

DISSIPATION MEASURES IN WEAKLY-COLLISIONAL PLASMAS

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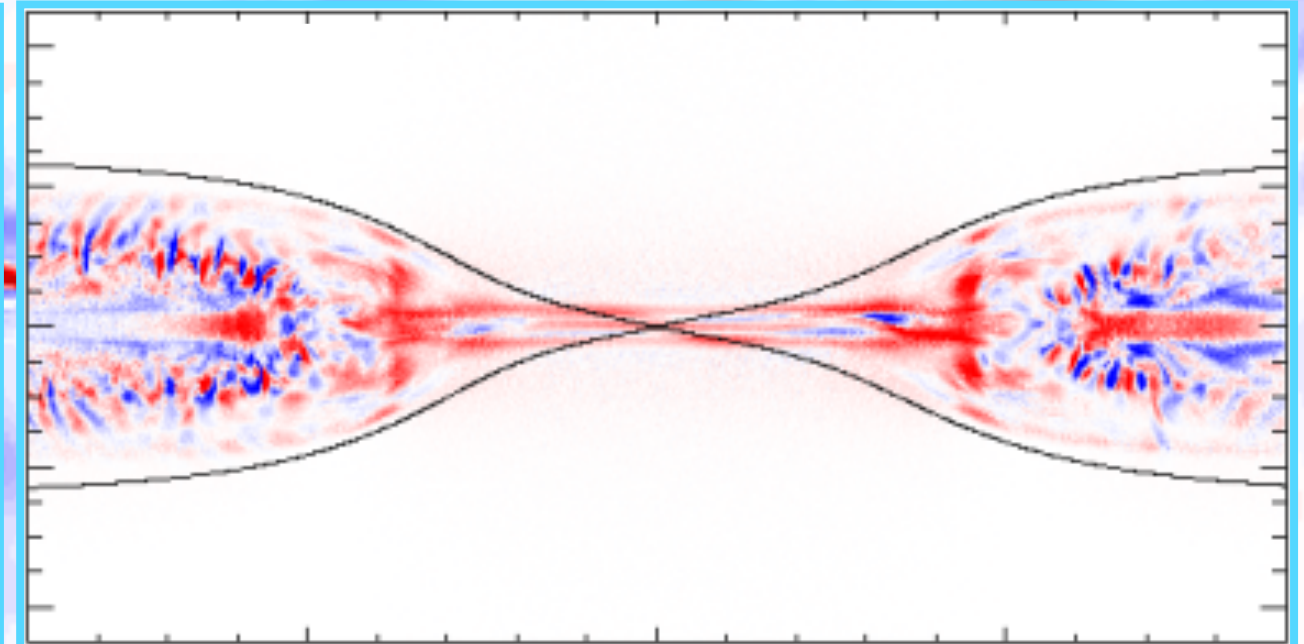
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OVERVIEW AND CONCLUSIONS

(PEZZI ET AL., MNRAS, SUBMITTED)

- Several measures have been used to characterize kinetic-scale energy conversion and dissipation in weakly-collisional plasmas
 - We categorize them as “energy-based” and “velocity distribution function (VDF)-based”
- We compare and contrast a number of them in kinetic simulations of magnetic reconnection and decaying plasma turbulence
- We use three different codes that can include collisions
 - Particle-in-cell (VPIC) - reconnection, fully-kinetic continuum (Gkeyll) - reconnection, Eulerian Hybrid Vlasov-Maxwell (HVM) - turbulence
- Results:
 - There are similarities, but also differences, between the different measures which can be understood physically
 - In simulations of reconnection, there is overall agreement in PIC and continuum, with slight differences due to secondary islands
 - VDF-based measures are similar in reconnection and self-consistent current sheets in turbulence, but energy-based can be different
 - All parameters we investigated are non-zero near regions of intense magnetic stress, thus exhibiting a local correlation
 - VDF-based measures are broader than energy-based near current sheets → kinetic effects can be important beyond coherent structures
- Both energy- and VDF-based can be useful, and using multiple measures is likely best to identify key physics

“DISSIPATION” MEASURES — ENERGY-BASED

- It is strange to even discuss “dissipation” measures in collisionless plasmas, since the connotation of dissipation is irreversibility, which does not occur for collisionless systems

