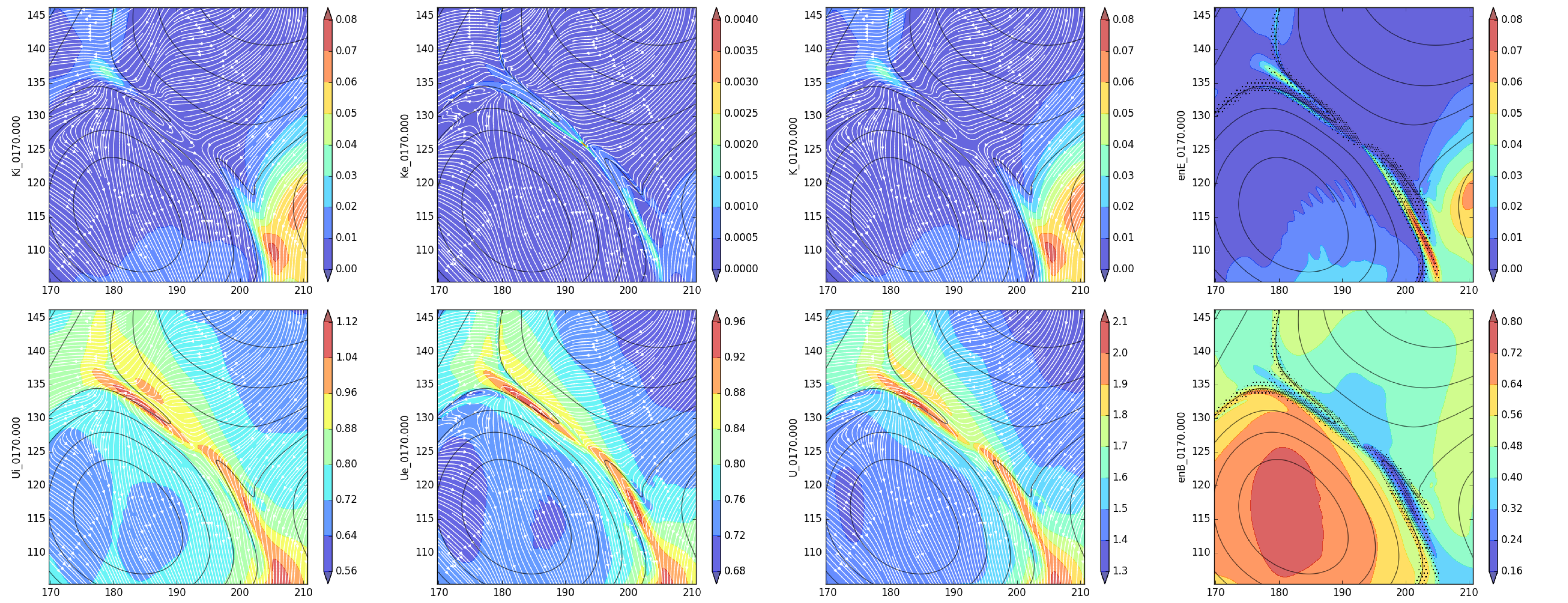


Reconnection zone of focus, from hybrid two-dimensional simulation. Magnetic field lines in black, magnitude of current density is given by the colorscale.

Hybrid **Vlasov-Maxwell simulations** in **2D-3V plasma** box with **guide field** and **periodic boundary conditions** (electron fluid: same density as ions, isothermal closure)

Valentini 2007

Energy densities:



Energy densities in the portion of system considered in the color scheme. Top row: kinetic energy density for ions, electrons, barycentre fluid. Electric energy density. Bottom row: internal energy density for ion, electron and barycentre fluid. Magnetic energy density.

Magnetic field lines in black, in white flow lines while current density is dashed. All terms have been evaluated in the reference frame where plasma velocity at X point is null (see the characteristic flow circulation in the inner reconnection region).

Note that the two reconnection inflow regions possess different magnetic field intensities (see last panel, bottom row) implying that reconnection region is slightly asymmetric. Density profile (proportional to internal energy of electrons) shows clear piling-up in the exhaust regions.

