Disordered collective motion in dense assemblies of persistent particles

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Motivation

- Active matter is an important and rapidly developing class of **non-equilibrium systems**. Examples span all the scales of the living, from cell tissues to bird flocks to human crowds.
- **Self-propelled particles** is a paradigmatic model of active matter with non-trivial **collective behaviour**.
- **Disordered dense matter** experiences **dynamical arrest** when **crowding** overcomes **excitation**. At large packing fractions ϕ, disordered colloidal packings have two-step relaxation dynamics, with slow, spatially correlated motion (dynamical heterogeneity).
- **Dense active matter** (*e.g.*, cell tissues, dense self-propelled colloids) associates active physics and dense physics, with new interesting **collective motion**. We explore in 2D how it emerges from the competition between **crowding** and **active forcing**.

Model

Overdamped Langevin equation for disordered repulsive self-propelled particles at zero temperature, with positions $\boldsymbol{r}_i$, diameters σ_i, and active forces $\boldsymbol{p}_i$

$$\xi\dot{\boldsymbol{r}}_i = -\nabla_i U + \boldsymbol{p}_i \qquad (1)$$

where U is a WCA potential with energy scale ε.

Ornstein-Uhlenbeck active forces with persistence time τ_p

$$\tau_p\dot{\boldsymbol{p}}_i = -\boldsymbol{p}_i + \xi\sqrt{2D_0}\boldsymbol{\eta}_i \qquad (2)$$

with $\boldsymbol{\eta}_i$ a component-wise unit-variance zero-mean Gaussian white noise, such that $\tau_p \to 0 \Leftrightarrow$ Brownian limit at temperature $T_{\text{eff}} = D_0/\xi$.

System is disordered with polydispersity index $I = \text{Var}(\sigma_i^2)^{1/2}/\overline{\sigma_i} = 20\%$.

We set length $\sigma = \overline{\sigma_i} = 1$, energy $\varepsilon = 1$, and time $\xi\sigma^2/\varepsilon = 1$.

Control parameters: ϕ, τ_p, D_0. Main features of phase space do not depend on the free particle diffusion constant D_0, and are presented for $D_0 = 1$.

