Statistics of Total Pressure in Kinetic Plasma Turbulence

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January 3, 2023

Abstract

Although pressure plays a vital role in the dynamics of the turbulent plasmas, pressure statistics have not been studied as extensively as other plasma properties. The studies that have focused on pressure are mostly based on hydrodynamic turbulence or have been formulated in the nearly incompressible magnetohydrodynamics (NIMHD) framework. However, less attention has been paid to the scaling properties of pressure in kinetic plasma. In this study, we explore the statistics of magnetic, thermal, and total pressure fluctuation in kinetic collisionless turbulence. A 2.5D kinetic particle-in-cell (PIC) simulation of turbulence is used to investigate pressure balance via the evolution of thermal and magnetic pressure. Further, the behavior of thermal, magnetic, and total pressure structure function and their corresponding spectrum is explored. Finally, we evaluate higher-order total pressure structure functions to discuss intermittency and compare the power exponents with higher-order structure functions of velocity and magnetic fluctuations.

Statistics of Total Pressure in Kinetic Plasma Turbulence

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I. Introduction

- Pressure plays a vital role in turbulent plasmas.
- For example: energy transfer through the Pressure strain interaction, or routine interval of pressure balance in the solar wind.
- Density, as a linear response to pressure fluctuations, has beenexplored in the nearly incompressible (NI) MHD framework[1, 2, 3].
- However, mechanical and total pressure statistics in Vlasov-Maxwell plasmas have not been extensively studied.

II. Simulation

- Kinetic particle-in-cell (PIC) simulation of turbulence in a 2.5D setup with initial Fourier modes k ϵ [2,4] (See 4,5)
- Details: background density (n_b), mass (m) of ions (i)/electrons(e), temperature (T), plasma beta ($\boldsymbol{\beta}$), particles per grid (ppg)

$L_x=L_y$	n_b	m_i/m_e	$T_i=T_e$	$\boldsymbol{\beta_i=\beta_e}$	ppg
149.6 d_i	1.0	25	0.3	0.6	3200

III. Results

- As turbulence evolves, volume averaged total pressure remains constant (Fig. 1). The thermal and magnetic pressure compensate for each other (Figs. 2 and 3)
- In the inertial range, while magnetic and thermal pressures have similar spectral slopes comparable to -5/3, the total pressure spectrum exhibits a slope of -7/3 (Fig. 4)
- Probability distribution functions of the increment of different forms of pressure show the departure from gaussianity. For two increments d_i and d_e, the total pressure pdf is close to a gaussian for d_i (Fig. 5, and 6)

