香 港 中 文 大 學
The Chinese University of Hong Kong

The decay of MHD turbulence with self-gravitation

Shibo Yuan, Hua-bai Li

Introduction

Magnetic fields can channel gas flows into anisotropic turbulence, while turbulence can amplify and distort the magnetic fields. The relative importance of magneto-turbulence and gravity determines the regimes of formation of prestellar cores, such as super-Alfvénic or sub-critical, which have different properties and evolution pathways (see Li 2017, chapter 5).

Directly observing the time evolution of the interstellar medium (ISM) is not currently possible. However, there is evidence of the decay of MHD turbulence in the ISM through a few observations, such as those reported by Pon et al. (2014) and Larson et al. (2015). Numerical simulations of magnetohydrodynamics (MHD) have long been a valuable tool to investigate the more detailed properties of magneto-turbulence. For instance, Mac Low et al. (1998) investigated the power law index of the kinetic energy decay over time in magneto-turbulence. Mac Low (1999) provided scaling laws for the dissipation rate in continuously driven turbulence. However, these studies focused on the entire molecular cloud without considering self-gravitation. To address this, Ostriker et al. (2001) analysed the local dependence of turbulence quantities in self-gravitating clouds, such as velocity dispersion, on size and mass from regions of contrast. However, this study did not examine the time evolution of these local scaling relations.

Methods

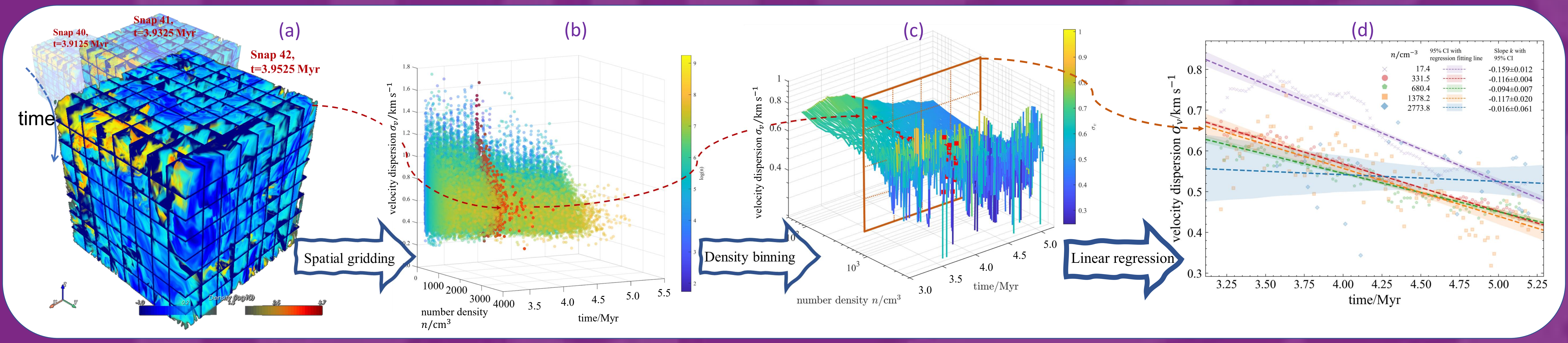

Figure 1: The flow chart of data analysis procedures. Subfigure (a) is the 3D rendering of one octant of the cloud’s density field with spatial gridding length. Subfigure (b) is the result of gridding in 3D scatter form. By density binning of (b), the waterfall plot (c) gives the average behavior. Subfigure (d) is the quantitative results of five samples by linear regression. The dashed arrows show the flow of data forms’ changes.

MHD simulation: To get a self-gravitational isothermal cloud with supersonic and sub-Alfvénic turbulence, we use ZEUS-MP (Hayes et al. 2006) to perform an ideal MHD simulation on a periodic cube with a side length of 4.8 pc, resolved by 960 pixels (Cao et al. 2023).

Spatial gridding: To extract local information from the turbulent cloud, we divide the 3D cloud domain into sub-cubes with size $L_s = 60$ pixels, evenly spaced. Each sub-cube gives a velocity dispersion value σ_v , and an average number density n.

Density binning: To better examine the collective behavior of these dense scatter points, we apply density histogram binning with a width of $34.5\ \mathrm{cm}^{-3}$ for σ_v. Each bin gives a pair of averaged (σ_v, n), forming a line perpendicular to time axes.

Linear regression: To quantify the decay rate of turbulence, we use linear regression. For the short time less than $2t_{\mathrm{ff}}$, where t_{ff} is the free-falling time, the decay rate can be represented by the slope value from linear fitting instead of the function of time by power law fitting.