- “Energy conversion” measures is a better term
- Numerous proxies of energy conversion and dissipation have been developed; we group them into two categories - “energy-based” and “velocity distribution function (VDF)-based”
- “Energy-based” - terms in evolution equations for bulk flow energy $\mathcal{E}_\alpha^f$, thermal energy $\mathcal{E}_\alpha^{th}$, and EM energy $\mathcal{E}^m$

$$\frac{\partial \mathcal{E}_\alpha^f}{\partial t} + \nabla \cdot (\mathbf{u}_\alpha \mathcal{E}_\alpha^f + \mathbf{u}_\alpha \cdot \mathbf{P}_\alpha) = (\mathbf{P}_\alpha \cdot \nabla) \cdot \mathbf{u}_\alpha + n_\alpha q_\alpha \mathbf{u}_\alpha \cdot \mathbf{E}$$

$$\frac{\partial \mathcal{E}_\alpha^{th}}{\partial t} + \nabla \cdot (\mathbf{u}_\alpha \mathcal{E}_\alpha^{th} + \mathbf{h}_\alpha) = -(\mathbf{P}_\alpha \cdot \nabla) \cdot \mathbf{u}_\alpha$$

$$\frac{\partial \mathcal{E}^m}{\partial t} + \frac{c}{4\pi} \nabla \cdot (\mathbf{E} \times \mathbf{B}) = -\mathbf{j} \cdot \mathbf{E}$$

- Work done on/by electric field D (Zenitani et al., PRL, 2011)

$$D_\alpha = \mathbf{j}' \cdot \mathbf{E}' = \mathbf{j} \cdot \left(\mathbf{E} + \frac{\mathbf{u}_\alpha}{c} \times \mathbf{B} \right) - \rho_c (\mathbf{u}_\alpha \cdot \mathbf{E})$$

- Local Energy Transfer rate (LET) ϵ (Sorriso-Valvo et al., Solar Phys., 2018)

$$\epsilon_{p,\ell} = (|\Delta \mathbf{u}_p|^2 + |\Delta \mathbf{b}|^2) \frac{\Delta u_{p,\ell}}{\ell} - 2(\Delta \mathbf{u}_p \cdot \Delta \mathbf{b}) \frac{\Delta b_\ell}{\ell} - \frac{d_p}{2} |\Delta \mathbf{b}|^2 \frac{\Delta j_\ell}{\ell} + d_p (\Delta \mathbf{b} \cdot \Delta \mathbf{j}) \frac{\Delta b_\ell}{\ell}$$

- Pressure-strain interaction Pi-D and P- θ (Yang et al., PoP, 2017)

$$-(\mathbf{P}_\alpha \cdot \nabla) \cdot \mathbf{u}_\alpha = -P_\alpha \theta_\alpha - \mathbf{\Pi}_\alpha : \mathcal{D}_\alpha$$

“DISSIPATION” MEASURES — VDF-BASED

- “VDF-based” - from distribution function f_α

- Pressure agyrotropy Q (Scudder and Daughton, JGR, 2008; Aunai et al., PoP, 2013; Swisdak, GRL, 2016)

$$Q_\alpha = \frac{P_{\alpha,12}^2 + P_{\alpha,13}^2 + P_{\alpha,23}^2}{P_{\alpha,\perp}^2 + 2P_{\alpha,\perp}P_{\alpha,\parallel}}. \quad \mathbf{P}_\alpha = \begin{pmatrix} P_{\alpha,\perp} & P_{\alpha,12} & P_{\alpha,13} \\ P_{\alpha,12} & P_{\alpha,\perp} & P_{\alpha,23} \\ P_{\alpha,13} & P_{\alpha,23} & P_{\alpha,\parallel} \end{pmatrix}$$

- Quadratic non-Maxwellianity ξ (Greco et al., PRE, 2012)

$$\xi_\alpha(\mathbf{r}, t) = \frac{v_{th,\alpha}^{3/2}(\mathbf{r}, t)}{n_\alpha(\mathbf{r}, t)} \sqrt{\int d^3v [f_\alpha(\mathbf{r}, \mathbf{v}, t) - g_\alpha(\mathbf{r}, \mathbf{v}, t)]^2}$$

- g_α = “Maxwellianized” distribution based on f_α

$$\bar{M}_{\text{KP},\alpha}(\mathbf{r}, t) = \frac{s_{\text{M},\alpha}(\mathbf{r}, t) - s_\alpha(\mathbf{r}, t)}{(3/2)k_B n_\alpha(\mathbf{r}, t)} = \frac{s_{\text{M},\alpha}^{\text{vel}}(\mathbf{r}, t) - s_\alpha^{\text{vel}}(\mathbf{r}, t)}{(3/2)k_B n_\alpha(\mathbf{r}, t)}$$

- Entropy-based non-Maxwellianity M (Kaufmann and Paterson, JGR, 2009; Liang et al., JPP, 2020)

