ORIENTATIONAL ORDER AND CLUSTERING CHARACTERIZATION OF INTERACTING SPHERICAL MICROSWIMMERS.

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ABSTRACT

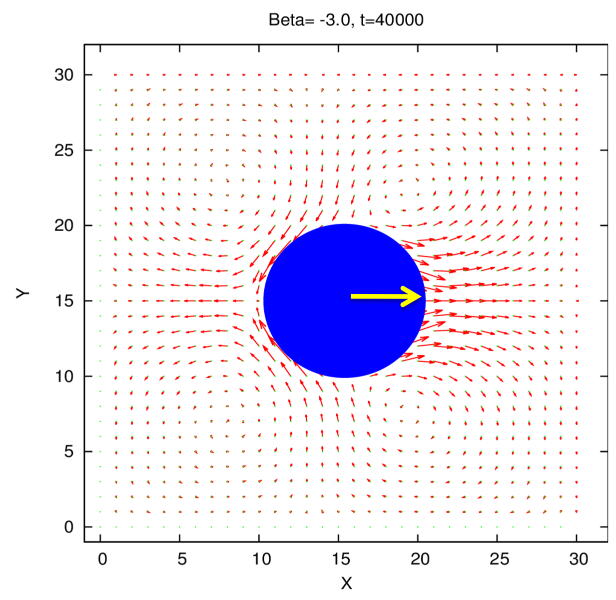
We study systematically the collective motion that emerge from suspensions of interacting squirmers, a model swimmer at low Reynolds numbers. We will analyse the interplay between the direct interaction strength among squirmers and their hydrodynamic coupling. This analysis will allow us to predict in which range either swimming or direct squirmer interaction are dominant and the characteristic patterns they give rise to. We will describe how the competition between direct interaction and hydrodynamic coupling tune the self assembly abilities of active suspensions and identify a new regime of giant fluctuations.

INTRODUCTION & MOTIVATION

Collective motion is one of the most common and spectacular manifestation of coordinated behaviour [1]. Suspensions of self-driven micro-organisms are an example of these kind of systems, refereed to generically active matter. These systems are out of equilibrium, thus to analyze their behavior it is not an easy task. Previous studies have addressed the analysis of coordinated behaviour using a variety of temporal dependent parameters, such as orientational [2] and nematic order parameters, temporal density fluctuations [3], mean cluster distance [4], mean square displacements [5] or even static parameters like pair correlation functions, or probability density functions.

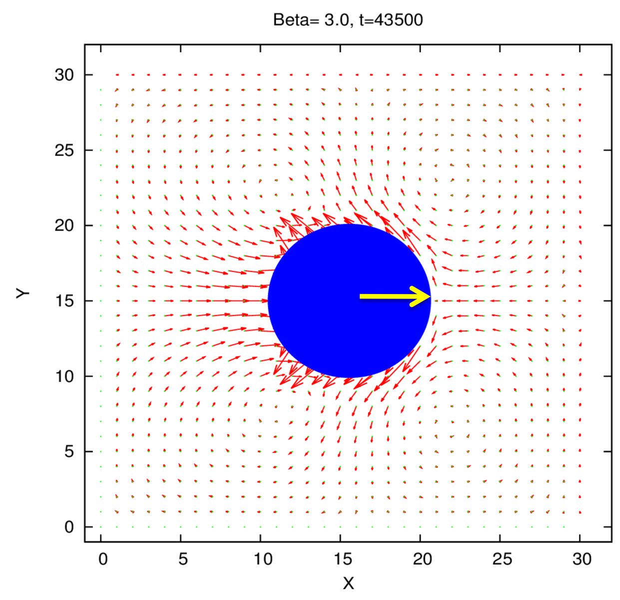
SQUIRMER MODEL

$$\mathbf{U}_p(\tilde{\mathbf{r}},\mathbf{e}) = -\frac{1}{3}\frac{a^3}{\tilde{r}^3}B_1\mathbf{e} + B_1\frac{a^3}{\tilde{r}^3}\mathbf{e}\cdot\hat{\tilde{r}}\hat{\tilde{r}} - \frac{a^2}{\tilde{r}^2}B_2P_2\left(\mathbf{e}\cdot\hat{\tilde{r}}\right)\hat{\tilde{r}}.$$