Results

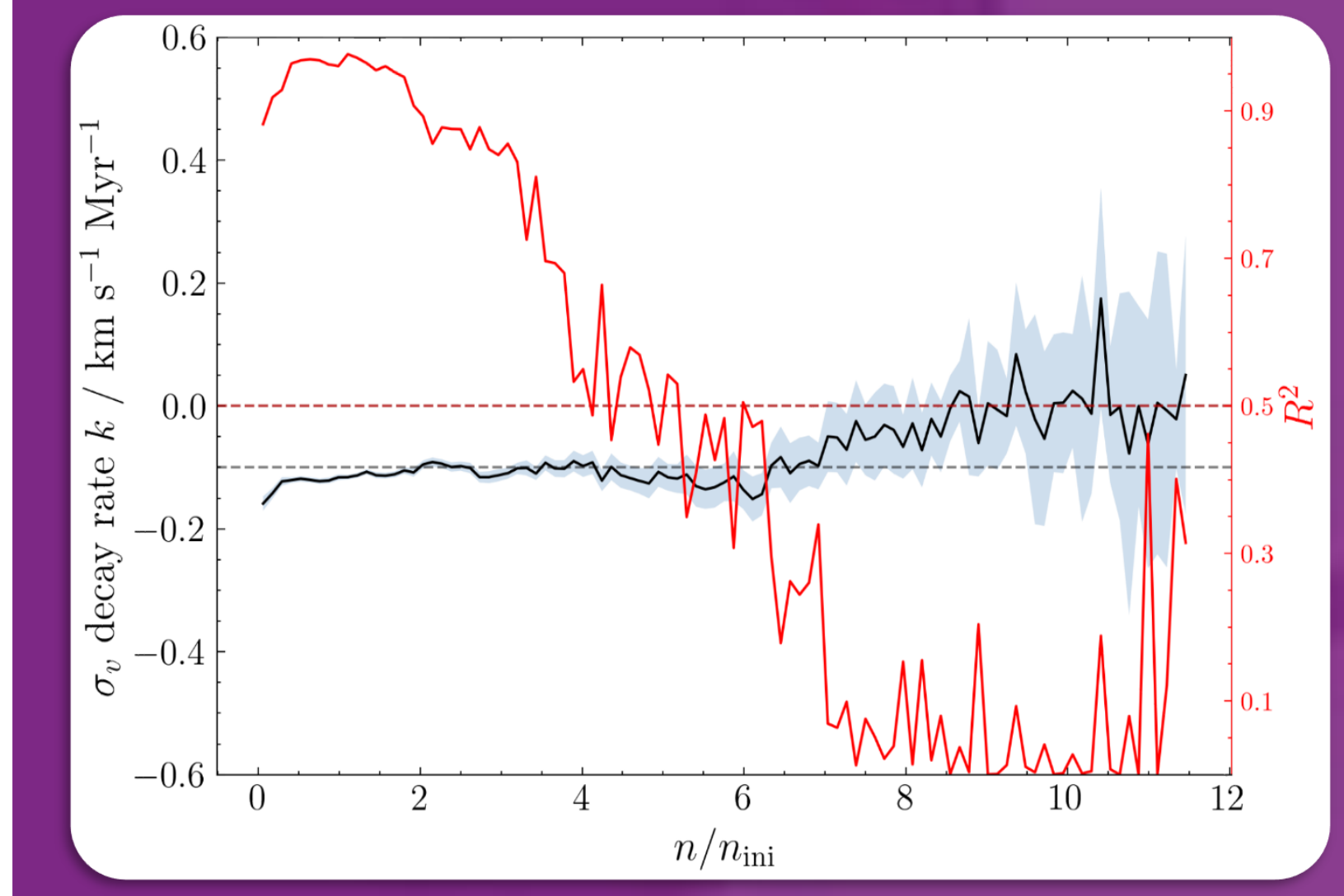

Figure 2: the turbulent velocity decay rates with determination coefficients versus number density.

