Quantifying Agyrotropy of Proton-Electron Heating in Collisionless Plasmas

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Agyrotropy

- Isotropic pressure in MHD modeling $\boldsymbol{P} = \begin{pmatrix} p & 0 & 0 \\ 0 & p & 0 \\ 0 & 0 & p \end{pmatrix}$
- Gyrotropic pressure in CGL closure $\boldsymbol{P} = \begin{pmatrix} p_{\parallel} & 0 & 0 \\ 0 & p_{\perp} & 0 \\ 0 & 0 & p_{\perp} \end{pmatrix}$ Chew et al, *PRSL*, 1956
- Non-gyrotropy in collisionless plasmas $\boldsymbol{P} = \begin{pmatrix} p_{\parallel} & p_{12} & p_{13} \\ p_{12} & p_{\perp} & p_{23} \\ p_{13} & p_{23} & p_{\perp} \end{pmatrix}$

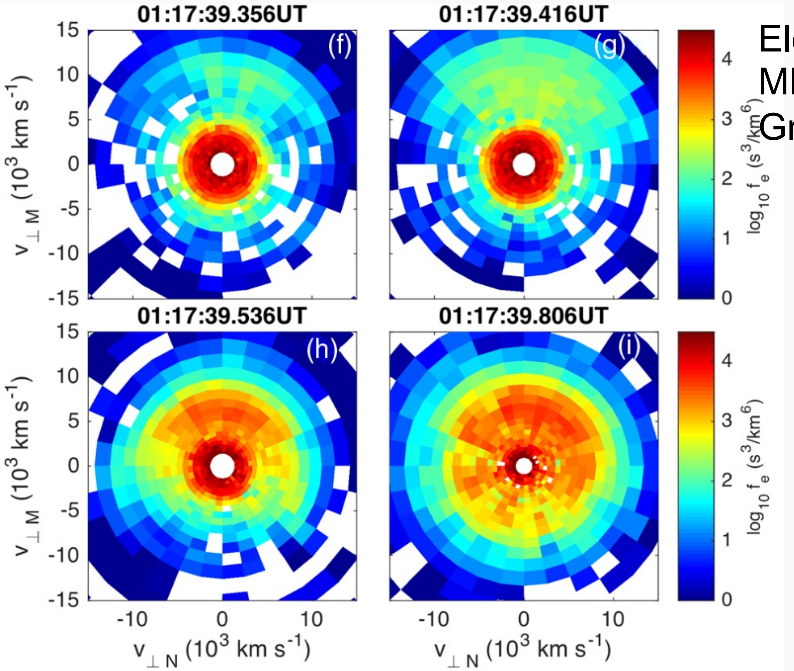
$$Q = \frac{P_{12}^2 + P_{13}^2 + P_{23}^2}{P_{\perp}^2 + 2P_{\perp}P_{\parallel}}$$