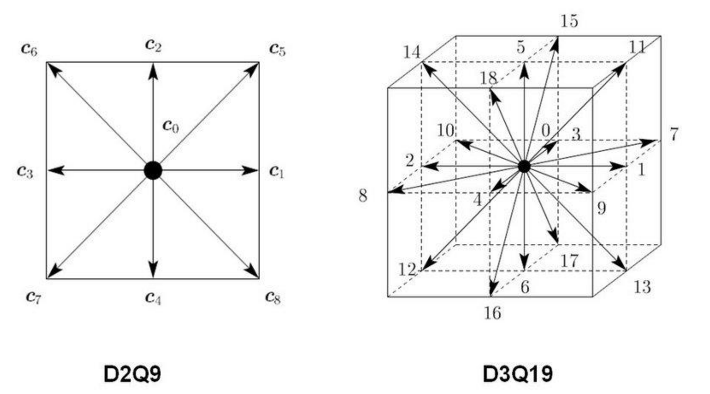


$$\beta = \frac{B_2}{B_1}$$

$$v_s = \frac{2}{3}B_1$$



NUMERICAL SIMULATION MODEL

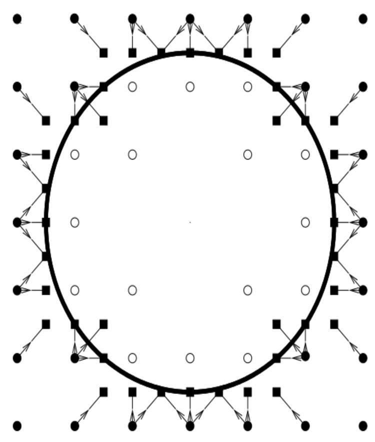


Lattice Boltzmann (LB) kinetic model: lattice-based model that simulates the **hydrodynamics** of a liquid and shows excellent scalability on parallel computers. LB is useful in analyzing the hydrodynamics of complex fluids and to deal with **suspensions of colloidal particles**.

The main fluid quantities are obtained by simple (linear) summation upon the **discrete velocities.**

$$f_i\left(\vec{r}+\vec{c}_i\Delta t, t+\Delta t\right) = f_i\left(\vec{r};t\right) + \Omega_{ij}\left(f_j^{eq}\left(\vec{r};t\right) - f_j\left(\vec{r};t\right)\right)$$

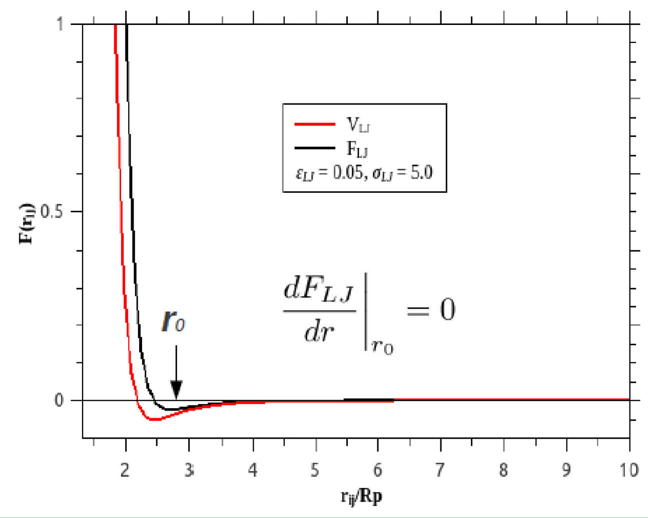
Discretized analog of the Boltzmann equation (BE)



Boundary nodes for a curved surface. The velocities along links are cutting the boundary surface are indicated by arrows. The location of the boundary nodes are shown by solid squares, and fluid nodes by solid circles. The open circles indicate nodes in the solid adjacent to fluid nodes.