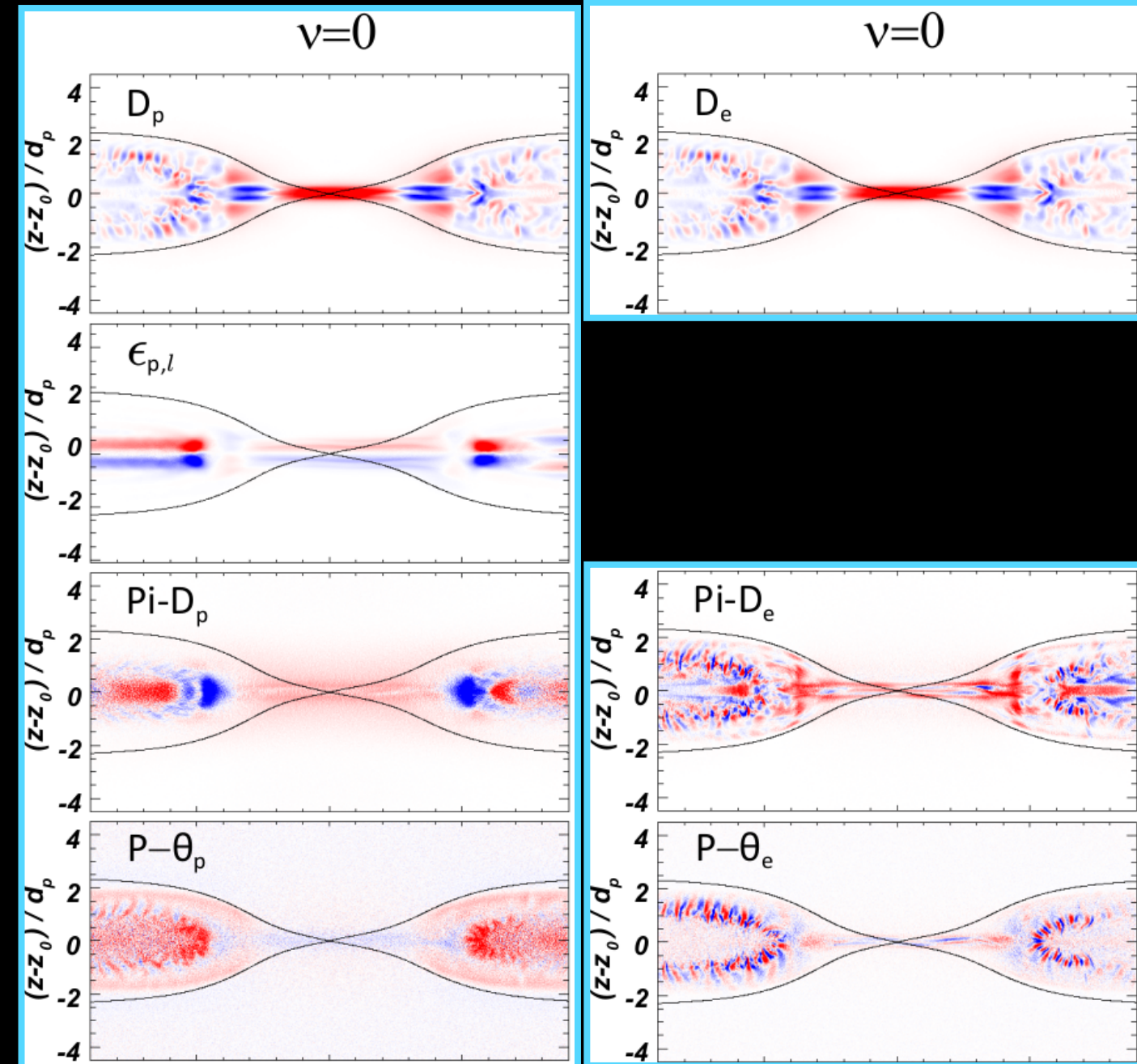
$$\bar{M}_\alpha(\mathbf{r}, t) = \frac{\bar{M}_{\text{KP},\alpha}(\mathbf{r}, t)}{1 + \log \left(\frac{2\pi k_B T_\alpha}{m_\alpha (\Delta^3 v)^{2/3}} \right)}$$

- We did not compare with the field-particle correlation (Klein and Howes, ApJL, 2016); should be done for future work

$$s_\alpha^{\text{vel}} = s_\alpha + k_B n_\alpha \log \left(\frac{n_\alpha}{\Delta v^3} \right) = -k_B \int d^3v f_\alpha \log f_\alpha + k_B n_\alpha \log \left(\frac{n_\alpha}{\Delta v^3} \right)$$