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A. Pressure balance

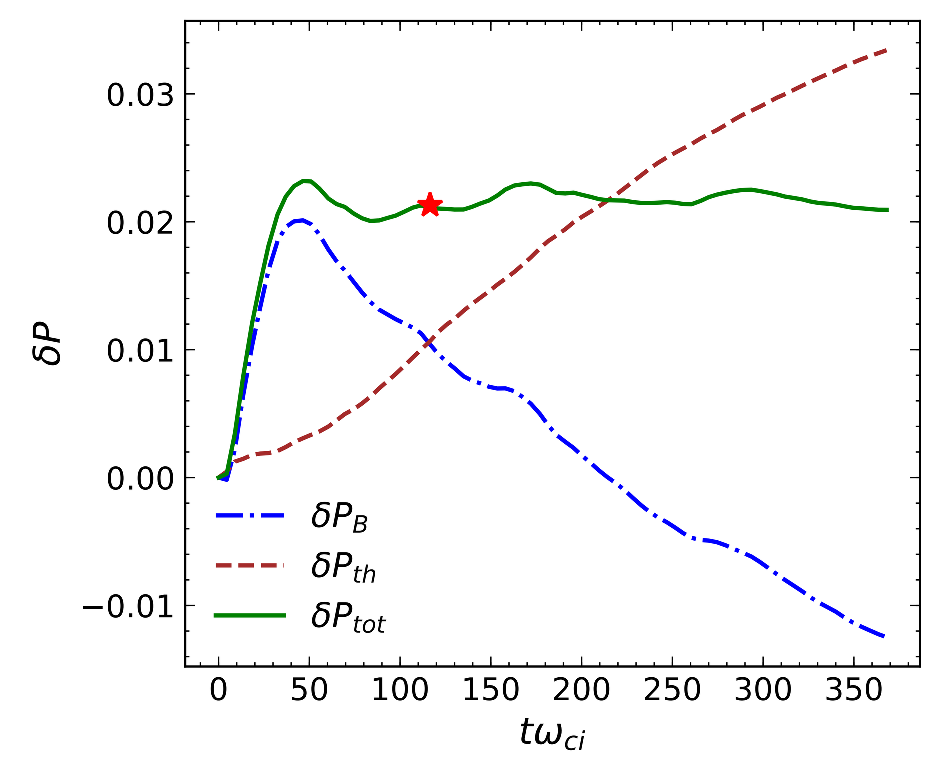

Figure 1: Time evolution of the change in thermal ($\boldsymbol{\delta} P_{th}$), magnetic ($\boldsymbol{\delta}$ P_B), and total pressure ($\boldsymbol{\delta}$ P_{tot}). Red star represents the time of analysis (tw_{ci} = 116.5).

B. Pressure spectrum

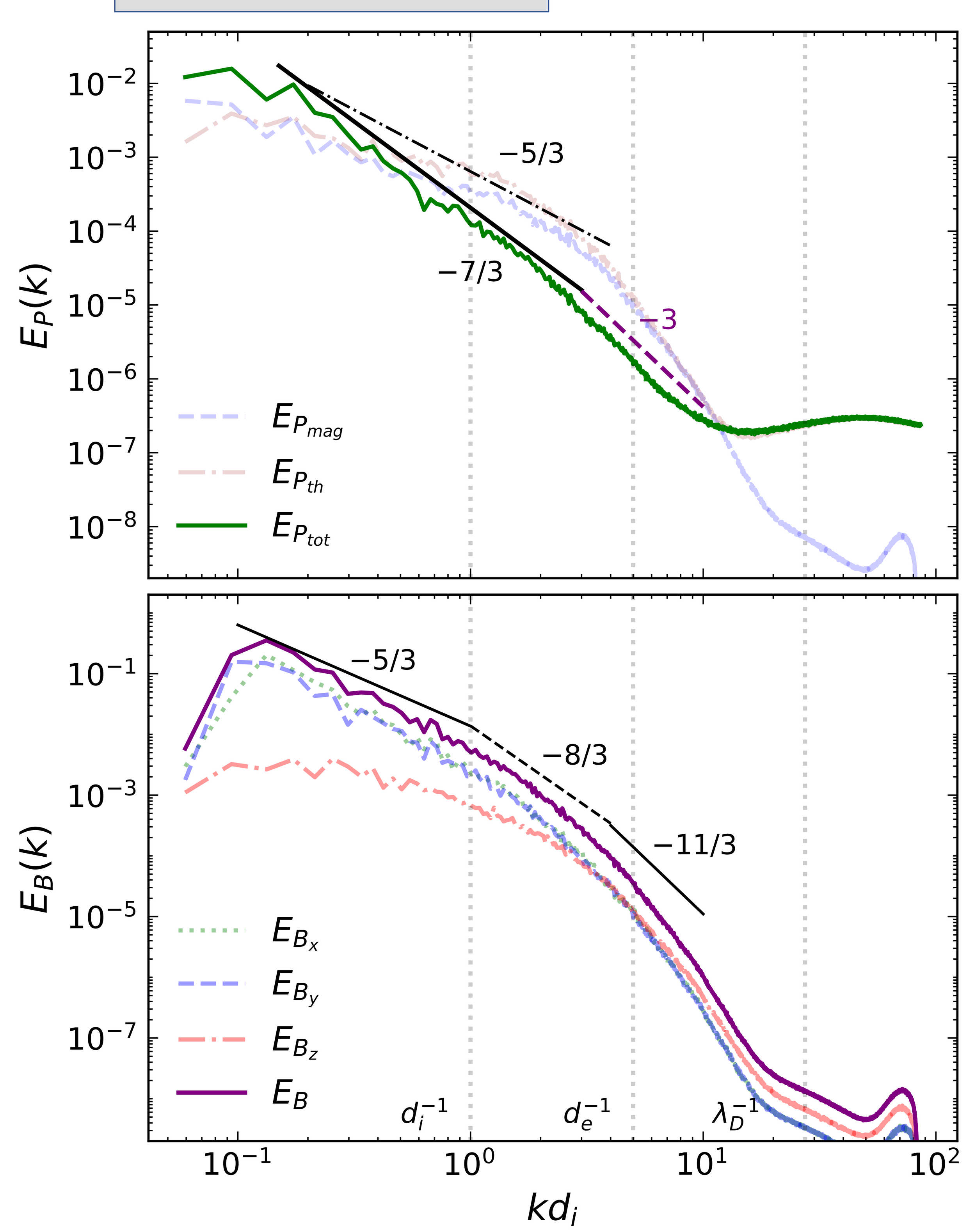

Figure 4: (Top) Pressure spectra for all types of pressure as a function of wavenumber. Black and purple lines with slopes -7/3, -5/3, and -3 are drawn for reference. (Bottom) Magnetic energy spectra at the same time of analysis. Lines of slope -5/3, -8/3, and -11/3 are drawn for reference.