Swisdak et al, *GRL*, 2016

$$\epsilon_i = \frac{1}{n_i}\sqrt{\int (f_i - g_i)^2 \mathrm{d}^3 v}$$

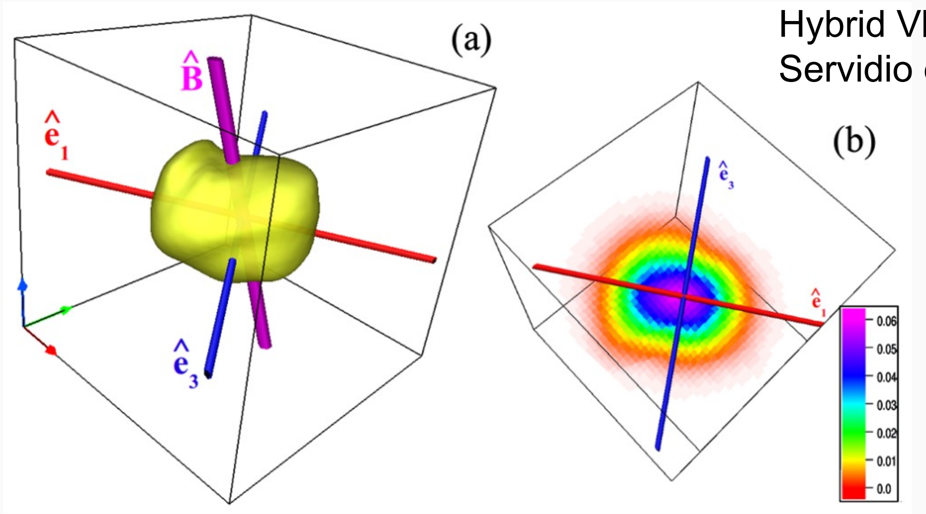
Greco et al, *PRE*, 2012

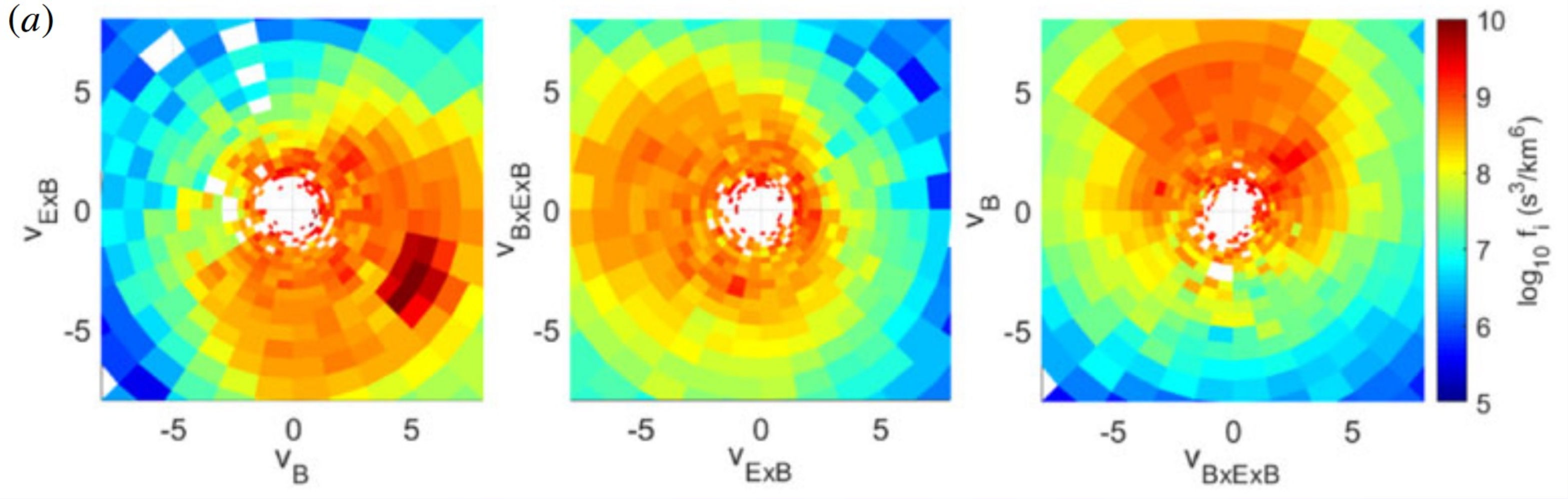
Agyrotropy



Electron VDF
MMS Magnetopause Crossing
Graham et al, *PRL*, 2017

Ion VDF
Hybrid Vlasov-Maxwell
Servidio et al, *PRL*, 2012





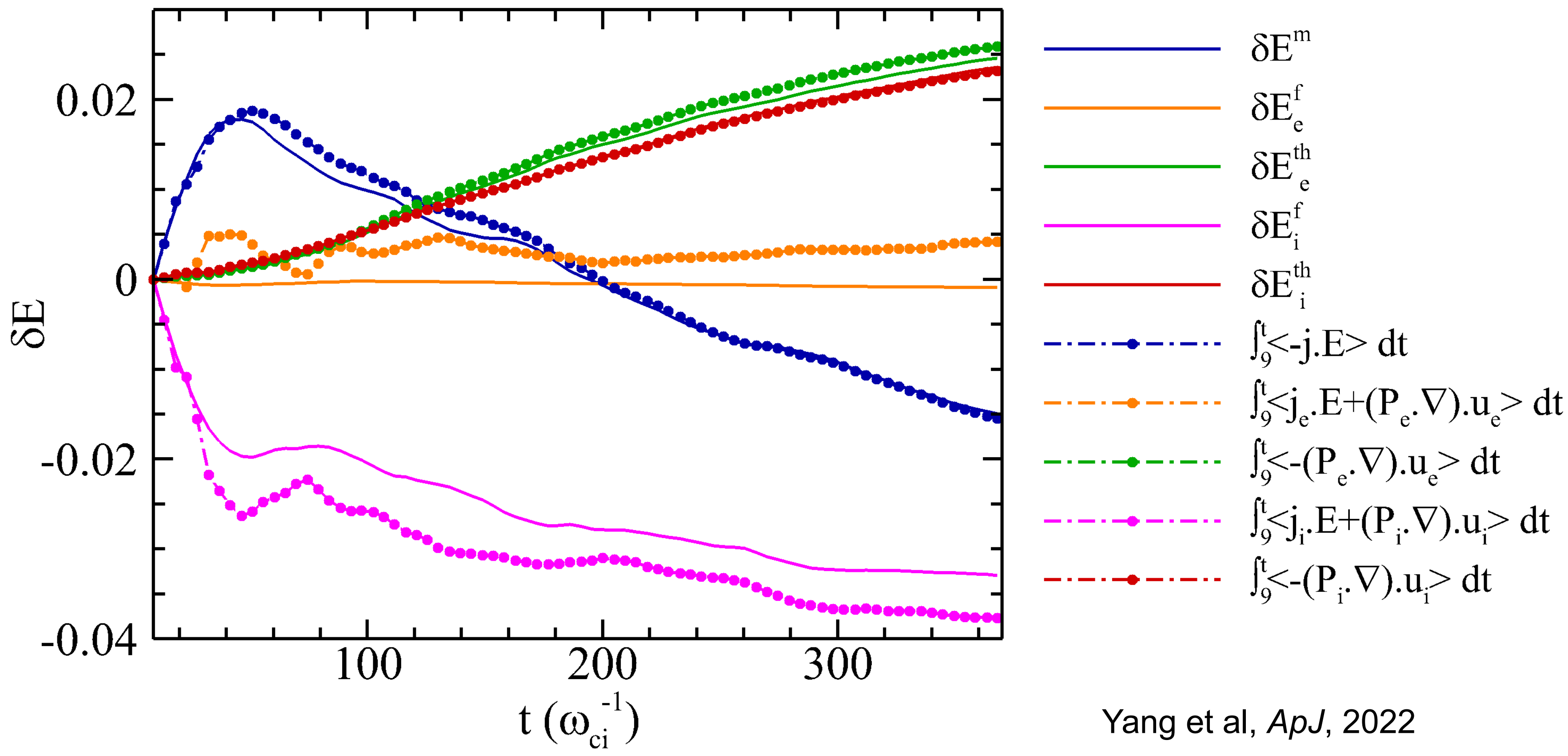
Ion VDF,
MMS Magtosheath,
Perri et al, *JPP*, 2020