$$\mathbf{u}_b = \mathbf{U} + \boldsymbol{\Omega}\times(\mathbf{r}_b - \mathbf{R}),\ \mathbf{r}_b = \mathbf{r} + \tfrac{1}{2}h\mathbf{c}_b$$

INTERACTION STRENGTH



$$V_{LJ}(r) = 4\epsilon_{LJ}\left[\left(\frac{\sigma_{LJ}}{r}\right)^{12} - \left(\frac{\sigma_{LJ}}{r}\right)^6\right]$$

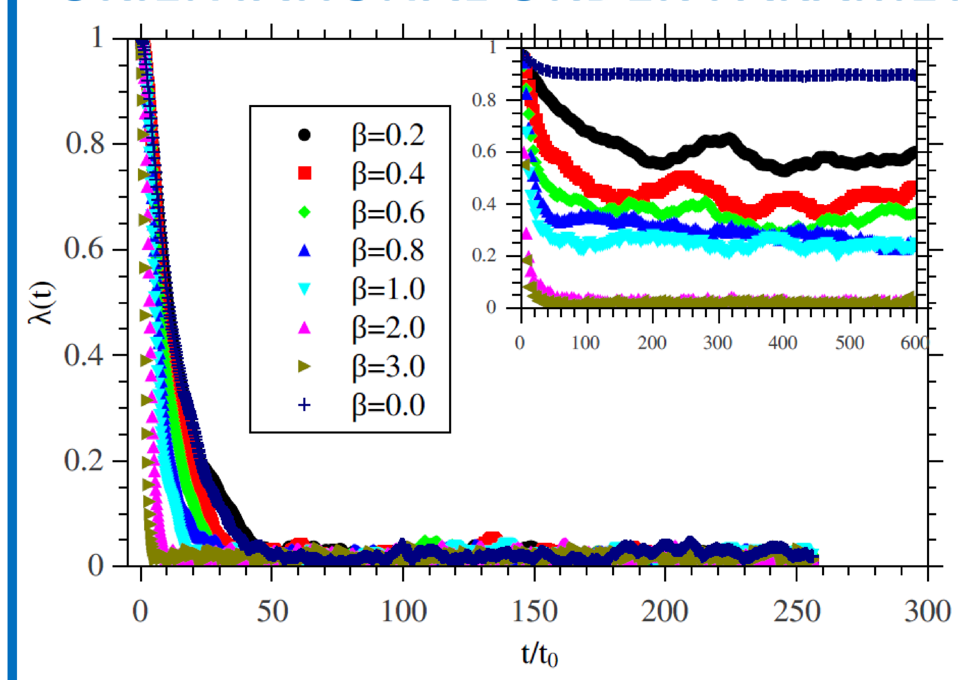
$$\left|F_{LJ}(r_0)\right| \sim 2.4\frac{\epsilon_{LJ}}{\sigma_{LJ}}$$

