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Turbulent dissipation in weakly-collisional plasmas

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in collaboration with a large group of colleagues and friends: L. Sorriso-Valvo, S. Servidio, F. Valentini, F. Malara, P. Veltri, D. Perrone, P. Cassak, W.H. Matthaeus ...

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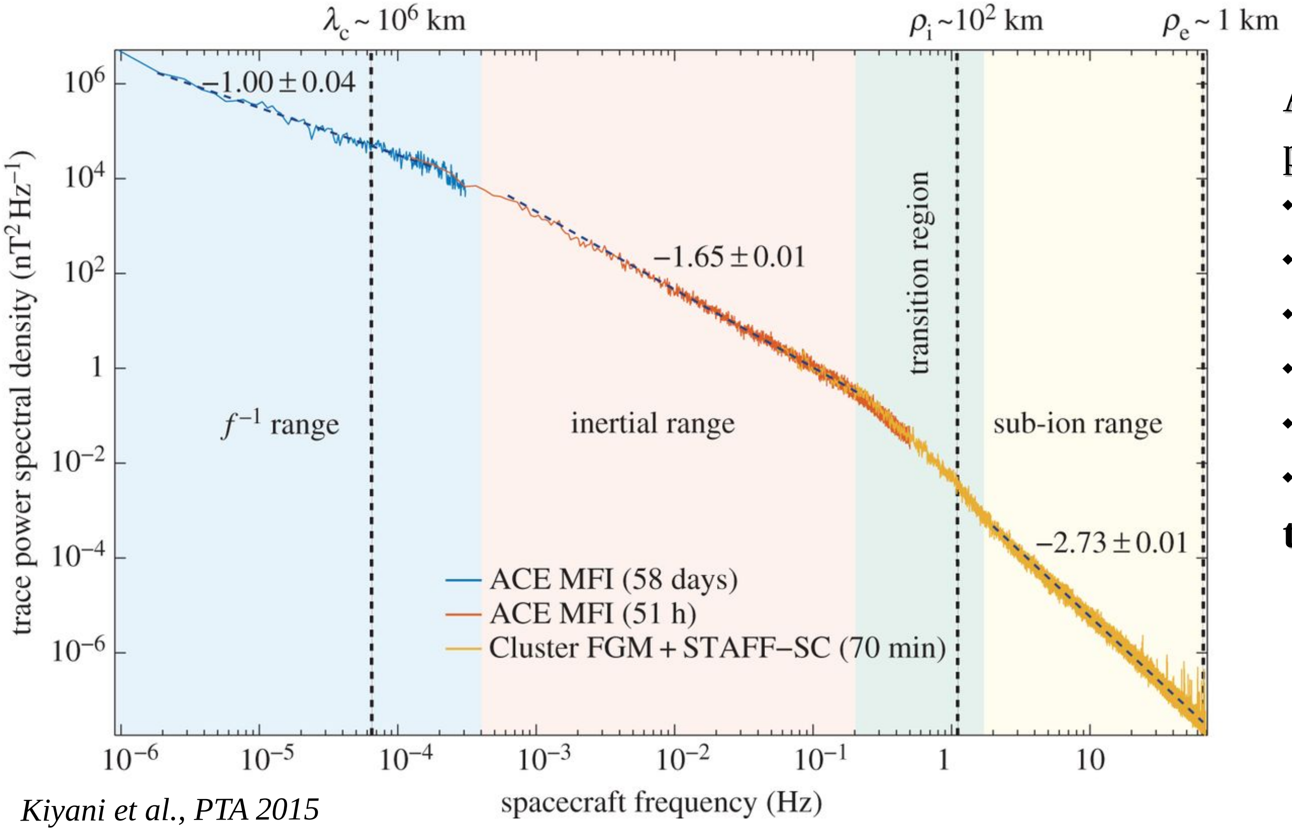
Turbulence in weakly-collisional plasmas

Kinetic, “dissipative” range

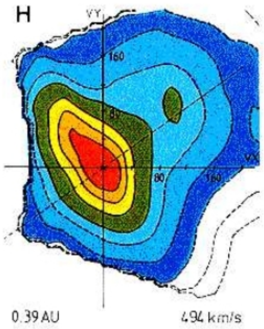
Dissipation function in plasmas **is unknown**!