Pressure-Strain Interaction

Fluid flow energy $\partial_t \langle E_a^f \rangle = \langle (\boldsymbol{P}_a \cdot \nabla) \cdot \boldsymbol{u}_a \rangle + \langle \boldsymbol{j}_a \cdot \boldsymbol{E} \rangle$

Thermal (random) energy $\partial_t \langle E_a^{th} \rangle = \langle -(\boldsymbol{P}_a \cdot \nabla) \cdot \boldsymbol{u}_a \rangle$

Electromagnetic energy $\partial_t \langle E^m \rangle = \langle -\boldsymbol{j} \cdot \boldsymbol{E} \rangle$



Yang et al, *ApJ*, 2022

Decomposition of Pressure Work

- Unit magnetic vector $\widehat{\boldsymbol{b}} = \boldsymbol{B}/|\boldsymbol{B}|$
- Pressure tensor

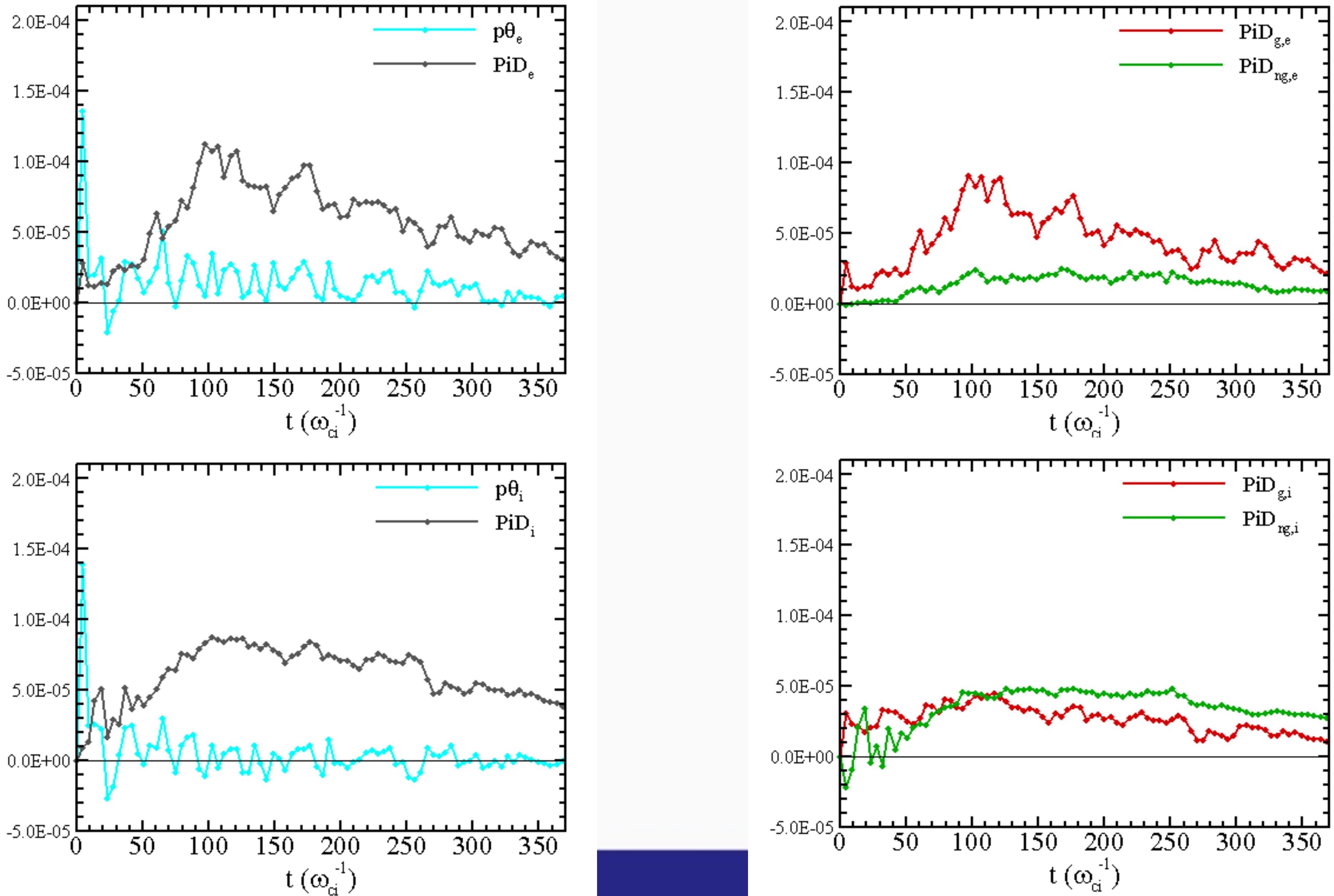
$$\boldsymbol{P} = p\boldsymbol{I} + \boldsymbol{P}_g + \boldsymbol{P}_{ng}$$
$$p = \frac{1}{3}\left(P_{xx} + P_{yy} + P_{zz}\right)$$
$$\boldsymbol{P}_g = (p_\parallel - p_\perp)\left(\widehat{\boldsymbol{b}}\widehat{\boldsymbol{b}} - \boldsymbol{I}/3\right)$$
$$p_\parallel = \widehat{\boldsymbol{b}} \cdot \boldsymbol{P} \cdot \widehat{\boldsymbol{b}}$$
$$p_\perp = (P_{xx} + P_{yy} + P_{zz} - p_\parallel)/2$$