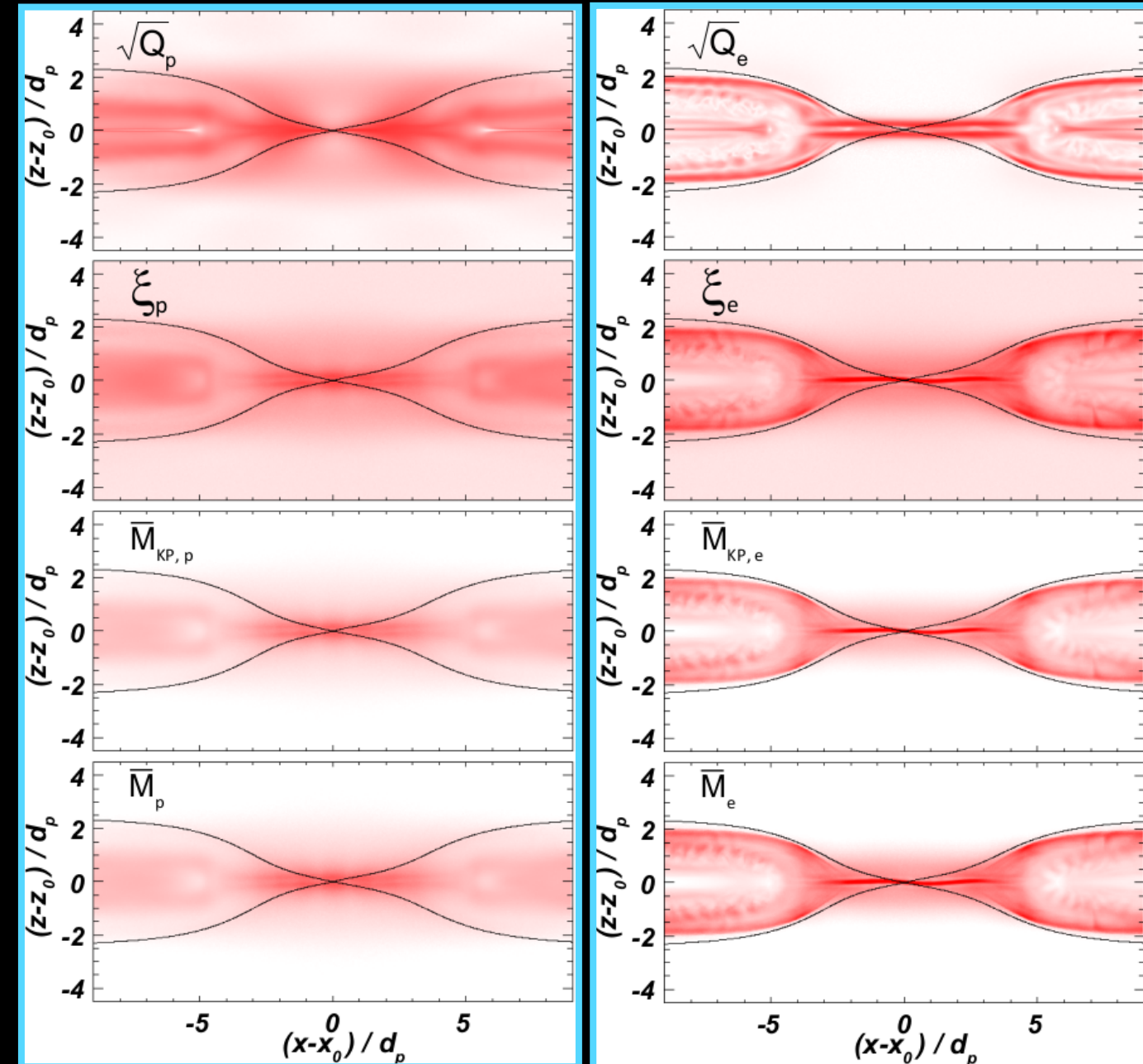
ENERGY-BASED MEASURES - COLLISIONLESS RECONNECTION IN VPIC

- Energy-based measures for protons (left) and electrons (right)
 - $D_p \sim D_e$ is positive in electron diffusion region (EDR), small in IDR; can have either sign in exhaust presumably due to time-domain structures (electron holes, etc.)
 - LET ϵ_p is non-zero in EDR and near neutral line in exhaust; not calculated for electrons); meaning of this parameter in a non-turbulent system is not terribly clear
 - Pi-D_p is positive in EDR and IDR due to meandering orbits and velocity shear, Pi-D_e only important in EDR; both can have either sign in the exhaust with spatial scale dependent on mass
 - $\text{P-}\theta_p$ is mostly negative in EDR due to expansion of flux tubes entering EDR and mostly positive in exhaust due to compression by the island; $\text{P-}\theta_e$ is weaker in EDR, highly oscillatory in exhaust
- All energy-based measures considered here do have structure in the EDR, $D_p \sim D_e$ and Pi-D_e are strongest in EDR, all can be non-zero in the exhaust, some oscillate strongly, not much structure near separatrix