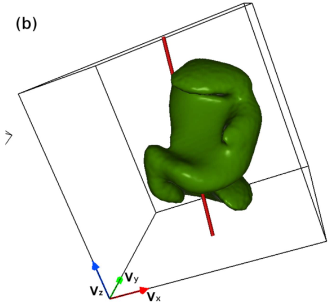
Kiyani et al., PTA 2015

A complex, cross-scale interplay of diverse phenomena:

- **Anisotropy and intermittency;**
- **Macro- and micro- instabilities;**
- **Current sheets, magnetic islands, vortices;**
- **Magnetic reconnection;**
- **Wave-particle interactions;**
- **Generation of non-Maxwellian features in the particle VDF;**



Marsch+, JGR 1982

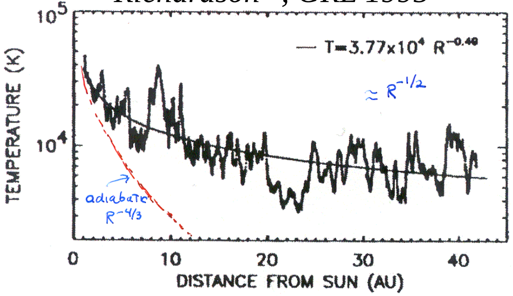


Valentini,…,OP+, NJP 2016

The issue of plasma heating and energy dissipation

Energy is ultimately **“dissipated”** at small spatial scales. Several local **“heating”** mechanisms, often based on the ***collisionless assumption***, have been proposed but a definitive answer is still missing.

Richardson+, GRL 1995



linear

waves in coherent structures:
- wave generation & damping
- secondary instabilities

waves:
- cyclotron damping
- Landau damping
- stochastic heating

non-linear

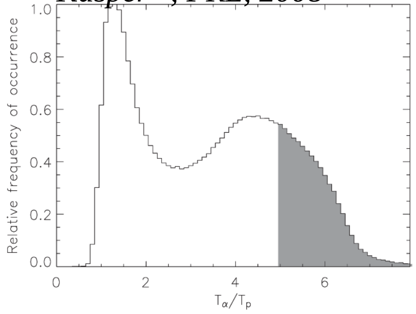
coherent structures:
- reconnection
- scattering & acceleration
- trapping & betatron
- vortex dynamics

non-linear waves:
- steepened waves
- phase space holes
- nonlinear Landau damping

localized — *uniform*

THOR proposal

Kasper+, PRL, 2008



How are plasmas heated and particles accelerated?

How is the dissipated energy partitioned between different species?

Dissipation *surrogates* in weakly-collisional plasmas

Several diagnostics have been implemented to identify kinetic-scale energy conversion and dissipation in weakly-collisional plasmas. We categorize them in: ***energy-based*** and ***VDF-based*** parameters

OP+, MNRAS 2021

Energy-based diagnostics: energy transfers between bulk, thermal and magnetic energy

$$\frac{\partial \mathcal{E}^f_\alpha}{\partial t} + \nabla \cdot \left(\boldsymbol{u}_\alpha \mathcal{E}^f_\alpha + \boldsymbol{u}_\alpha \cdot \boldsymbol{P}_\alpha \right) = (\boldsymbol{P}_\alpha \cdot \nabla) \cdot \boldsymbol{u}_\alpha + n_\alpha q_\alpha \boldsymbol{u}_\alpha \cdot \boldsymbol{E}$$

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

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

Work done by EM field
(Zenitani+, PRL 2011; Wan+, PRL 2015)

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

Local Energy Transfer (LET) rate
(Sorriso-Valvo,…,OP,+, JPP 2018, PRL 2019)

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

Pressure-strain interaction (Pi-D and P-θ)
(Yang+, PRE 2017, POP 2018, MNRAS 2020; ***OP+, POP 2019****)*