Phase diagram

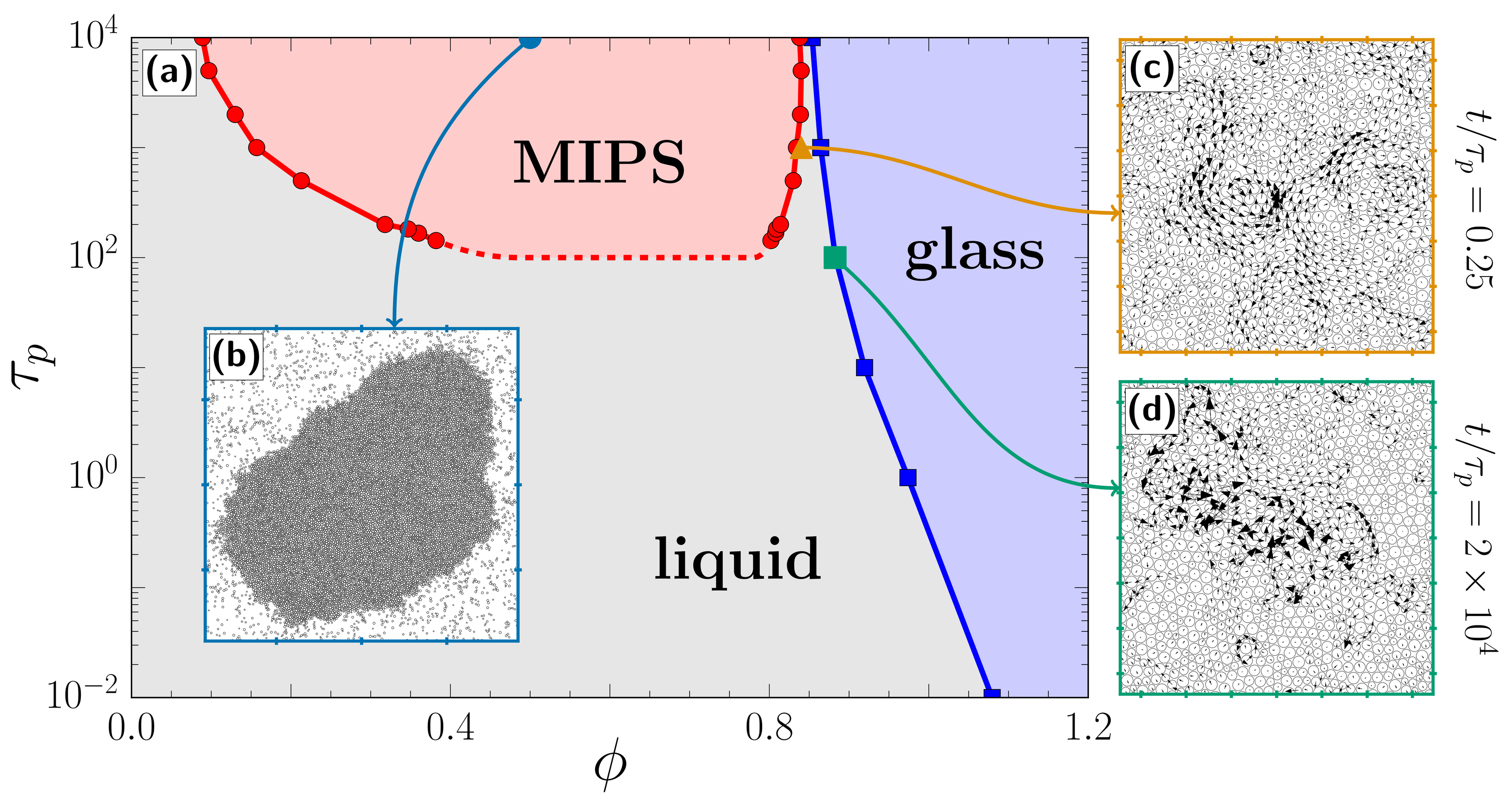

Fig. 1: **(a)** Phase diagram at $D_0 = 1$. **(b)** Phase separated system. **(c)** Displacement field $\boldsymbol{r}_i(t) - \boldsymbol{r}_i(0)$ in persistent active liquid close to MIPS ($t/\tau_p = 0.25$). **(d)** Displacement field in persistent active liquid close to dynamical arrest ($t/\tau_p = 2\times10^4$).

- There is a **macroscopic phase separation** at large τ_p.
- Polydispersity stabilises the **homogeneous liquid at large** τ_p.
- At large ϕ, this liquid undergoes a **nonequilibrium glass transition**.
- Homogeneous liquids close to MIPS and dynamical arrest are both **dynamically heterogeneous**, although the correlations have different origins.