$$F_d = 6\pi\eta R_p v_s$$

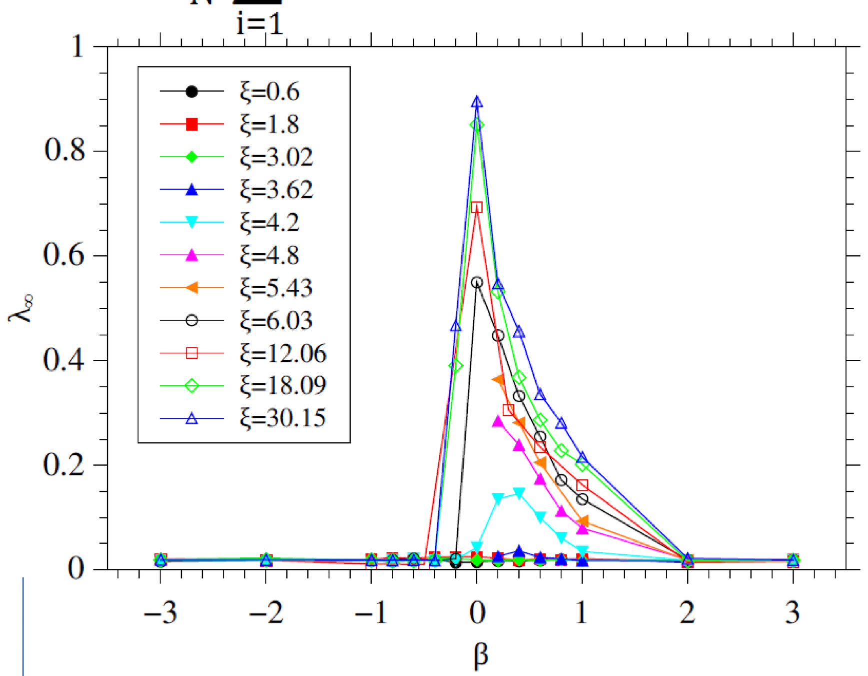
$$\xi = \frac{F_d}{|F_{LJ}(r=r_0)|}$$

ORIENTATIONAL ORDER PARAMETER

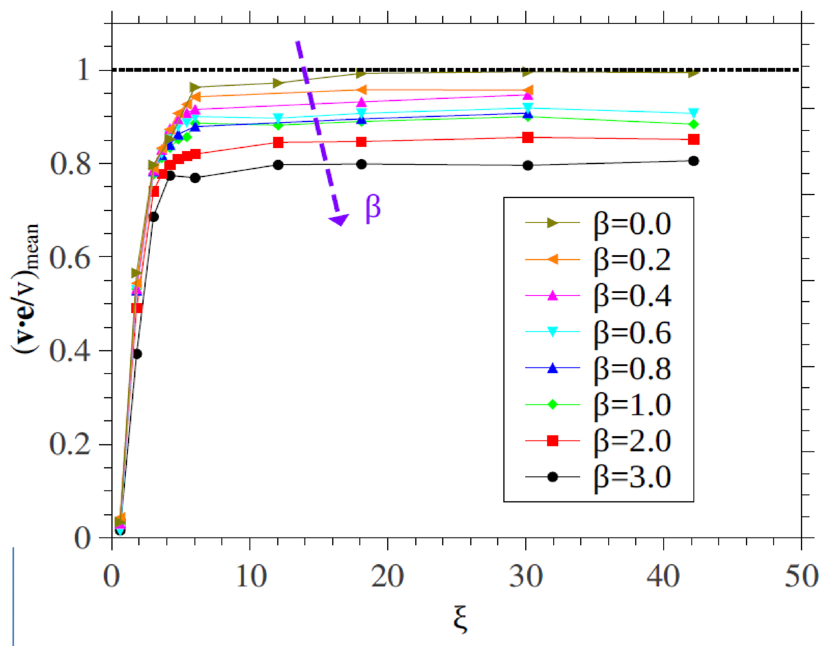
$$A_{mn} = \frac{1}{N}\sum_{i=1}^{N} e_{mi}\cdot e_{ni} \qquad \det(\mathbf{A}-\lambda I) = 0$$



Orientational order parameter $\lambda(t)$ for puller suspensions with different values of β with an interaction strength of ξ = 1.8. Inset: Same $\lambda(t)$ but ξ = 30.15 for the same values of β. For all system with ξ =1.8 it relaxes to an isotropic state, independently of hydrodynamic signature of the squirmers while ξ = 30.15 systems relax to either aligned or isotropic state depending on β.