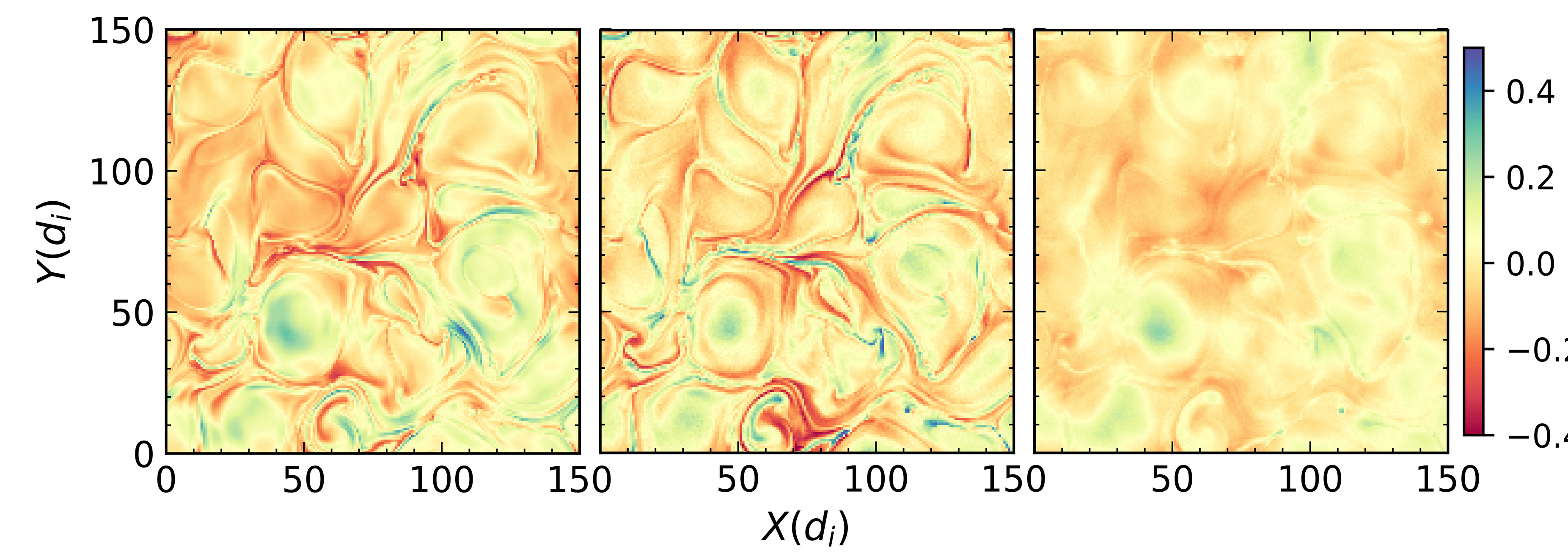

Figure 2: Two-dimensional image of the change in magnetic, thermal and total pressure normalized to the corresponding mean value at tw_{ci} = 116.5.