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

Dissipation *surrogates* in weakly-collisional plasmas

Consiglio Nazionale delle Ricerche

Several diagnostics have been implemented to identify kinetic-scale energy conversion and dissipation in weakly-collisional plasmas. We categorize them in: ***energy-based*** and ***VDF-based*** parameters

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VDF-based diagnostics**:** non-equilibrium features in the particle VDF

Pressure agyrotropy

(Scudder+, POP 2008; Aunai+, POP 2013; Swisdak+, GRL, 2016)

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

Non-Maxwellianity parameter ξ

(Greco+, PRE, 2012; ***OP+, JPP 2017, POP 2018****)*

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

g is the Maxwellian associated with the local VDF f

Entropy density-based parameters

(Kaufmann+, JGR 2009; **Liang,…,OP+, JPP 2020**)

$$\bar{M}_{\mathrm{KP},\alpha}(\boldsymbol{r},t) = \frac{s_{\mathrm{M},\alpha}(\boldsymbol{r},t) - s_\alpha(\boldsymbol{r},t)}{(3/2)k_B n_\alpha(\boldsymbol{r},t)}$$

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

$$s_\alpha(\boldsymbol{r},t) = -k_B \int d^3v\, f_\alpha(\boldsymbol{r},\boldsymbol{v},t)\log f_\alpha(\boldsymbol{r},\boldsymbol{v},t) \qquad s_{\mathrm{M},\alpha} = \frac{3}{2}k_B n_\alpha\left[1 + \log\frac{2\pi k_B T_\alpha}{m_\alpha n_\alpha^{2/3}}\right]$$

Dissipation *surrogates* in weakly-collisional plasmas

These parameters have been compared by using:

A. Two type of 2.5D kinetic simulations:

- **Magnetic reconnection.** Harris-like sheet perturbed with low-amplitude noise
  β_p=0.2 L_x=L_y~25 d_p m_p/m_e=25
  Analysis when reconnection is stationary

- **Decaying plasma turbulence.** Large-scale uncorrelated perturbations imposed on a homogeneous equilibrium with an out-of-plane background magnetic field B_0:
  $\delta B/B0$=0.5 β_p=1 L_x=L_y~120 d_p
  Analysis when turbulence and fluid-like dissipation are most intense

B. Three different codes:

i) Fully-kinetic **Particle-in-cell (VPIC)**
ii) Fully-kinetic **continuum Vlasov (Gkyell)**
iii) Eulerian **Hybrid Vlasov-Maxwell (HVM)**

C. Both collisionless and collisional cases are explored.

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Plasma turbulence at sub-proton scales