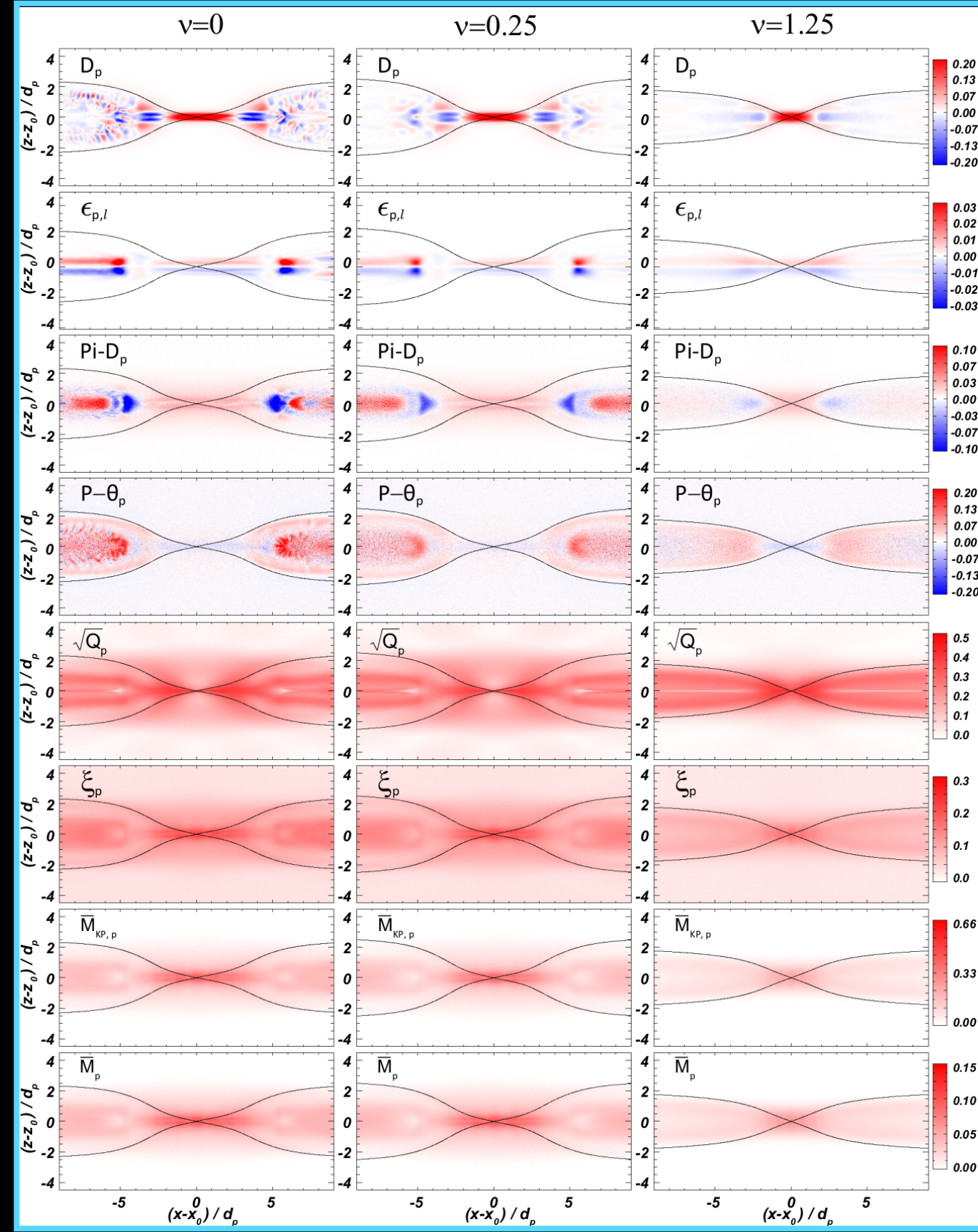
VDF-BASED MEASURES - COLLISIONLESS RECONNECTION IN VPIC

- VDF-based measures for protons (left) and electrons (right)
 - Pressure agyrotropy Q non-zero for protons in both EDR and IDR; non-zero for electrons only in EDR
 - Non-Maxwellianities ξ and M for both protons and electrons are non-zero both in EDR and IDR
 - Physical explanation is that electrons in IDR get trapped and become Egedal distributions, which are gyrotropic ($Q=0$) but non-Maxwellian (ξ and $M \neq 0$)
 - Entropy-based non-Maxwellianity more localized than quadratic non-Maxwellianity; bigger departure from Maxwellianity needed for entropy-based to be appreciable
- All VDF-based measures we investigate identify EDR, and all but Q_e identify IDR, all are non-zero in exhausts; all electron measures are strong near separatrices unlike energy-based