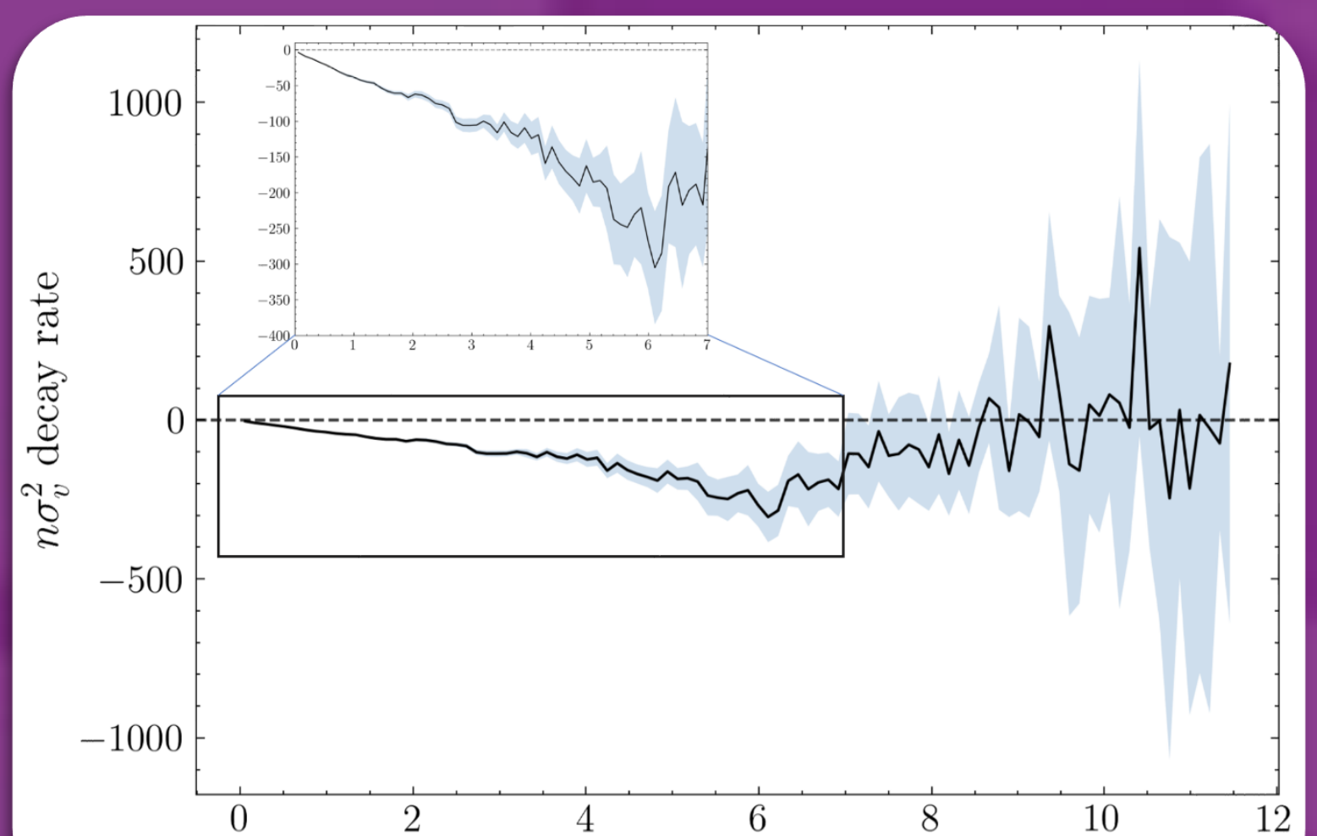

Figure 3: the turbulent kinetic energy decay rates versus number density.