Our analysis: evaluate all terms in energy evolution equations

The energy evolution equations single-species fluid and for the barycentre plasma fluid:

$$d_t\mathcal{U}_K^{(s)} = [\partial_t + \vec{u}^{(s)}\cdot\vec{\nabla}]\,\mathcal{U}_K^{(s)} = \boxed{-\mathcal{U}_K^{(s)}\vec{\nabla}\cdot\vec{u}^{(s)}}\ \boxed{-\vec{u}^{(s)}\cdot\vec{\nabla}\cdot\vec{\vec{P}}^{(s)}}\ \boxed{+\vec{u}^{(s)}\cdot[\varrho^{(s)}\wedge\vec{E}]}$$

$$d_t\mathcal{U}_I^{(s)} = [\partial_t + \vec{u}^{(s)}\cdot\vec{\nabla}]\,\mathcal{U}_I^{(s)} = \boxed{-\mathcal{U}_I^{(s)}\vec{\nabla}\cdot\vec{u}^{(s)}}\ \boxed{-\vec{\vec{P}}^{(s)}:\vec{\nabla}\vec{u}^{(s)}}\ \boxed{+\vec{\nabla}\cdot\vec{Q}^{(s)}}$$

$$d_t\mathcal{U}_K = [\partial_t + \vec{u}\cdot\vec{\nabla}]\,\mathcal{U}_K = \boxed{-\mathcal{U}_K\vec{\nabla}\cdot\vec{u}}\ \boxed{-\vec{u}\cdot\vec{\nabla}\cdot\vec{\vec{P}}}\ \boxed{+\vec{u}\cdot[\vec{J}\wedge\vec{B}]}$$

$$d_t\mathcal{U}_I = [\partial_t + \vec{u}\cdot\vec{\nabla}]\,\mathcal{U}_I = \boxed{-\mathcal{U}_I\vec{\nabla}\cdot\vec{u}}\ \boxed{-\vec{\vec{P}}:\vec{\nabla}\vec{u}}\ \boxed{+\vec{\nabla}\cdot\vec{Q}}\ \boxed{+\vec{J}\cdot[\vec{E}+\vec{u}\wedge\vec{B}]}$$

Note that by the previous equations we focus on plasma evolution along streamlines (in all of them the lagrangian derivative is extracted on the left-hand side).

Up-to-date findings

- both species by their own and the barycentre of plasma are subject to a condition in which electromagnetic and pressure forces generally balance each other and therefore do not accelerate the plasma bulk (this can be explained for single species by assuming gyration center approximation and noting that the strong out-of-plane guide field component constrains most energy transfer to happen perpendicularly to magnetic lines)

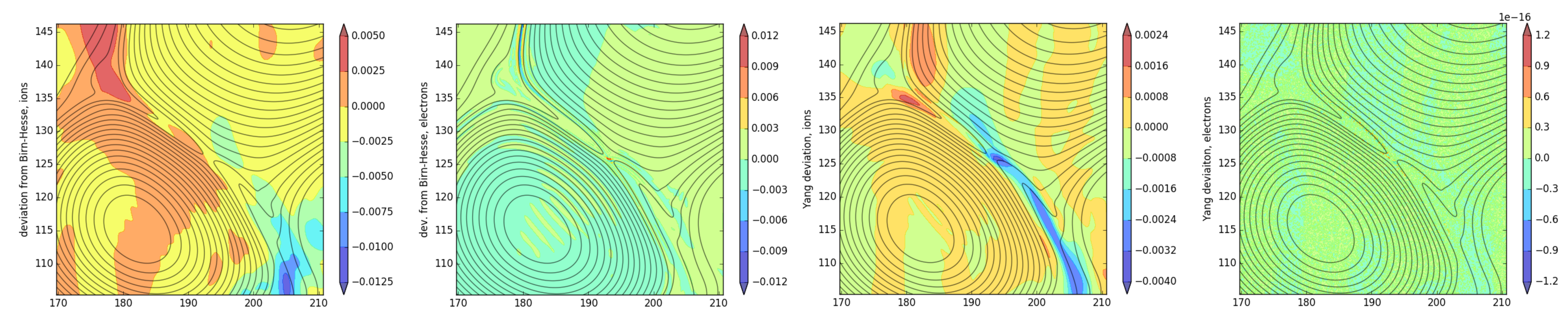
Birn and Hesse 2010

Breakup of this approximate balance is located in the far exhausts for ions and in close correspondence with the X point for electrons (possible diagnostic?)

NEW!