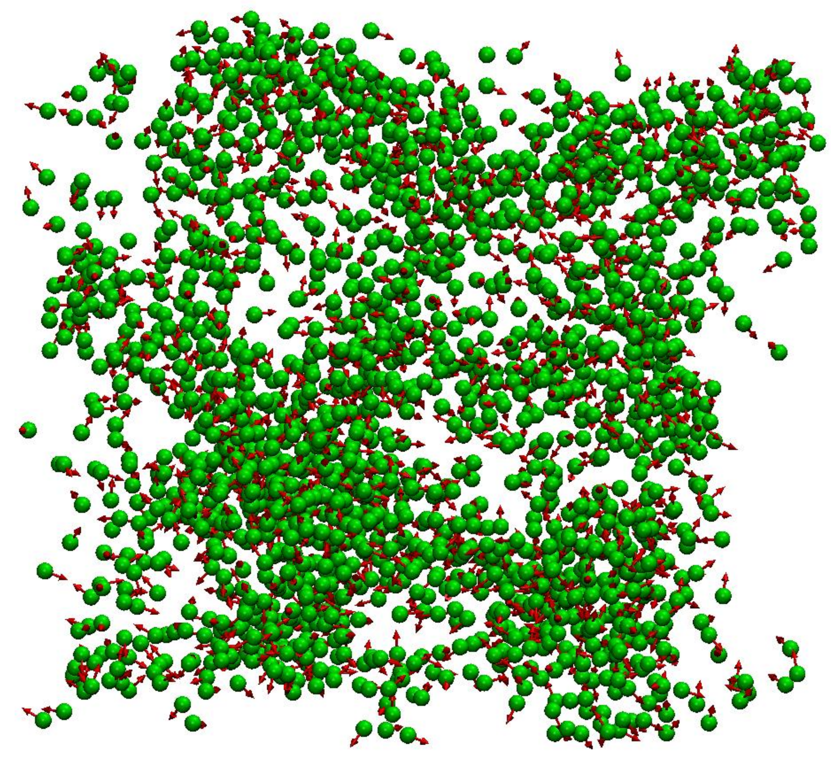


Long-time orientational order parameter λ_∞ for different values of interaction strength and hydrodynamic parameter β. We can see , that aligned suspensions are missed when LJ potential stronger than hydrodynamics interactions.

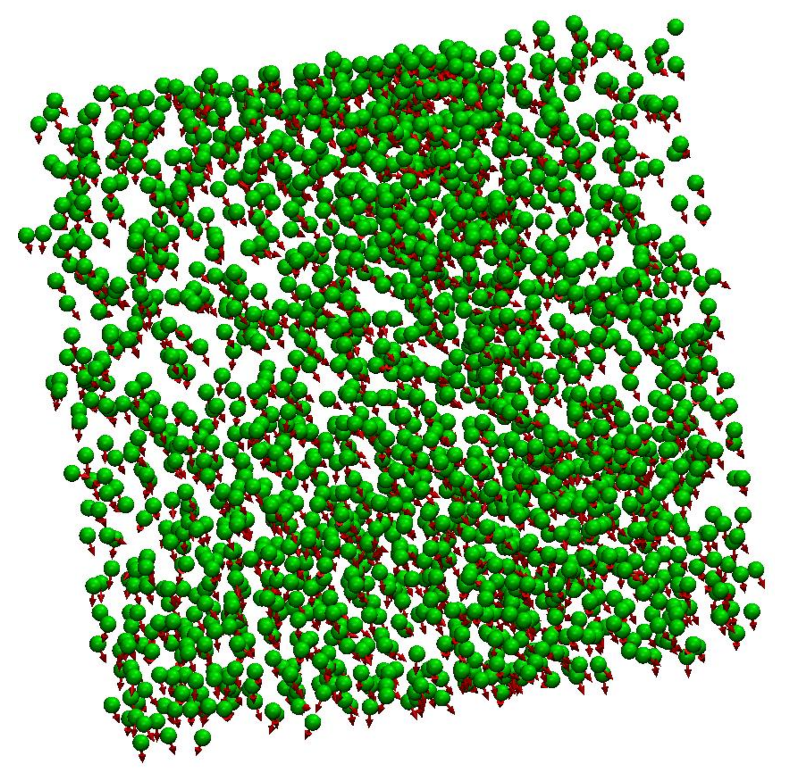


We show $(\mathbf{v}\cdot\mathbf{e}/|\mathbf{v}|)_{mean}$ taking in count all the particles in the suspension depending on the interactions strength. The global coherence in the movement is present when system relax to an aligned state.