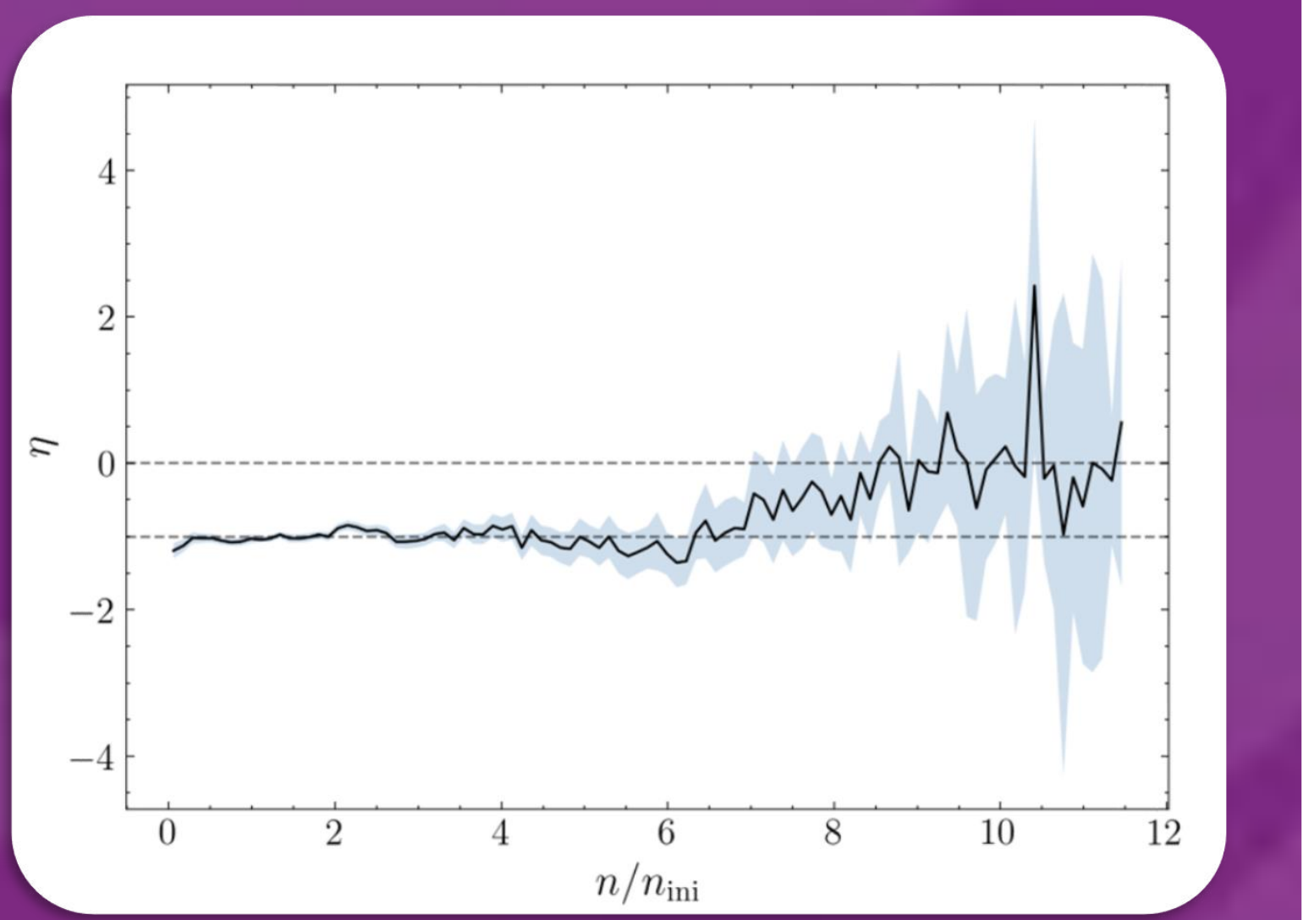

Figure 4: The power law index of turbulent kinetic energy versus number density.

The regimes of density lower than $6n_{\mathrm{ini}}$ have turbulence decay rates $k \sim -0.1\ \mathrm{km\ s^{-1}\ Myr^{-1}}$. In contrast, regimes with a higher density than $8n_{\mathrm{ini}}$ have k near 0, as shown in Figure 2. It gives that the turbulence at high-density regimes decays slower than the low-density regimes, which is consistent with hints found in Figure 1(b)(c)(d).

The highest decay rate of turbulent kinetic energy $E_{\sigma_v} \equiv n\sigma_v^2$ appears at $6n_{\mathrm{ini}}$. The coefficients of determination of E_{σ_v}−t regression in Figure 3 and 4 are very similar to the one in Figure 2, not shown for simplicity and expressiveness of the images. 95% confidence interval (CI) is shaded in the Figure 2, 3 and 4.

The power law index η defined by $E_{\sigma_v} \propto (1 + t/t_0)^{\eta}$ (see Mac Low 1999, equation 13), shows two phases distinguished by density. For the phase, less than $6\,n_{\mathrm{ini}}$, $\eta \simeq -1$, consistent with the value in the studies of Mac Low et al. (1998) and Ostriker et al. (2001). For the high-density phase, $\eta \simeq 0$, which agrees with the results in Figure 2 and 3.

Conclusions & Discussions

Based on our numerical simulations, we have studied the time evolution and decay of magneto-turbulence in molecular clouds with self-gravity. Our results show that

1) the turbulent velocity σ_v decay rate is density-dependent:

$$\frac{\mathrm{d}\sigma_v/\mathrm{d}t}{\mathrm{km\ s^{-1} Myr^{-1}}} = \begin{cases} -0.1, & n < 6n_{\mathrm{ini}} \\ \simeq 0, & n > 8n_{\mathrm{ini}} \end{cases}$$

2) the turbulence kinetic energy E_{σ_v} has the highest decay rate at the intermediate density regimes $n \sim 6n_{\mathrm{ini}}$
3) the turbulent energy power law index η is density-dependent:

$$\eta = \begin{cases} -1, & n < 6n_{\mathrm{ini}} \\ \simeq 0, & n > 8n_{\mathrm{ini}} \end{cases}$$

In conclusion, our study provides valuable insights into local magneto-turbulence's time decay in molecular clouds. In addition, the limited density range due to spatial gridding length raises some questions that remain unanswered: What would the decay behavior in higher density regime, and how to obtain it?

References

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Email 1155168091@link.cuhk.edu.hk