- deviation from the 2/3 proportion between internal energy changes due to compressions/dilations and variations from pressure-fluid interactions happens inside both exhausts, meaning that there is happening a true change in the shape of the velocity distribution (one that cannot be accounted for by rotations or re-scaling processes only). Basically, this quantity is Yang's Pi-D index (aside: note that because of the isothermal electron closure, the last panel is substantially null everywhere)

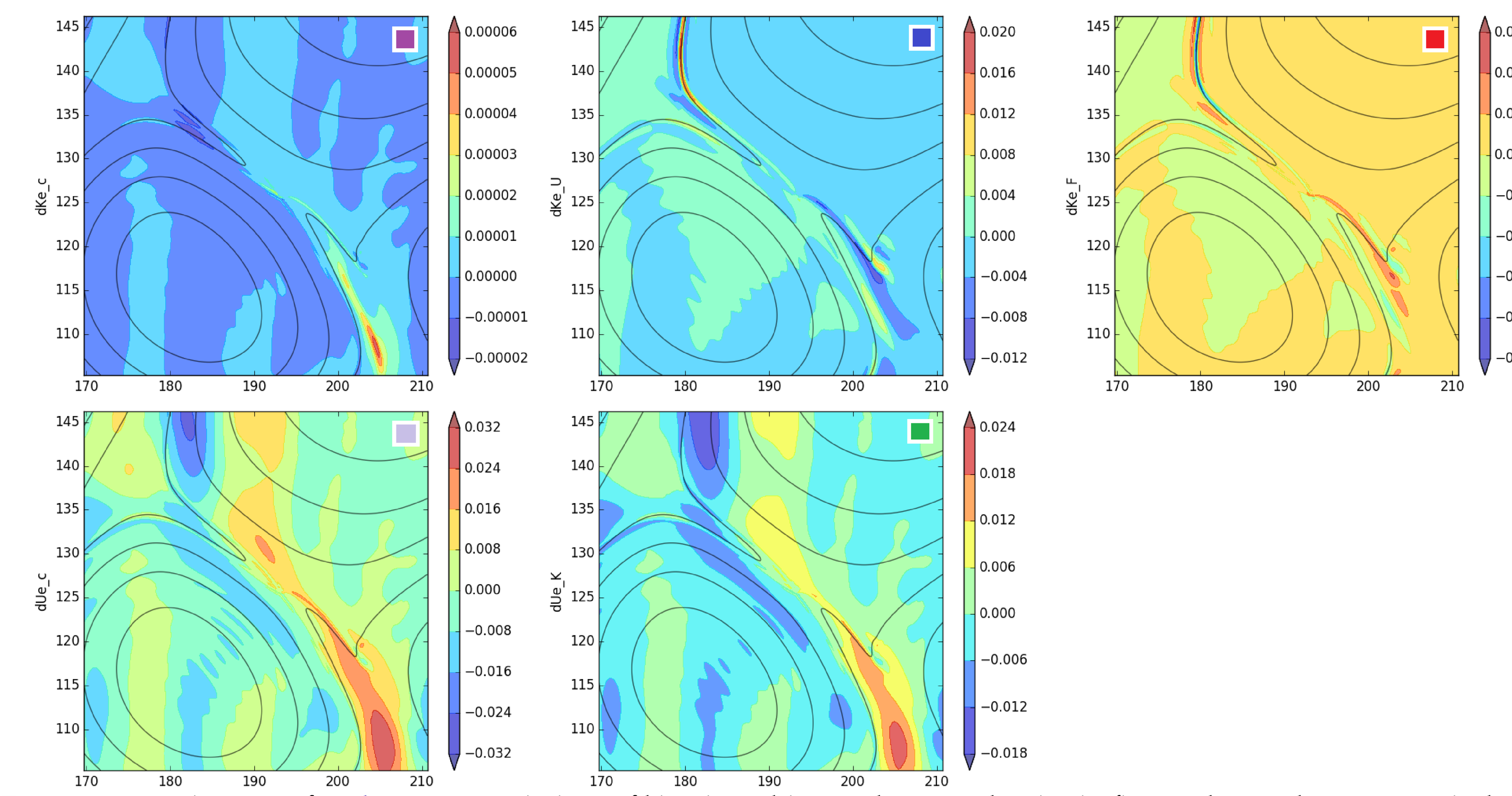