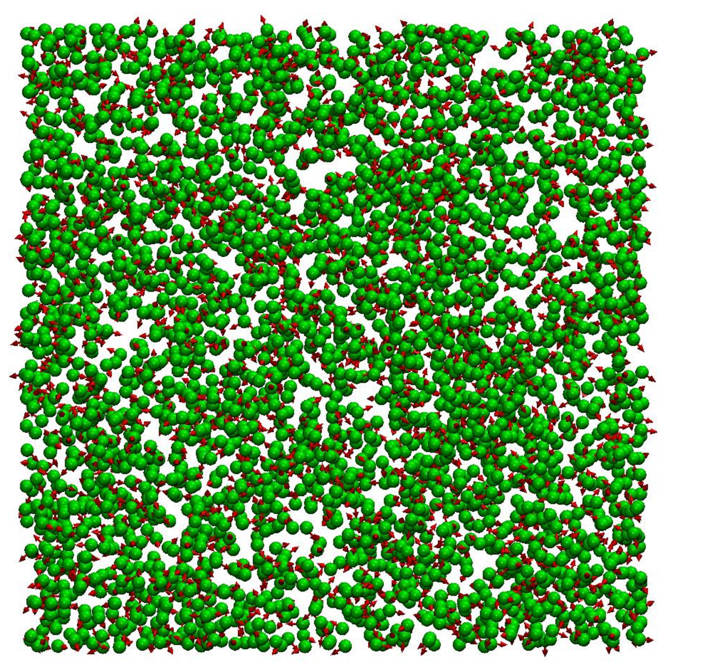
SNAPSHOTS



ξ = 1.8, β =0.2

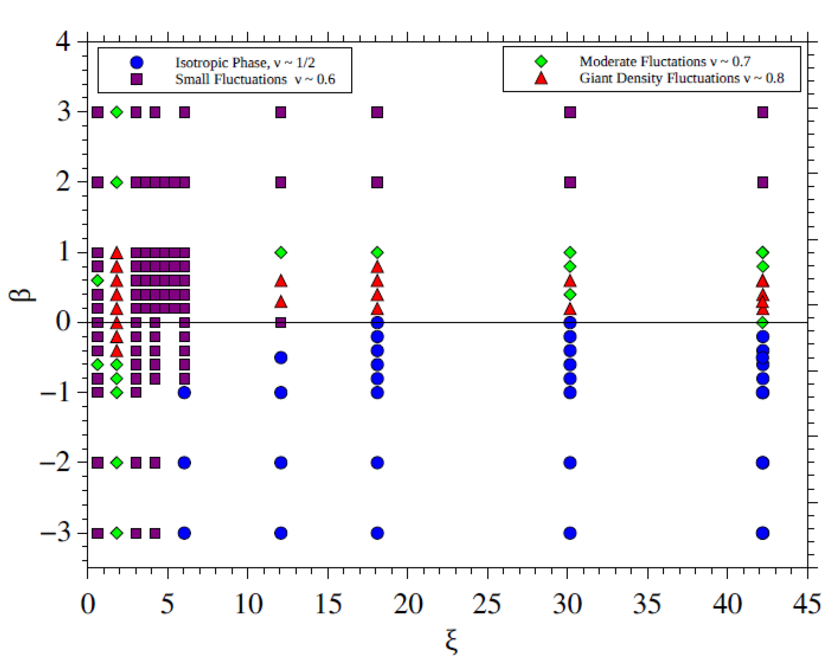


ξ = 42.17, β =0.3

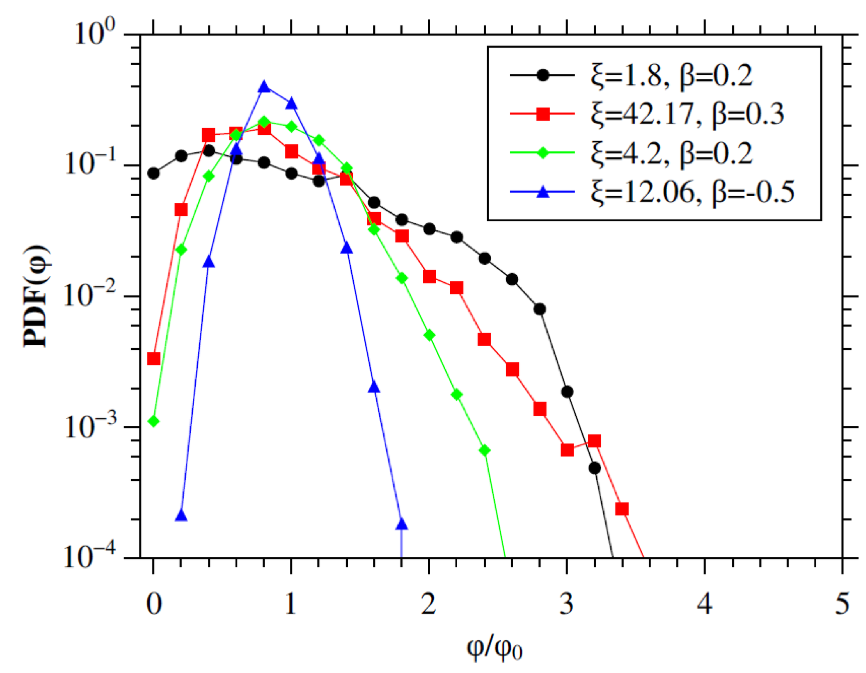


ξ = 12.06, β =-0.5

GLOBAL CLUSTERING CHARACTERIZATION

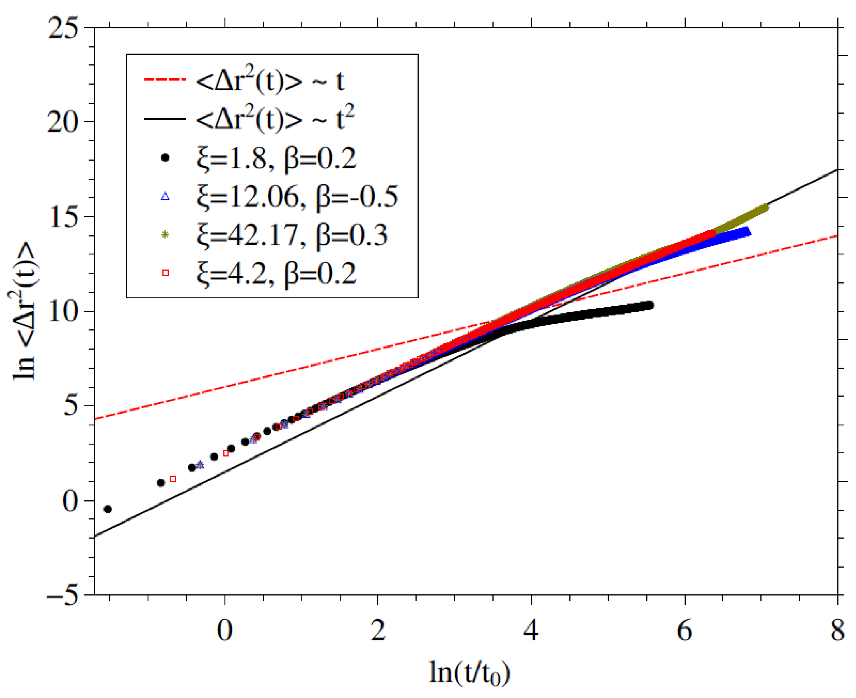


Phase diagram in terms of the scaling exponent of the fluctuation on the density. ΔN ~ N^v



Distribution function of the local volume fraction. A spread distribution is found when giant density fluctuations (GDF) are present. While isotropic phase has a narrow distribution.

MSD



Mean square displacement in representative cases. Pullers with high ξ evolve to ballistic regime, while low ξ goes to diffusive regime.

IMPORTANT REMARKS

- LJ helps to cohesion of the squirmers, but the orientational coherence is reduced.
- Alignment of squirmer suspensions is tuned by the interaction strength. Higher LJ lower alignment.
- Alignment and agglomeration in squirmers gives a slower suspension, even with high activity (ξ >> 1).
- New states of GDF emerge with LJ (ξ=1.8). Dynamic Clusters also, but without coherence in its movement.
- Ballistic motion is presented in aligned states, while isotropic squirmer suspensions have a diffusive regime.

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