Persistent active liquid

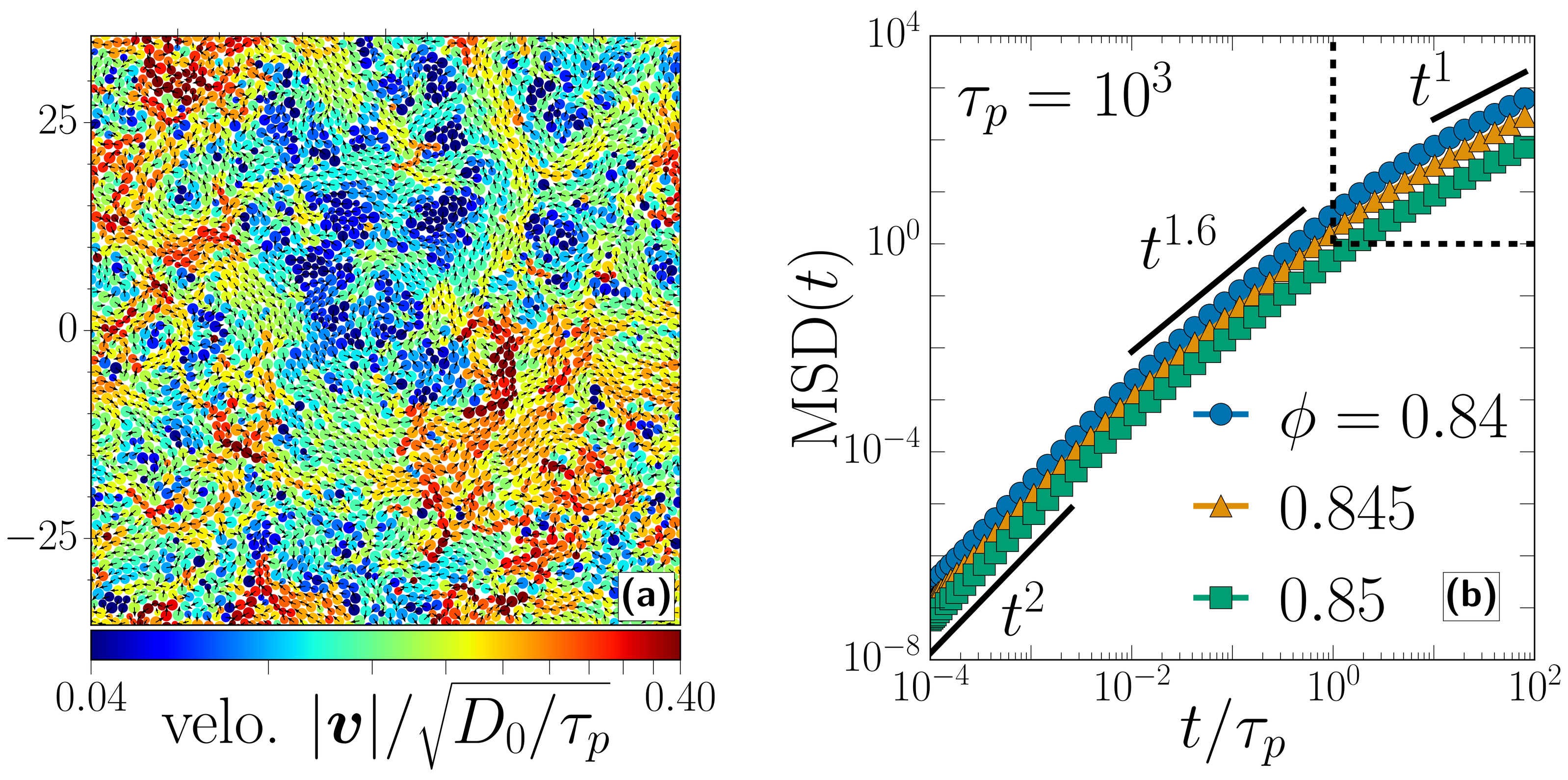

Fig. 2: **(a)** Snapshot of velocities $\boldsymbol{v}_i \equiv \dot{\boldsymbol{r}}_i$ ($\tau_p = 10^3$, $\phi = 0.84$). **(b)** Mean squared displacement $\text{MSD}(t) = \langle|\boldsymbol{r}_i(t) - \boldsymbol{r}_i(0)|^2\rangle$.

- **Velocity correlations** emerge from the interplay of persistence and repulsive interactions, and extend over **several diameters** on a **time scale of order** τ_p.
- These correlations lead to a **collective motion**, with particles moving **distances of order 1** with their neighbours, associated with a distinct **superdiffusive regime**.