- Pressure work

$$-(\boldsymbol{P} \cdot \nabla) \cdot \boldsymbol{u} = \overbrace{-p\nabla \cdot \boldsymbol{u}}^{p\theta} \overbrace{- (p_\parallel - p_\perp)\widehat{b}_i\widehat{b}_j D_{ij}}^{PiD_g} \overbrace{- \left(\boldsymbol{P}_{ng} \cdot \nabla\right) \cdot \boldsymbol{u}}^{PiD_{ng}}$$
$$D_{ij} = \frac{1}{2}(\partial_i u_j + \partial_j u_i) - \frac{1}{3}\theta\delta_{ij}$$

PIC Simulation Results

Dimension	$L(d_i)$	N	m_i/m_e	$B_0\hat{z}$	$\delta b/B_0$	β	ppg
2.5D	150	4096	25	1.0	0.5	0.6	3200



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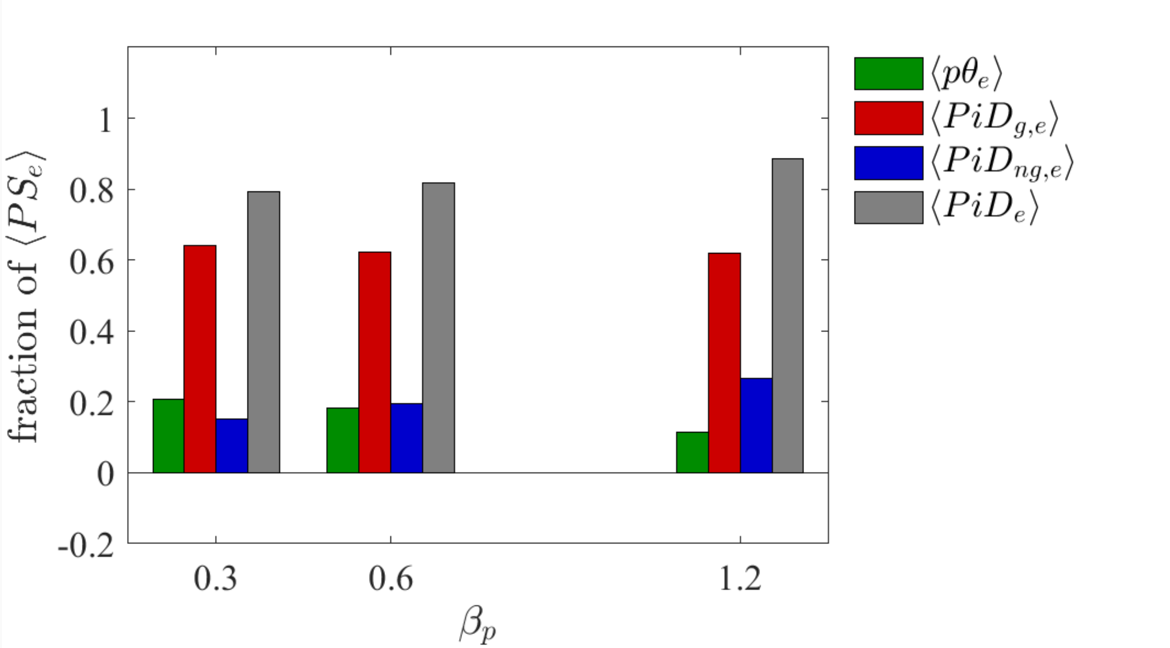
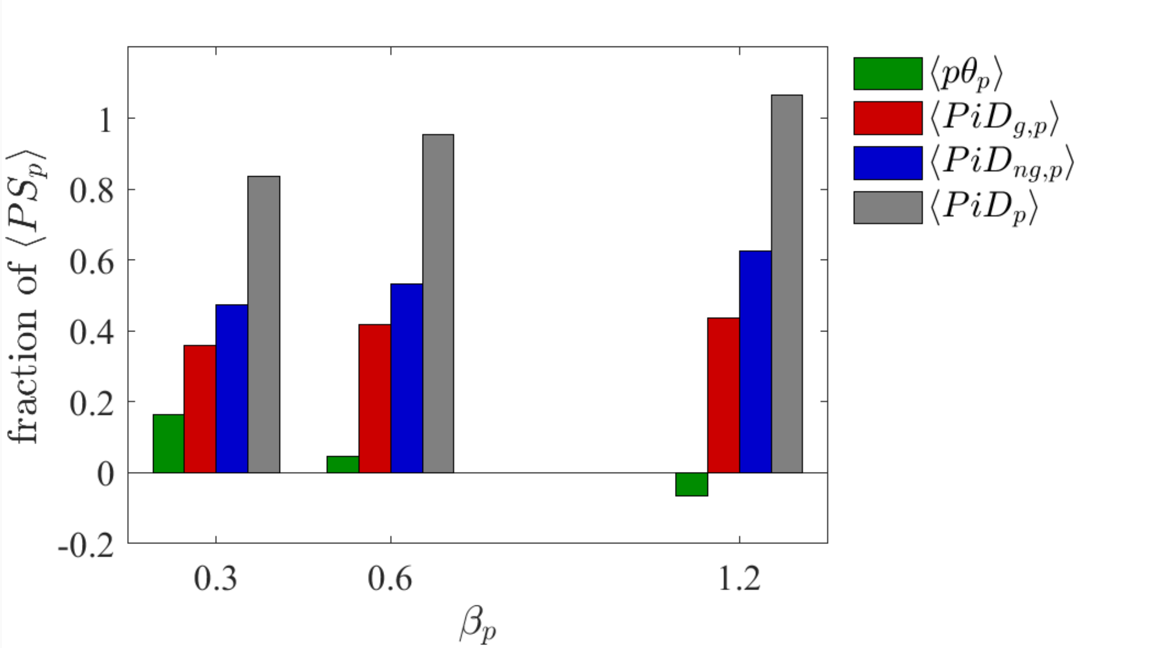
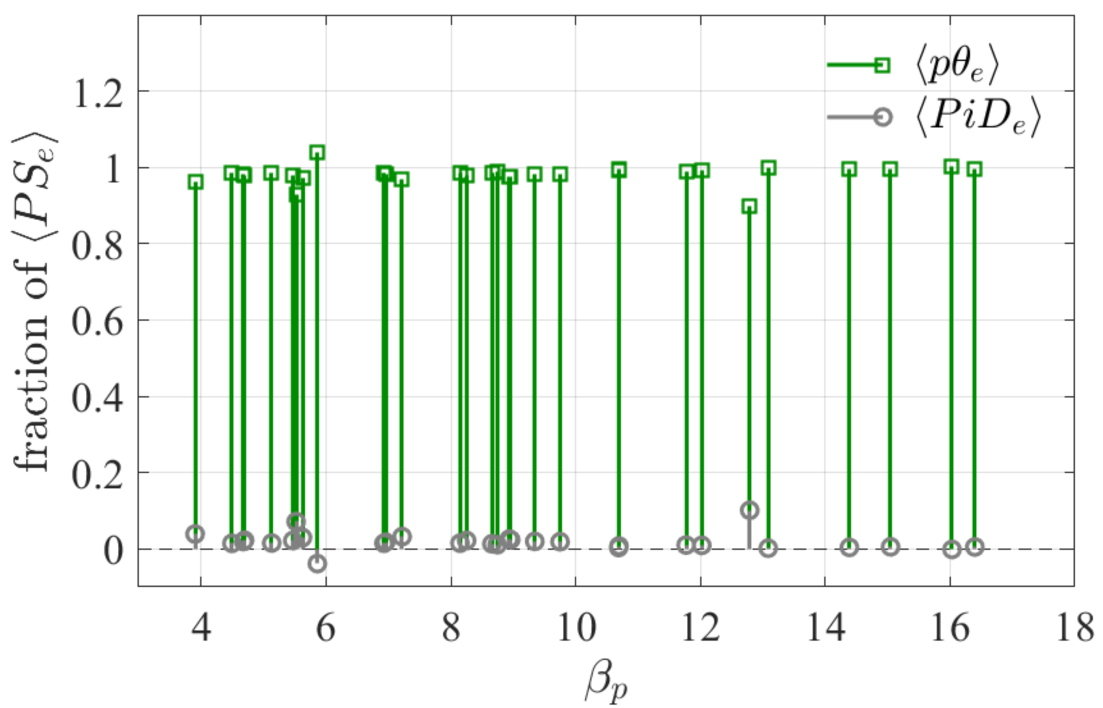