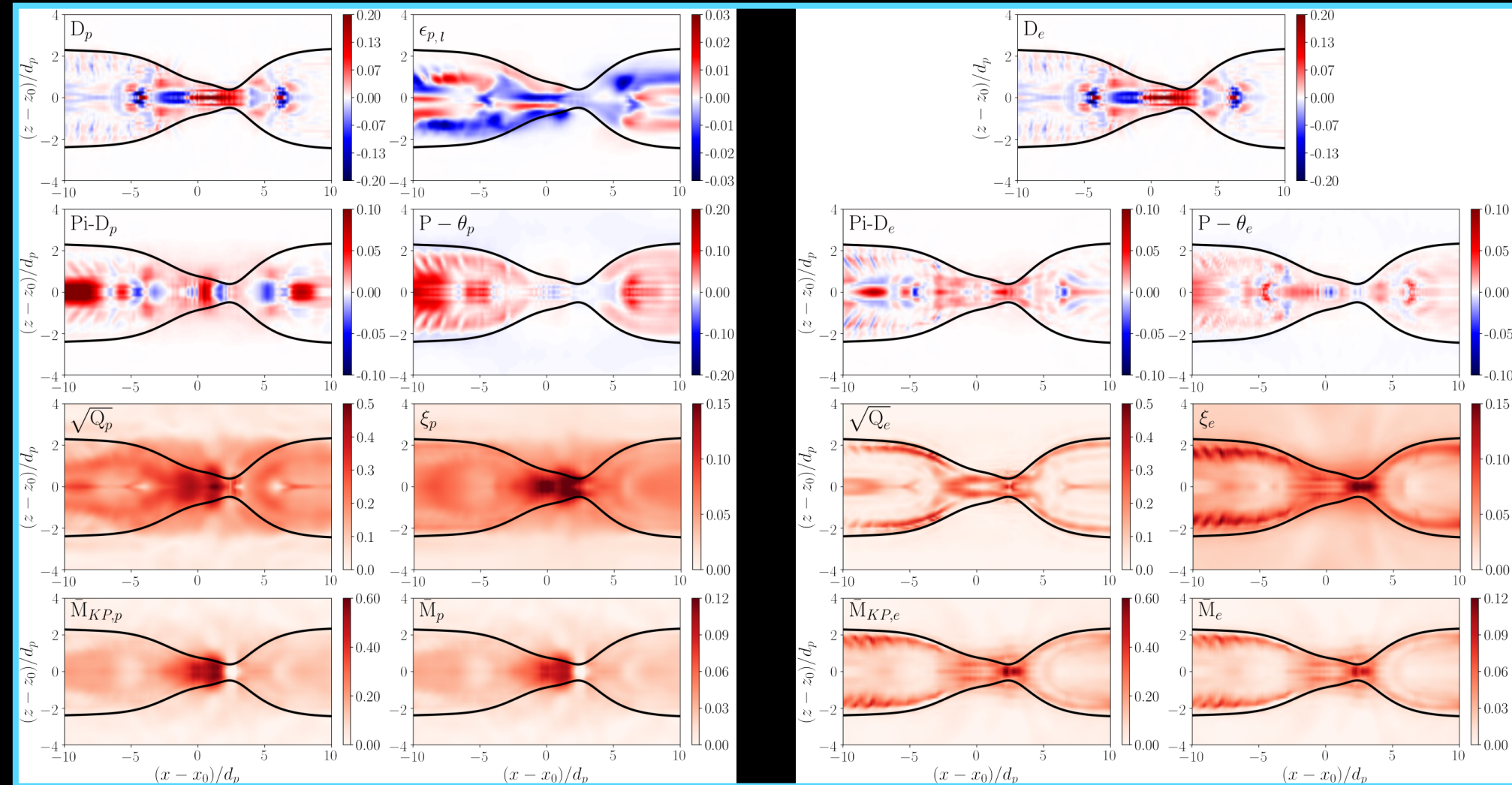
EFFECT OF COLLISIONS

- Energy- and VDF-based measures for protons for increasing collisionality left to right
- All measures find the diffusion regions, but collisions weaken the dissipation measures, including small-scale structure in the exhausts
- This is the case even though the reconnection is still "Hall-like" (as opposed to Sweet-Parker)
- Interestingly, none of the measures gets stronger; energy conversion is higher in the collisionless case