C. Pressure pdf

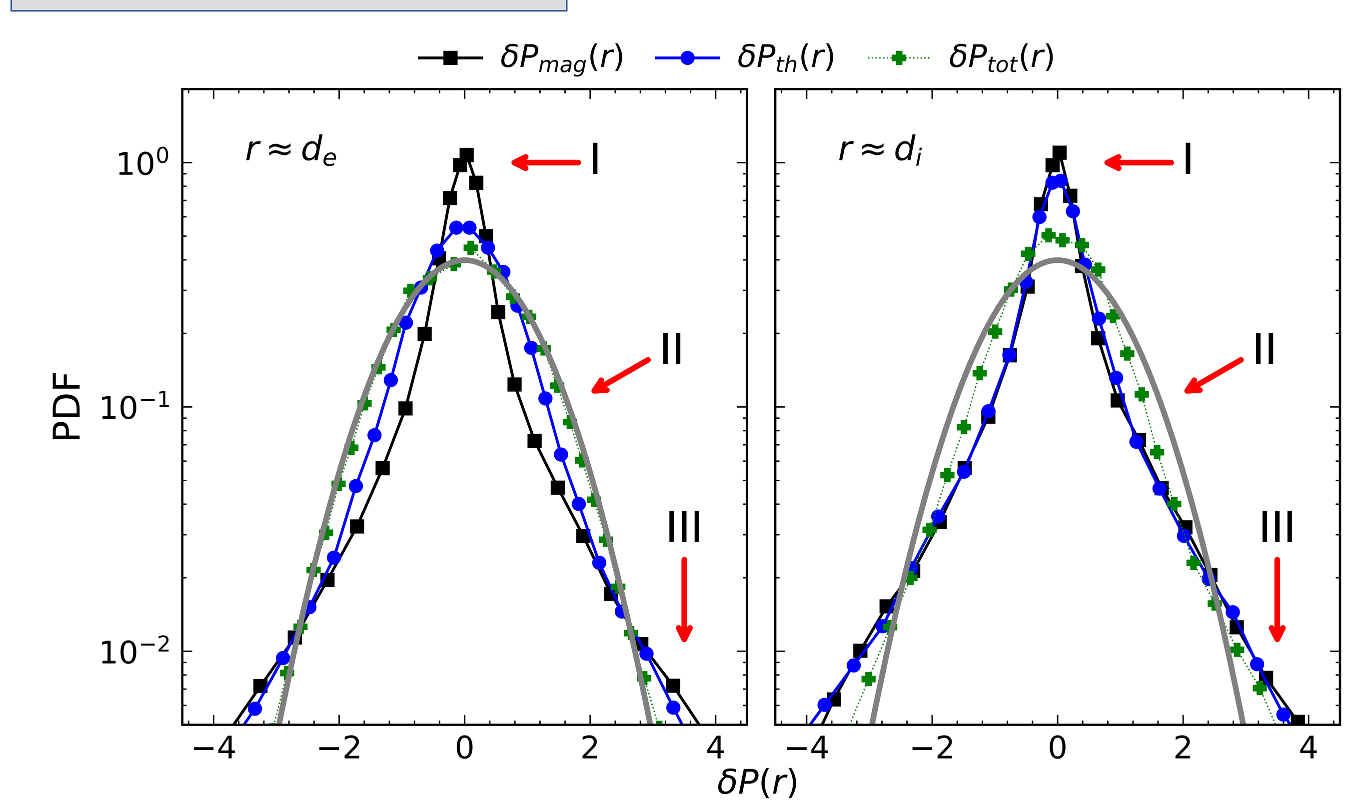

Figure 5: Probability distribution function of the increment of pressure dP at r=1d_e=0.2d_i (left) and r=1d_i (right) at tw_{ci} = 116.5. The gray curve represents the normal distribution for reference. Regions I, II and III are defined based on the pdf's intersection with the normal one.