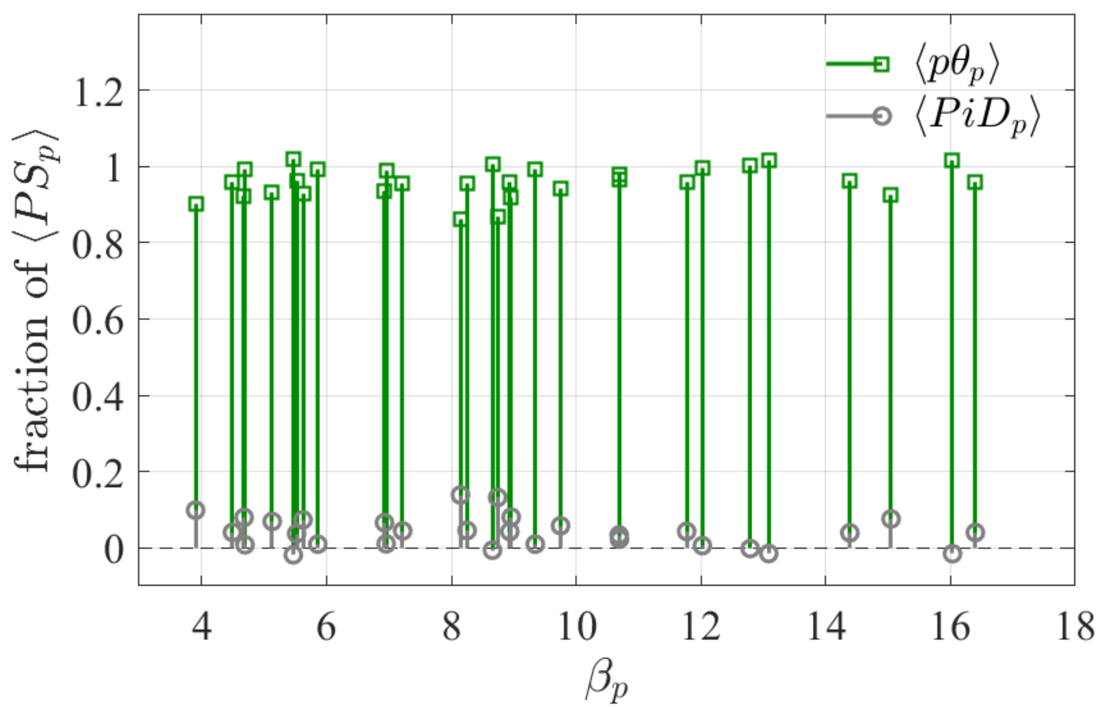


Yang et al, in prep, 2022

MMS Magnetosheath Results

30 magnetosheath intervals from 2016 Jan 11 to 2018 April 23





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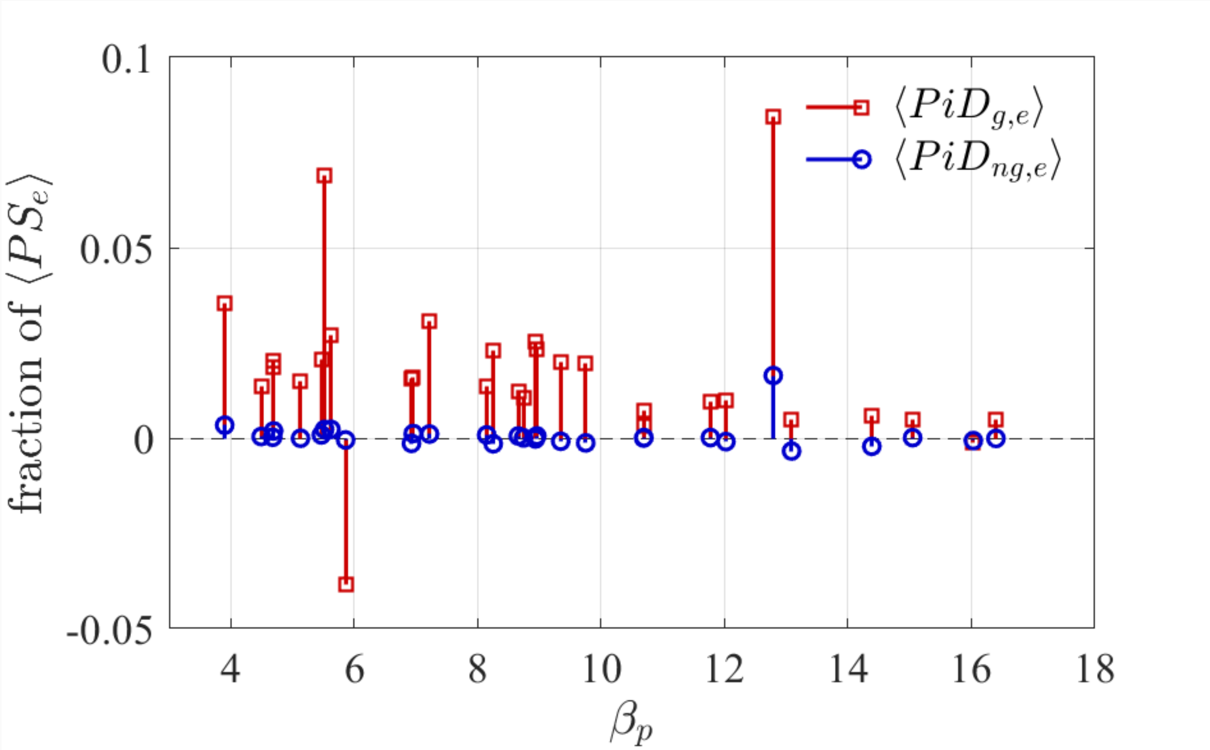