Glassy dynamics

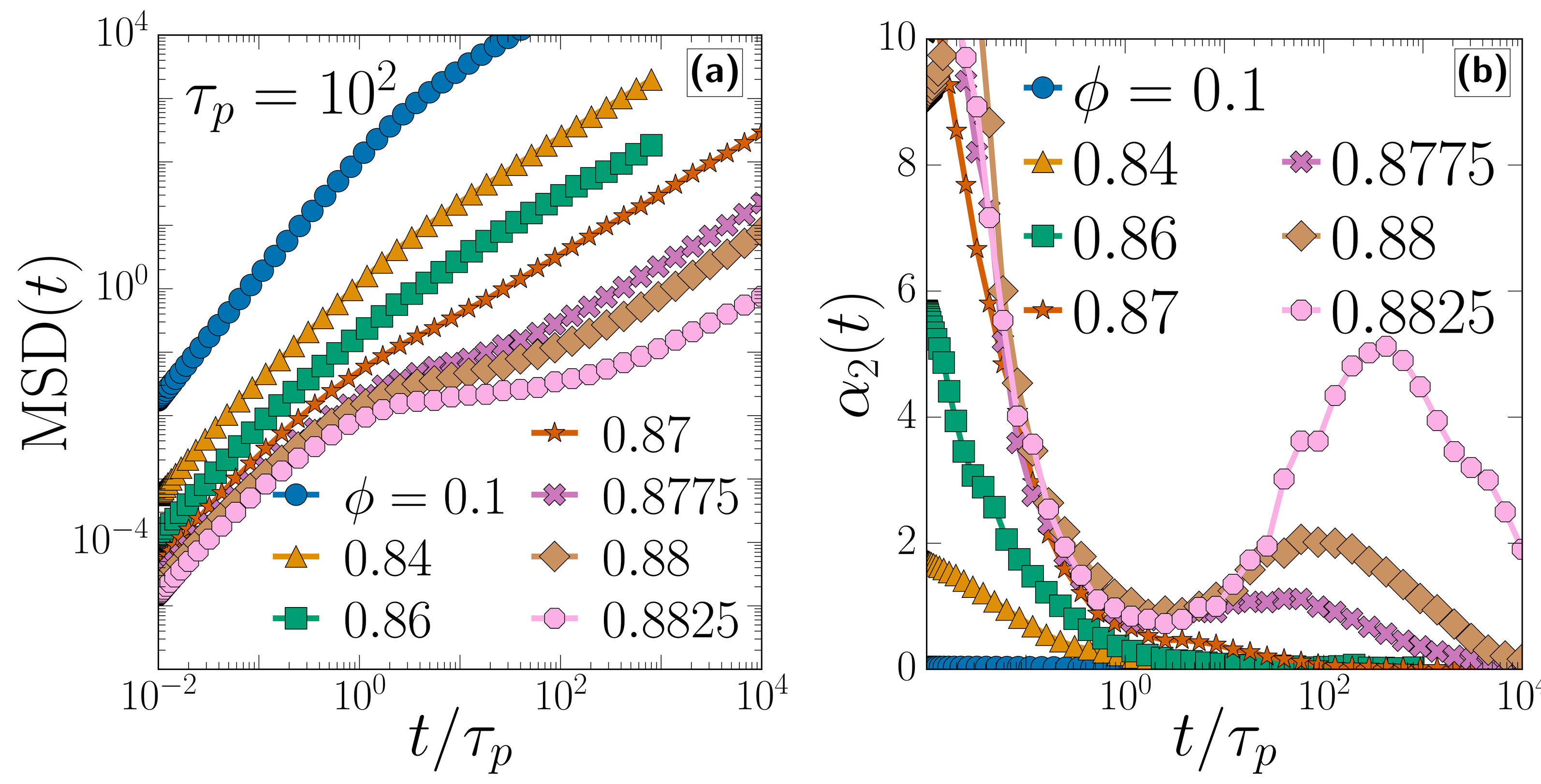

Fig. 3: **(a)** Mean squared displacement. **(b)** Non-Gaussian parameter of displacement distribution $\alpha_2(t) = \left(\langle|\boldsymbol{r}_i(t) - \boldsymbol{r}_i(0)|^4\rangle / \langle|\boldsymbol{r}_i(t) - \boldsymbol{r}_i(0)|^2\rangle^2\right)/2 - 1$.