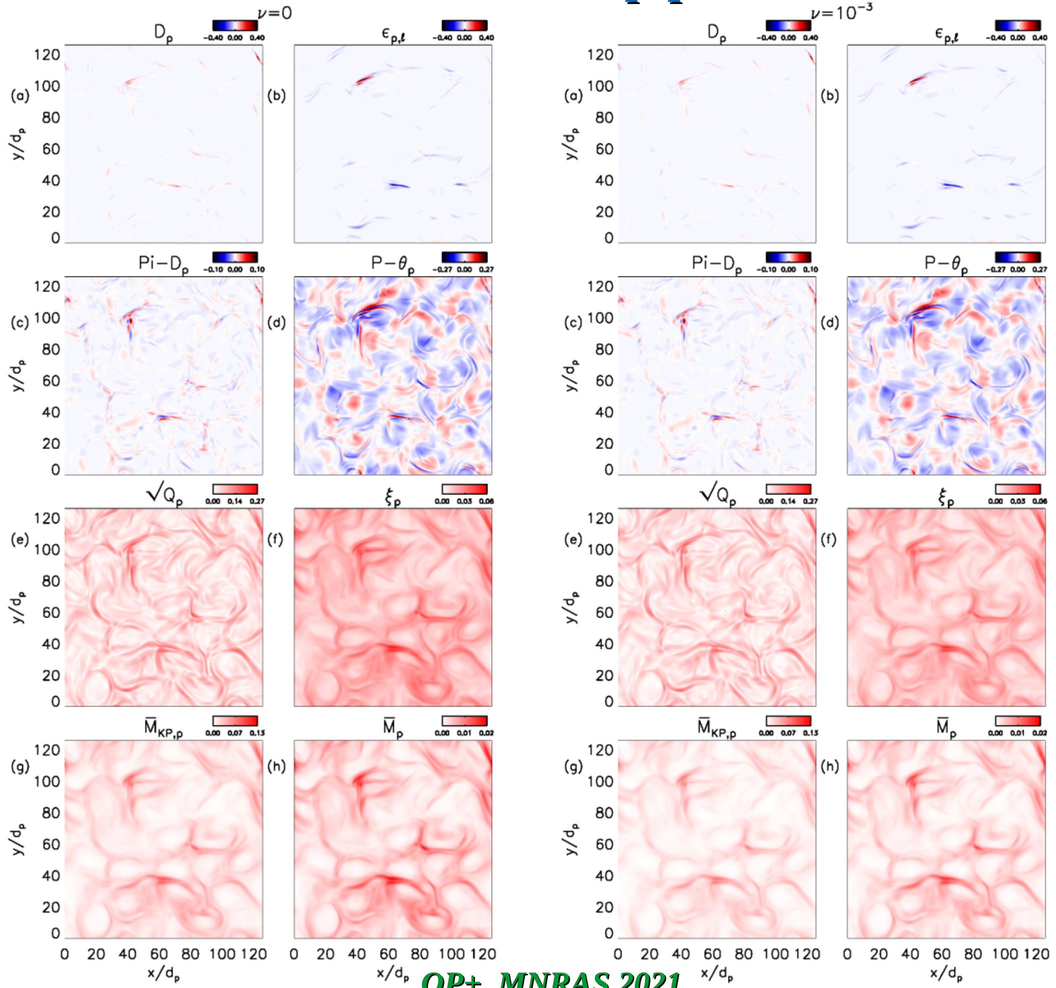
- Reconnecting current sheets are dynamically generated by turbulence as well as vortices, filaments…

- **Energy-based measures D, ε, and Pi-D peaked close to current sheets. P-θ also intense in islands due to compression and expansion. VDF-based diagnostics also peaked close to current sheets.**

- **D is net positive ⇒ field energy flows into plasma energy**
  LET ε is net negative ⇒ local cascade to smaller scales

- **Proton-proton collisions do not affect energy-based measures since do not produce a net energy transfer. VDF-based parameters are affected by collisions, that tend to Maxwellianize the particle VDF.**