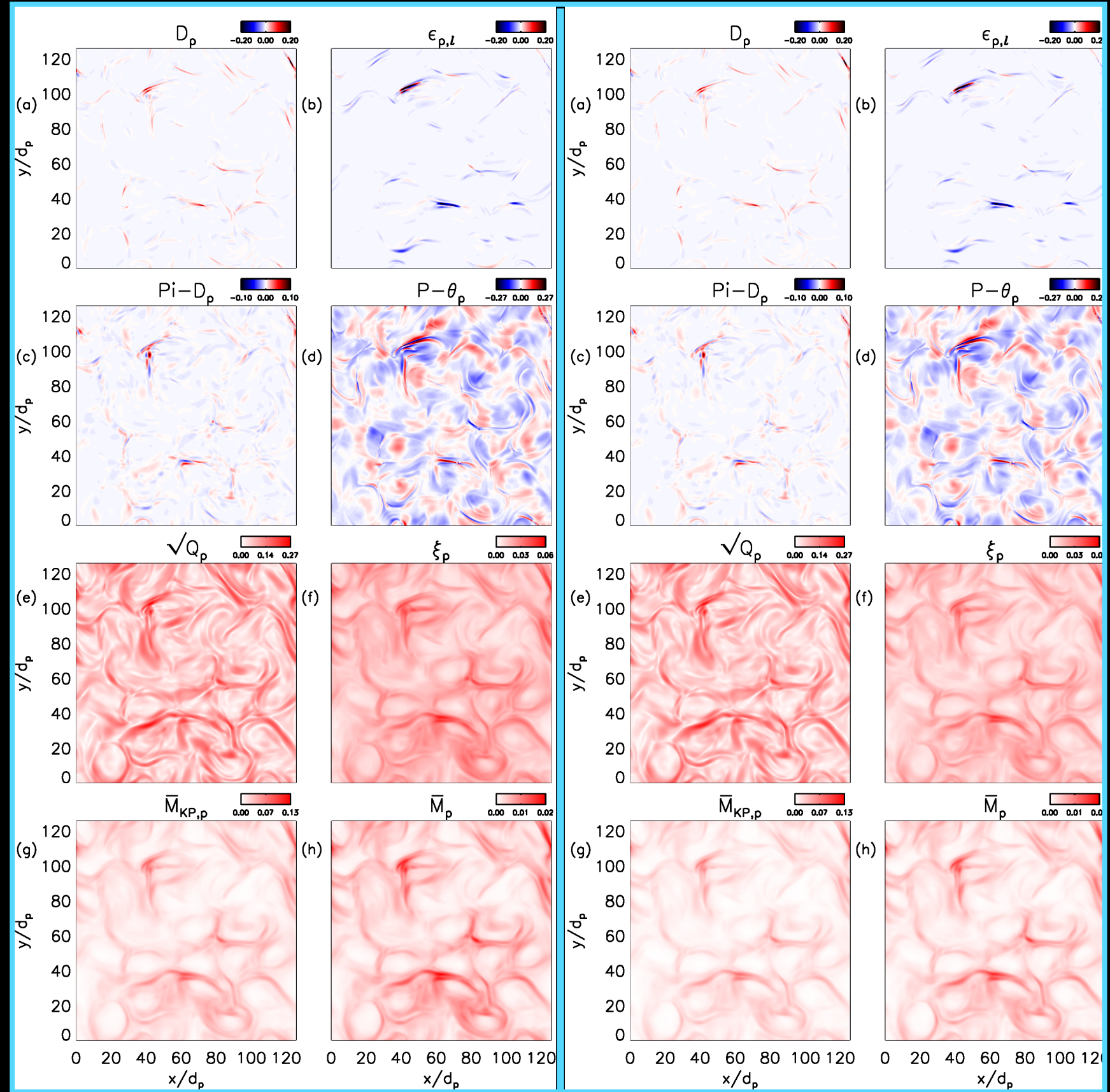
COMPARISON TO FULL VLASOV GKEYLL RECONNECTION SIMULATIONS

- Energy- and VDF-based measures for protons (left) and electrons (right) in Gkeyll simulations
- Unsurprisingly, most of the results are qualitatively consistent with the VPIC simulations
- An additional secondary island arises in the full Vlasov simulations, which leads to some differences