- **Separation of time scales** between initial liquid-like ballistic motion ($t \lesssim \tau_p$) and later relaxation ($t \gg \tau_p$).
- Relaxation dynamics is increasingly **heterogeneous** with increasing ϕ.
- At large τ_p and ϕ there is quasi-**force-balance** ($\boldsymbol{v} \to 0$)

$$0 = -\nabla_i\left(U - \textstyle\sum_j \boldsymbol{p}_j\cdot\boldsymbol{r}_j\right) = -\nabla_i U_{\text{eff}} \qquad (3)$$

and dynamics is **intermittent**. System sits at a minimum of U_{eff}, and rearranges once this minimum is destabilised when $\boldsymbol{p}_i$ evolve.

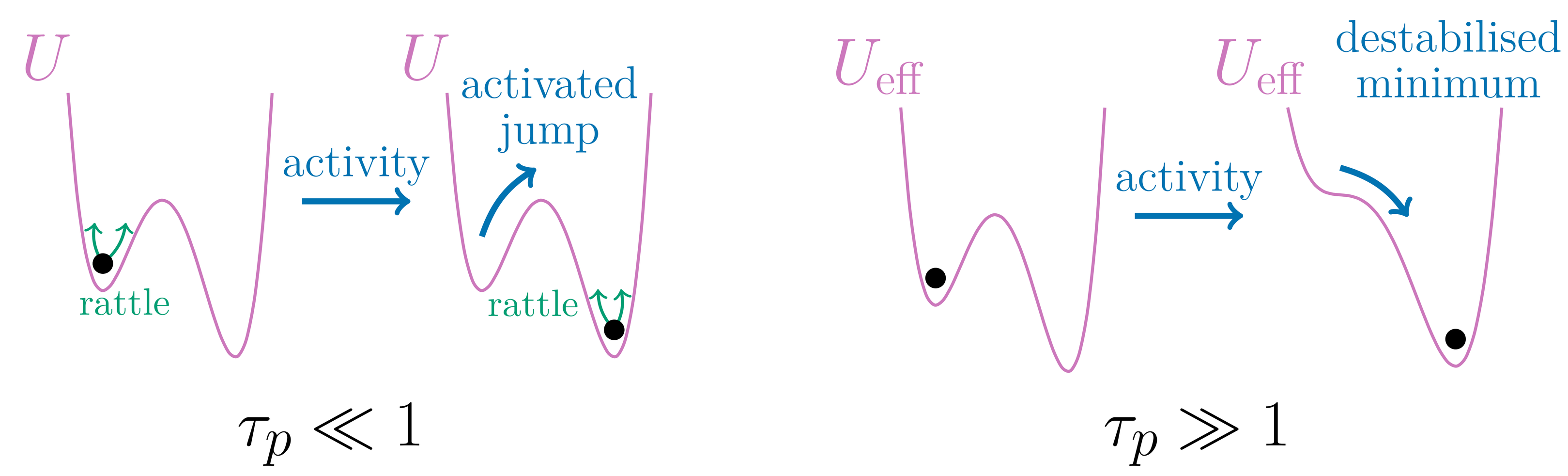

Fig. 4: Schematics of rare activation events over energy barriers ($\tau_p \ll 1$) and activity-driven plastic events ($\tau_p \gg 1$).

Conclusion

- Persistent motion and repulsive interactions lead to **velocity correlations**.
- Close to MIPS, activity overcomes crowding, with **correlated chaotic flow** on the time scale of τ_p.
- Close to dynamical arrest, dynamics is **intermittent** and **heterogeneous**.

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