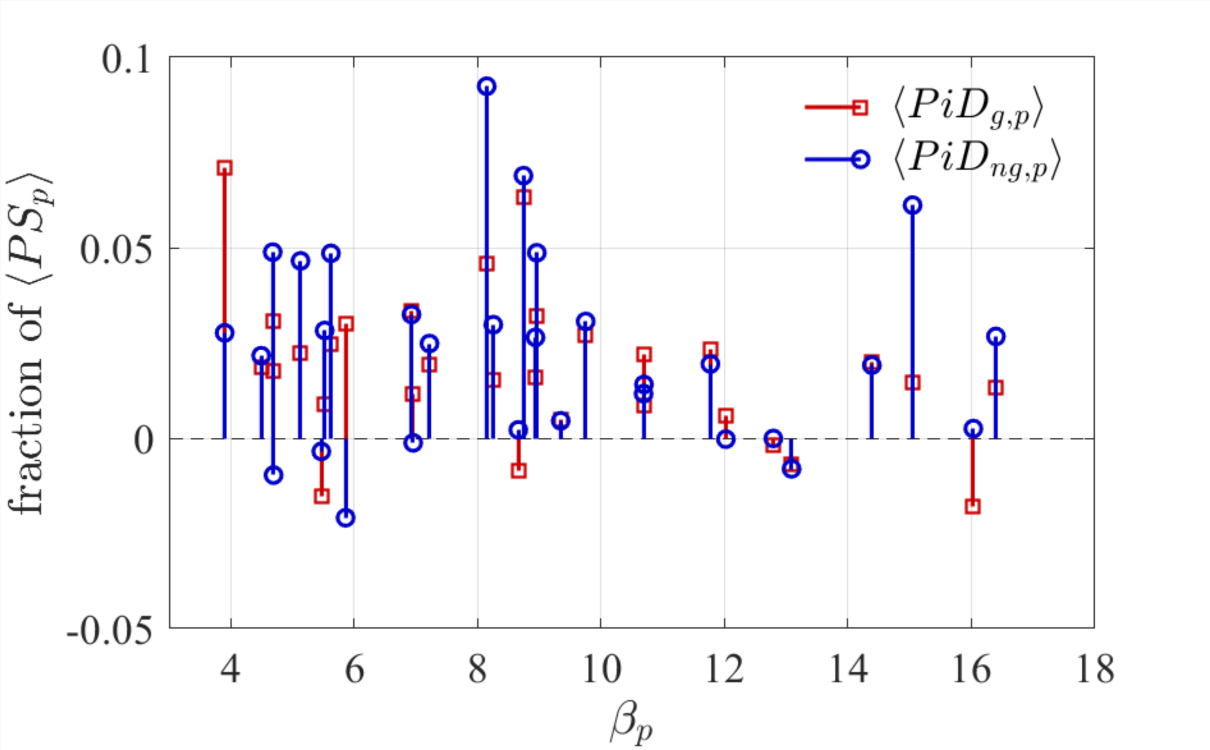
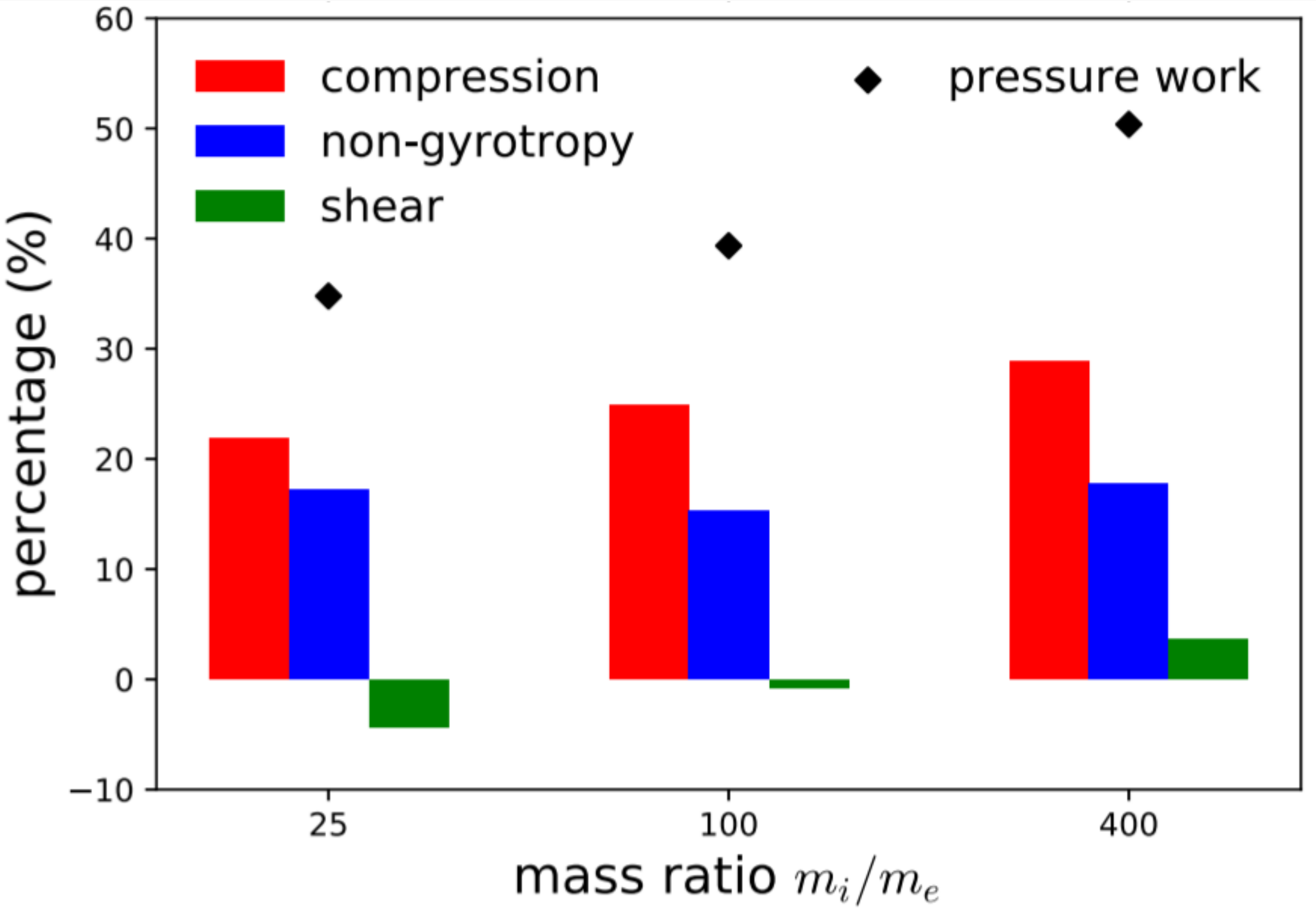
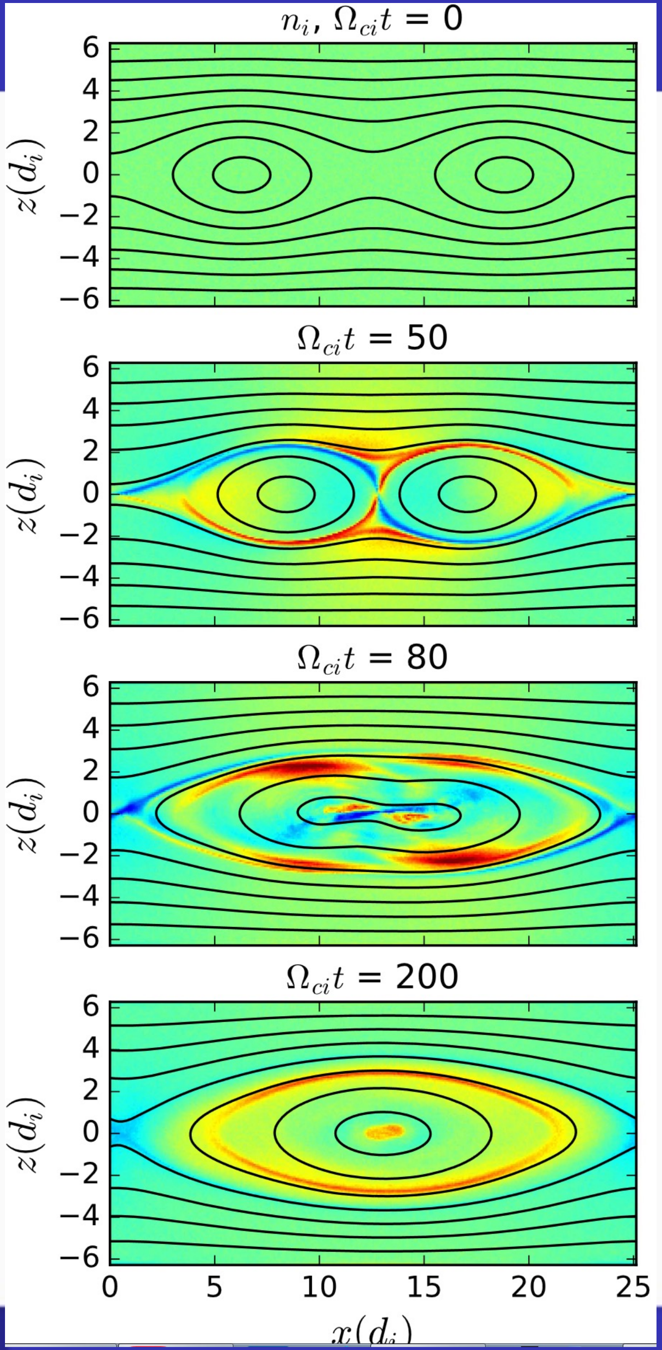




Yang et al, in prep, 2022

Colliding Magnetic Flux Ropes





Du, Guo, Zank et al, *ApJ*, 2018

Summary

- Local compressive contribution is stronger than incompressive contribution.

$$p\theta > PiD$$

- For electrons, the gyrotropic contribution is dominant over the non-gyrotropic part.

$$PiD_{g,e} > PiD_{ng,e}$$

- For ions, the non-gyrotropic contribution is enhanced.

$$PiD_{ng,i} \geq PiD_{g,i}$$