HVM + p-p



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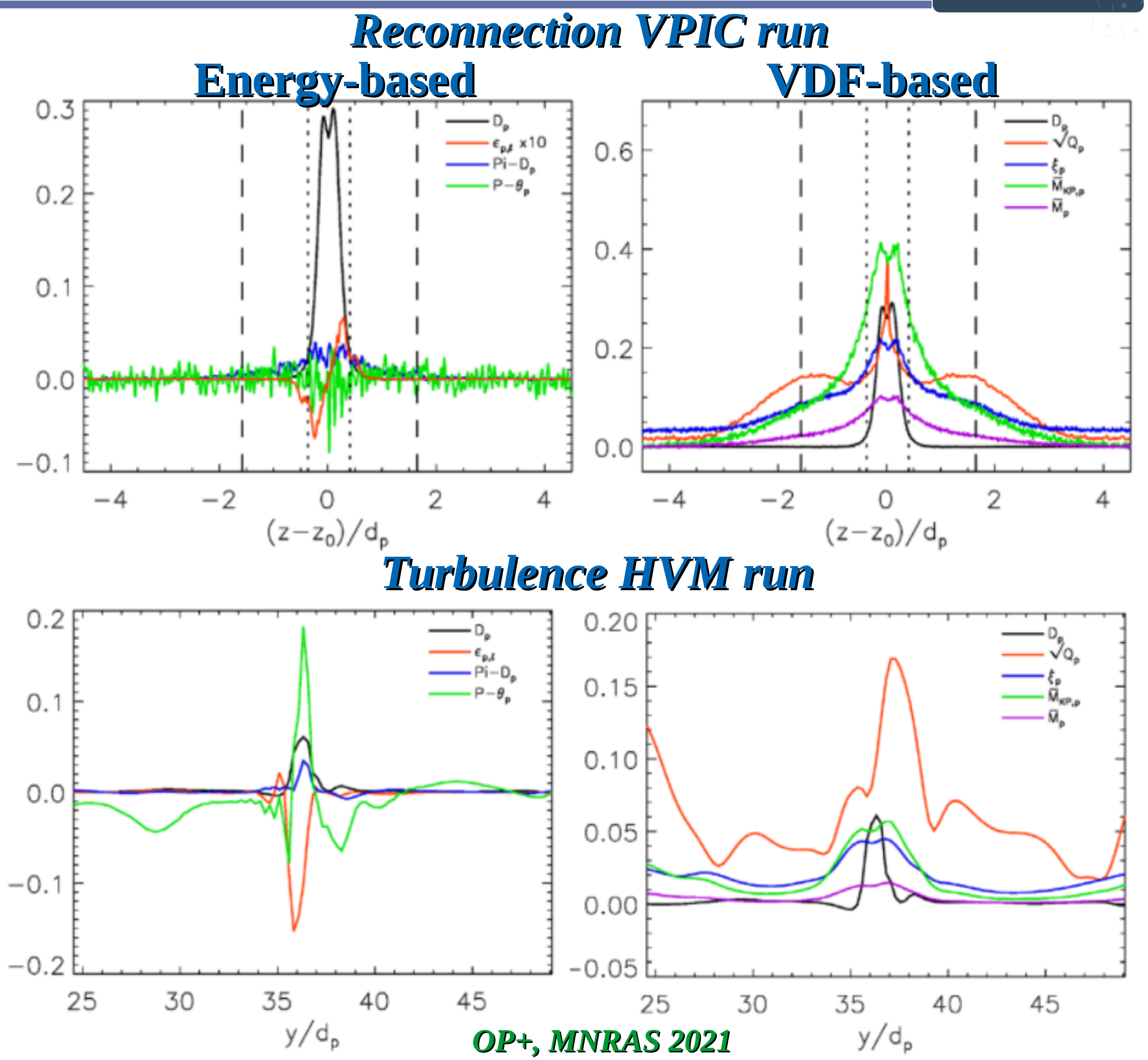
Profiles of dissipation proxies

- Reconnection: cuts in normal direction through X-line. Turbulence: cuts through a typical current sheet.
- **Measures all at elevated levels at and near current sheets, although not coincident: “*regional*” correlation**
- **Reasonable qualitative agreement for many quantities between cuts from reconnection and turbulence runs**, especially in the VDF-based measures
- Some differences appear, e.g. Dp is dominant in the reconnection run while this is not the case for the turbulence run.
- **Measures in turbulence have an intrinsic variability, while should be relatively steady in steady-state reconnection** *(Bandyopadhyay+, PoP 2021)*



OP+, MNRAS 2021

Conclusions

OP+, MNRAS 505, 4857-4873 (2021)

- **Defining dissipation in nearly-collisionless plasmas is rather complex**:
  - ✗ Dissipation as **energy conversion** (e.g. from magnetic to thermal…)
  - ✗ Dissipation as **production of kinetic effects in the particle VDF** (e.g. Landau damping or generic storage of free energy in velocity-space VDF structures)
  - ✗ Dissipation as **irreversible entropy growth**
- We categorize and compared several **dissipation *surrogates***, useful for identifying kinetic-scale energy conversion and dissipation, as **energy-** and **velocity distribution function**-based, in a suite of different numerical simulations (VPIC, Gkeyll and HVM) that also include inter-particle collisions:
  - **Different dissipation parameters show similar results** and all parameters exhibit a ***local correlation***: they are non-zero near regions of intense magnetic stress, thus confirming that **energy dissipation is non uniform**
  - **Collisional effects are particularly active in correspondence of strong current structures**
- Both energy- and VDF-based can be useful, and **using multiple measures is likely best to identify key physics**