Yang 2017



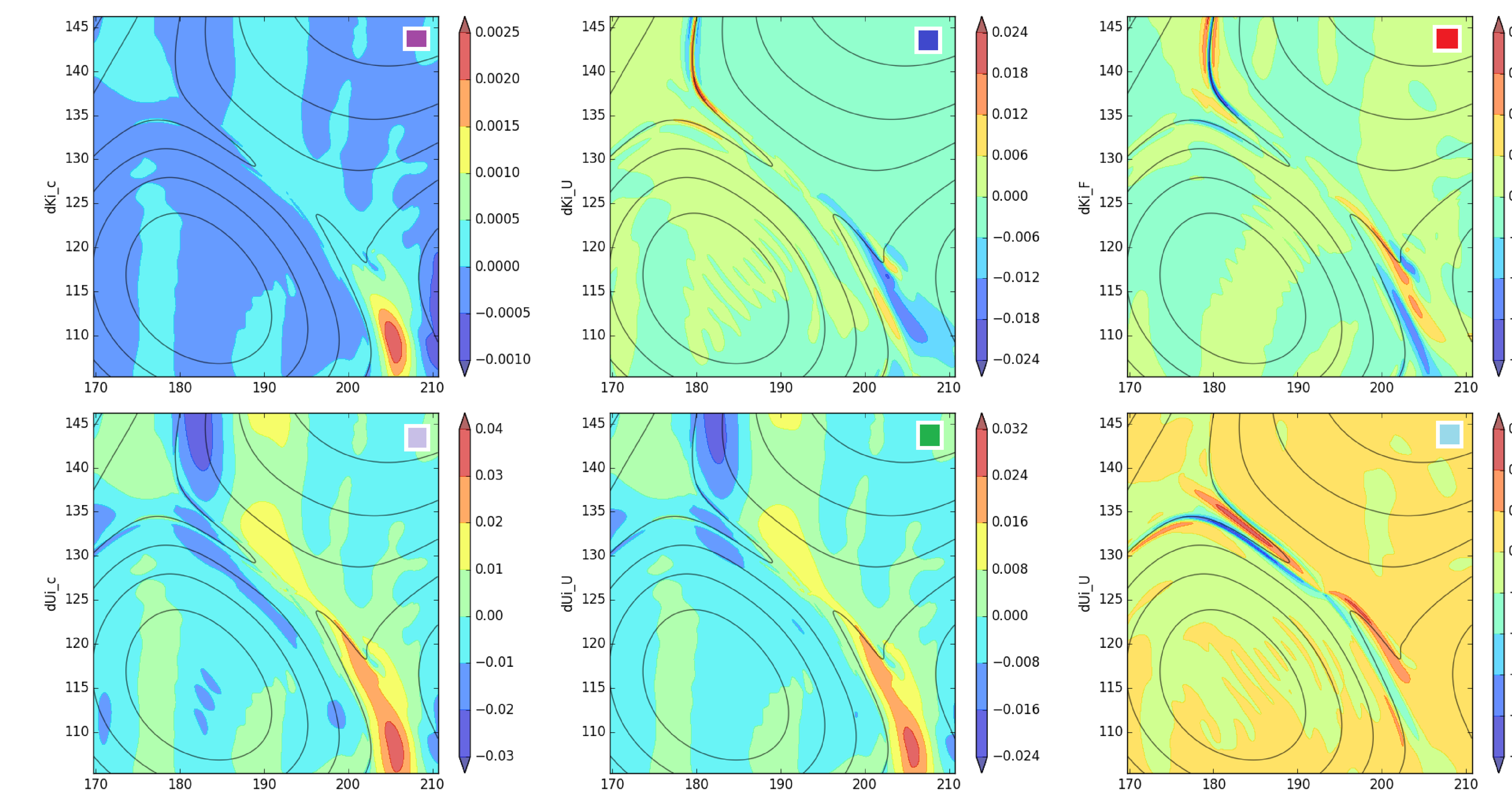
First couple: difference between bulk plasma energization due to electromagnetic and pressure effects (i.e. red term plus blue term). Left and right panels are for ions and electrons respectively.

Second couple: deviation from the 2/3 proportion between internal energy changes due to compressions/decompressions and pressure-fluid interactions (i.e. 2/3 lavender term minus green term). Ions and electrons are the left and right panel respectively.