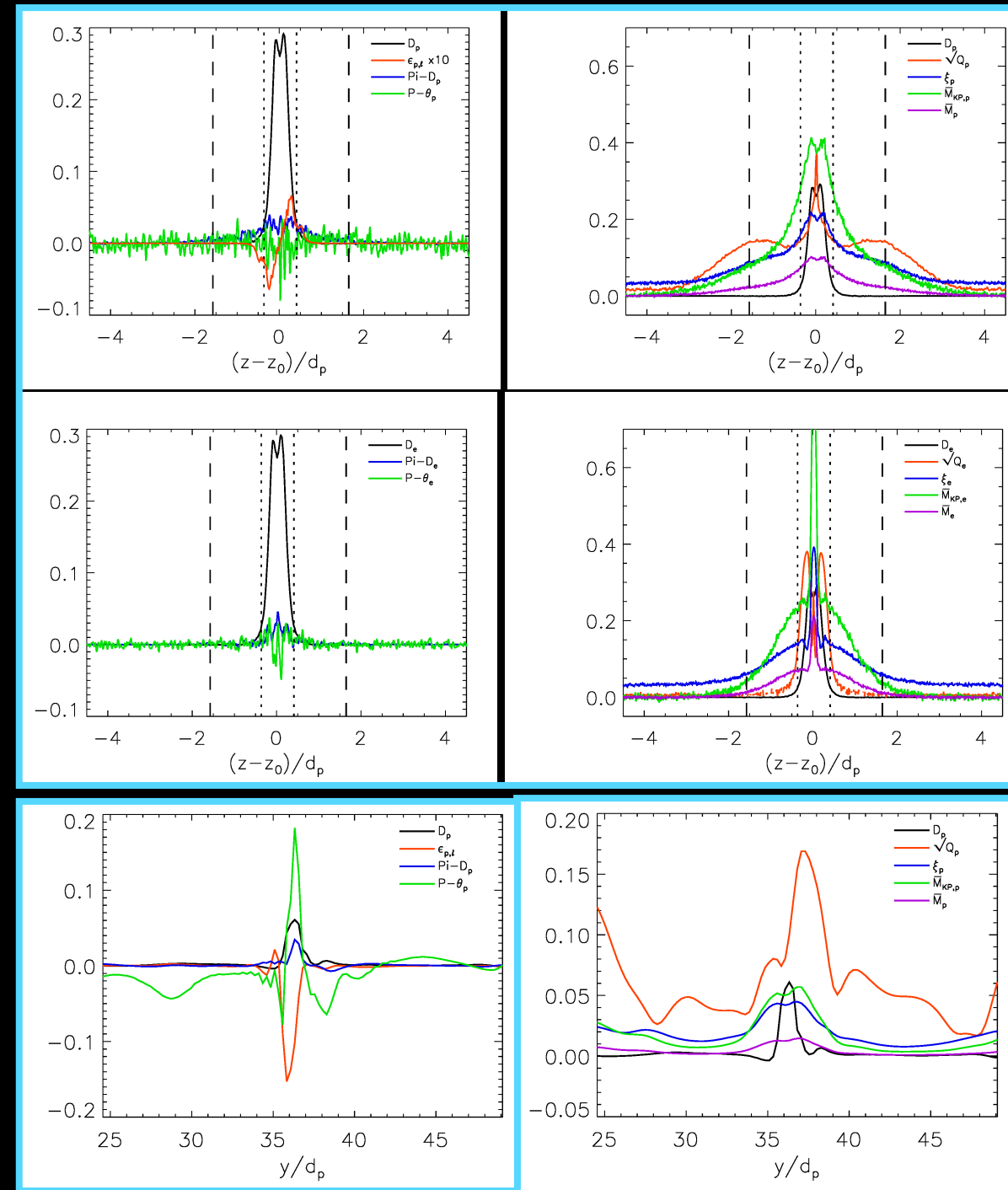
VLASOV-HYBRID HVM TURBULENCE SIMULATIONS

- Energy- and VDF-based measures for protons for collisionless (left) and collisional (right) HVM turbulence simulations
- Energy-based measures D , ε , and $Pi-D$ tend to be strongest near current sheets
 - D is net positive, so electric energy is being converted to plasma energy, ε is net negative which is consistent with a cascade to smaller scales as expected
- $P-\theta$ strongest in current sheets but also strong in magnetic islands, where compression and expansion occurs
- All four VDF-based are strongest near current sheets, but Q and ξ can be bigger than M within magnetic islands
- Effect of collisions
 - Energy-based measures — weak because only proton-proton collisions are included in simulation
 - VDF-based measures — are effected by collisions; qualitatively similar to the reconnection simulations



PROFILES OF “DISSIPATION” MEASURES

- Reconnection (collisionless VPIC), cuts in the normal direction through the X-line — protons (top row) and electrons (second row), energy-based (left), VDF-based (right)
- Turbulence (collisionless HVM) — same plots for protons through a typical current sheet; energy- (bottom left), VDF-based (bottom right)
- Measures all at elevated levels at and near current sheet — they are not coincident, but are spatially correlated
- Reasonable agreement for many quantities between cuts from reconnection and turbulence simulations, especially in the VDF-based measures
- There are quantitative and even qualitative differences — D dominates the reconnection simulation, but $P-\theta$ is biggest for current sheet in turbulence; LET is oscillatory for reconnection and negative for turbulence
- Measures in turbulence are expected to be functions of time, while should be relatively steady in steady-state reconnection
- May be useful for satellite observations of reconnection and/or turbulence



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