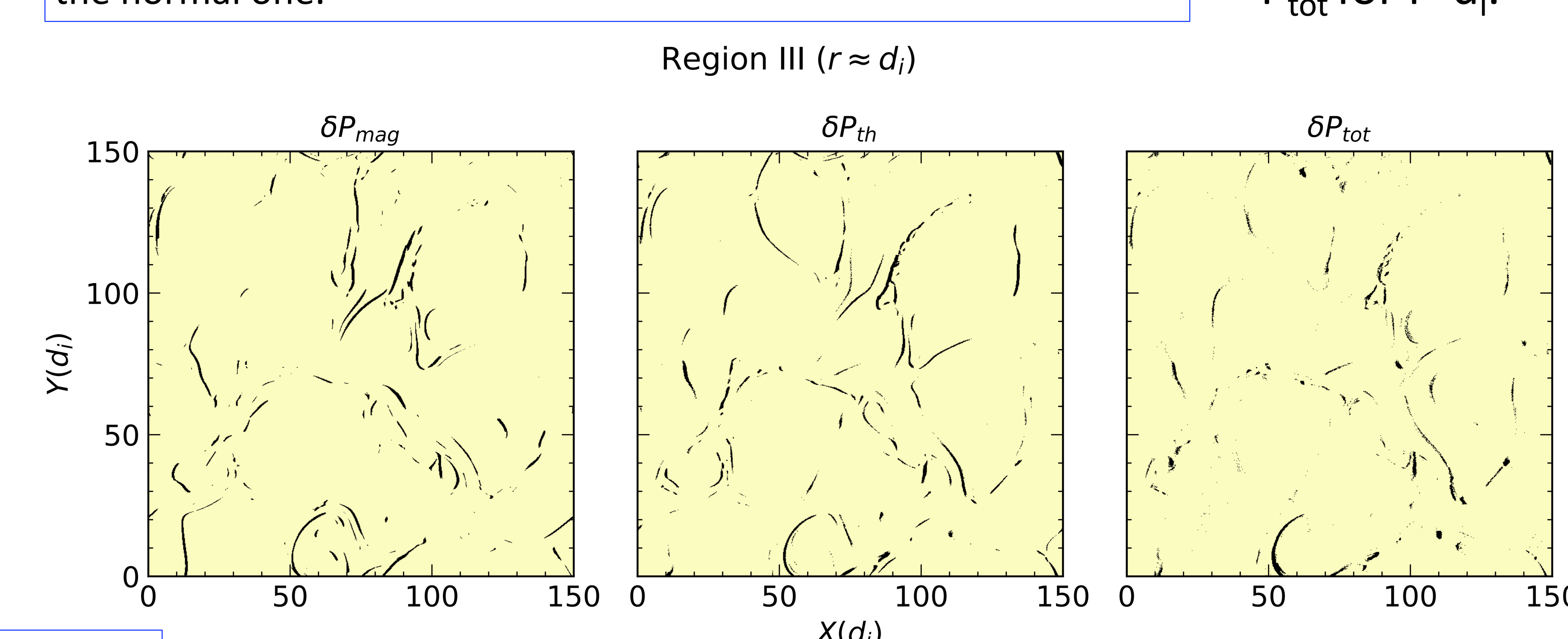

Figure 6: Structures in individual pressure terms contributing to the tails observed in Region III of Fig. 5 (right).

Acknowledgments

- NCAR/ UCAR Computational Resources

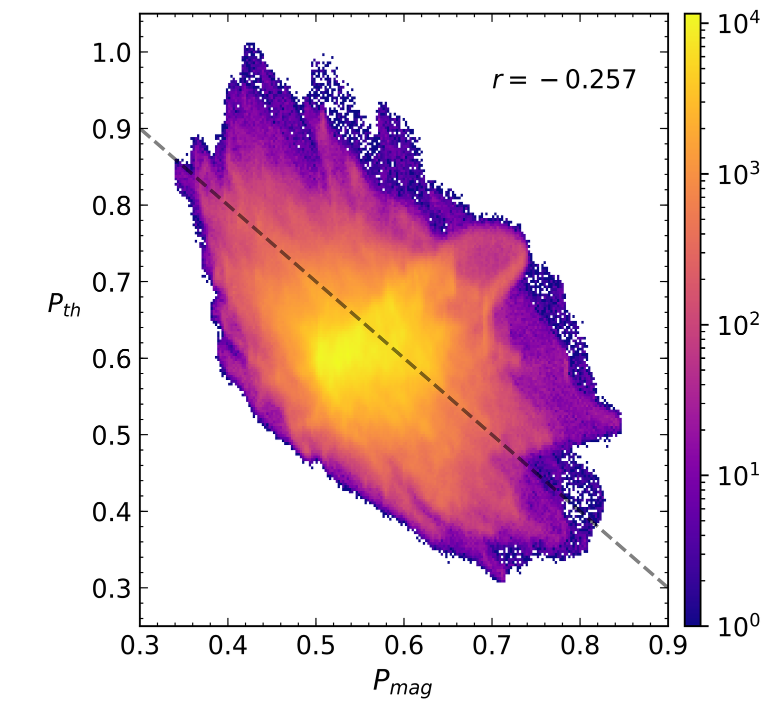

Figure 3: Joint probability distribution of the thermal and magnetic pressure at tw_{ci} = 116.5, where r is the correlation coefficient. A dashed line of slope -1 is drawn for reference.

IV. Discussion

- The change in thermal pressure is opposite to the change in magnetic pressure keeping the total pressure approximately constant.
- The anti-correlation between P_{mag} and P_{th} is supported by the joint pdf and a –ve correlation coefficient.
- The omnidirectional spectrum for P_{tot} shows a -7/3 slope over k, steeper than P_{mag} and P_{th}. This behavior is similar to hydrodynamic turbulence.
- Intermittency is observed in the pdfs of pressure increments, with elongated tails in P_{tot} for r~d_i.
- How these extrapolate to 3D and anisotropy is left for a future study.

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