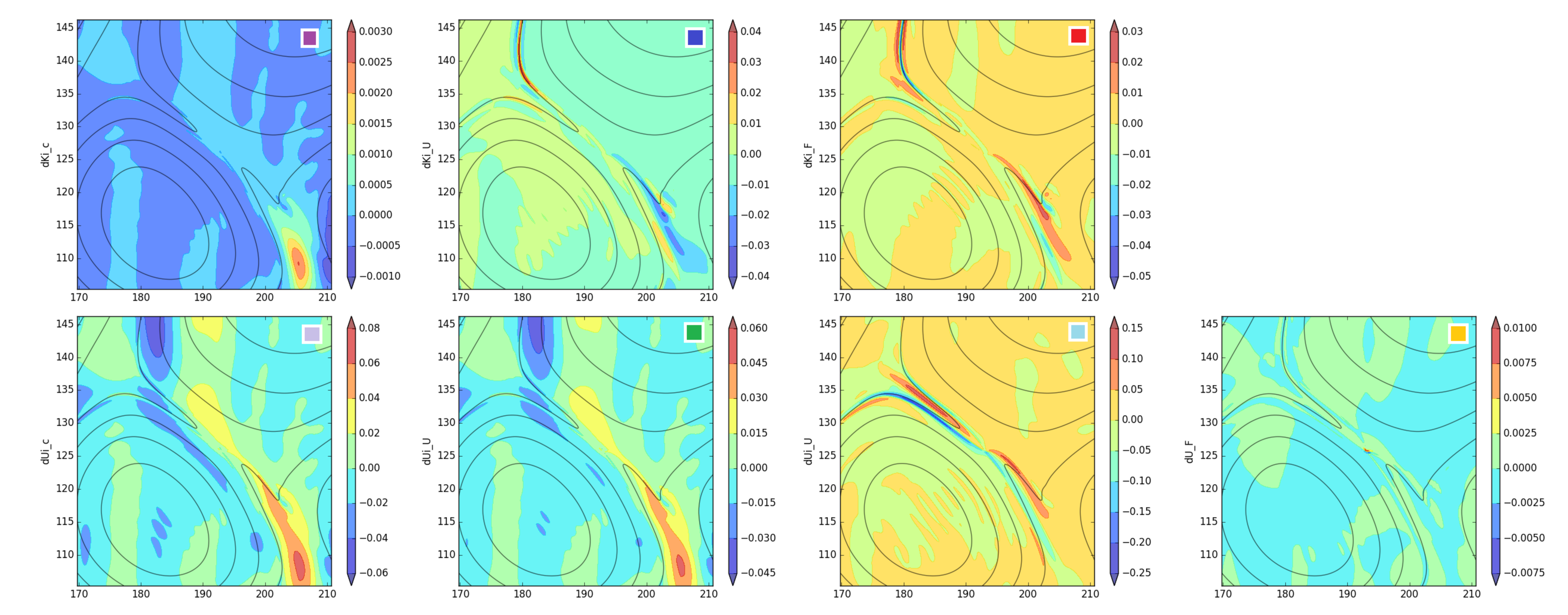
Energy conversion rates:



*Energy conversion rates for **electrons**: variations of kinetic and internal energy density in first and second row respectively. Note that the terms plotted in second and third panel of the first row are approximately one the opposite of the other, implying that acceleration or deceleration of bulk plasma due to electromagnetic forces are generally balanced by those given by pressure. Since a perfect isothermal closure is assumed, first and second panels in second row are proportional to each other by a 2/3 factor and heat flux is everywhere null.*



*Energy conversion rates for **ions**: variations of kinetic and internal energy density in first and second row respectively. As for electrons, terms plotted in second and third panel of the first row are approximately one the opposite of the other, implying that acceleration or deceleration of bulk plasma is impeded due to approximate balance between electromagnetic and pressure forces. First and second panels in second row are approximately proportional to each other by a 2/3 factor, implying that diagonal pressure terms generally dominate the heating and cooling of ions.*



*Energy conversion rates in the **barycentre fluid**: first and second row show variations of kinetic and internal energy density respectively. As for electrons and ions, an approximate balance is observed between terms plotted in second and third panels in the top row, while in bottom row first and second panels show 2/3 approximate proportionality. Fourth panel in second row, showing direct transfer between field and internal energies of is basically the D_e index by Zenitani.*

Upcoming work

- analysis of temporal stability of all patterns presented
- analysis of simulations with different initial forcing, to fully assess ion and electron behaviour
- analysis of 3D simulations
- realization of one ad-hoc simulation to compare with MMS satellite data

Minimal bibliography:

Valentini 2007 Valentini, F., Travnicek, P., Califano, F., Hellinger, P. & Mangeney, A. (2007). A hybrid-Vlasov model based on the current advance method for the simulation of collisionless magnetized plasma, Journal of Computational Physics, 225 1 753-770

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Yang 2017 Yang, Y., Matthaeus, W. H., Parashar, T. N., Haggerty, C. C., Roytershteyn, V., Daughton, W. et al. (2017). Energy transfer, pressure tensor, and heating of kinetic plasma. Physics of Plasmas 24, 072306

Affiliations:

[1] Dipartimento di Fisica "E. Fermi", Università di Pisa, Largo B. Pontecorvo 3, 56127 Pisa, Italy

[2] IRAP, Université de Toulouse, CNRS, CNES, UPS, Toulouse, France