Boids Model Applied to Cell Segregation

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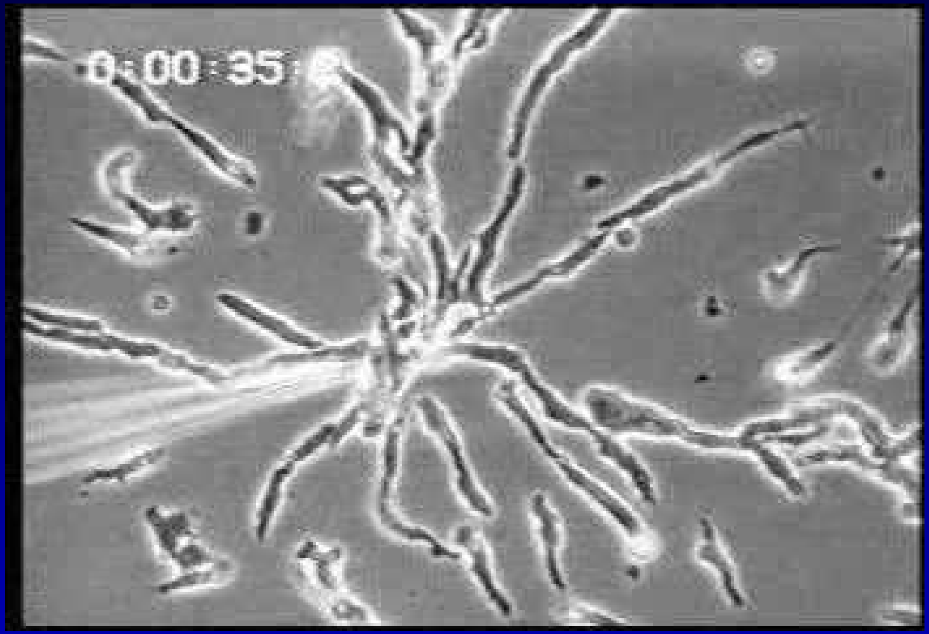
Motivation - General 1

- What is the advantage of being part of a community? What is the relevant information exchanged? What is the role of space in collective behavior?
- Why did it take so long for nature to start with multicellular systems?
- Bacteria produce shapes of snow flakes, vortices and spirals due to chemiotaxis.

Motivation - General 2

- Dictyostelium Discoideum under starvation form clusters following cAMP gradients.



- D. discoideum amoebae towards a point source of the chemoattractant cAMP.

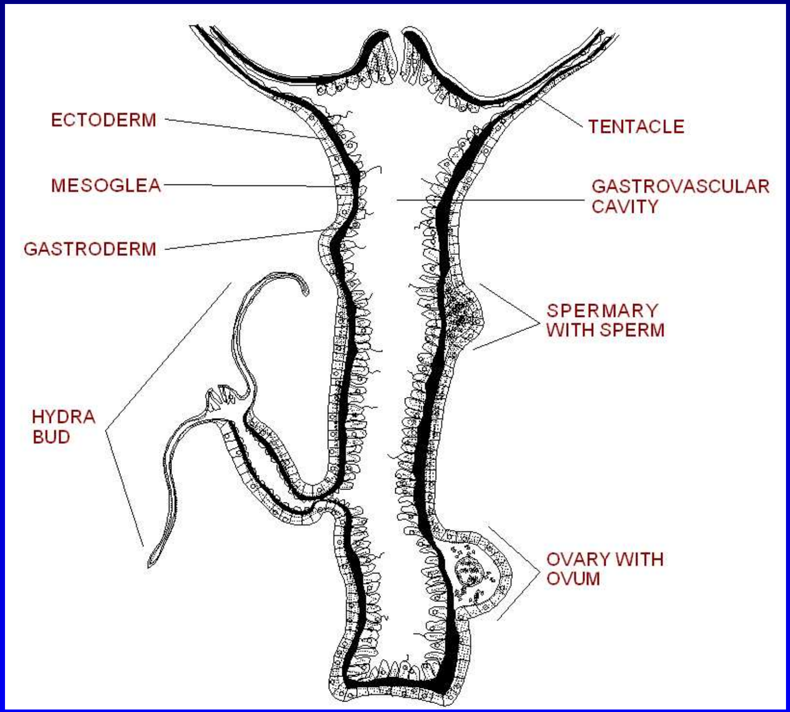
From G. Gerisch, Max-Planck-Institut fur Biochemie.

- (film ax320x.mov - From R. Firtel, University of California, San Diego)

Motivation - Focus

- Hydras: Two different kinds of tissues, external and internal.
- Differential adhesiveness and regeneration.
- Segregation during regeneration

Burst-2.mpg - film from R. Almeida et all., UFRGS, Brazil.



Boids I

- Collective motion without a leader (T. Vicsek, 1995).
- Defining fixed local rules among individuals may produce emergent non-trivial collective behavior, despite of the local noise.

$$\theta_i^{t+1} = arg \sum_{j \ i} \vec{v}_j + \eta \xi_i^t$$

$$\xi_i^t \in [-\pi, \pi] \ , \quad \eta \in [0, 1]$$

Boids II

- Once the velocity direction is defined all positions are updated in that direction *with a unitary step*.

$$\vec{x}_i^{t+1} = \vec{v}_i^{t+1} \Delta t + x_i^t$$

$$|\vec{v}_i| = v_0 = cte$$

- Self-propelling objects, non-equilibrium, no energy conservation.

Vicsek's results - I

- Transition ordered flight to random flight.
- Order parameter: Average velocity over the population.

$$\phi = \frac{|\langle \vec{v} \rangle|}{v_0}$$

Vicsek's results - II

T Vicsek et all., PRL **75** (1995) 1226.

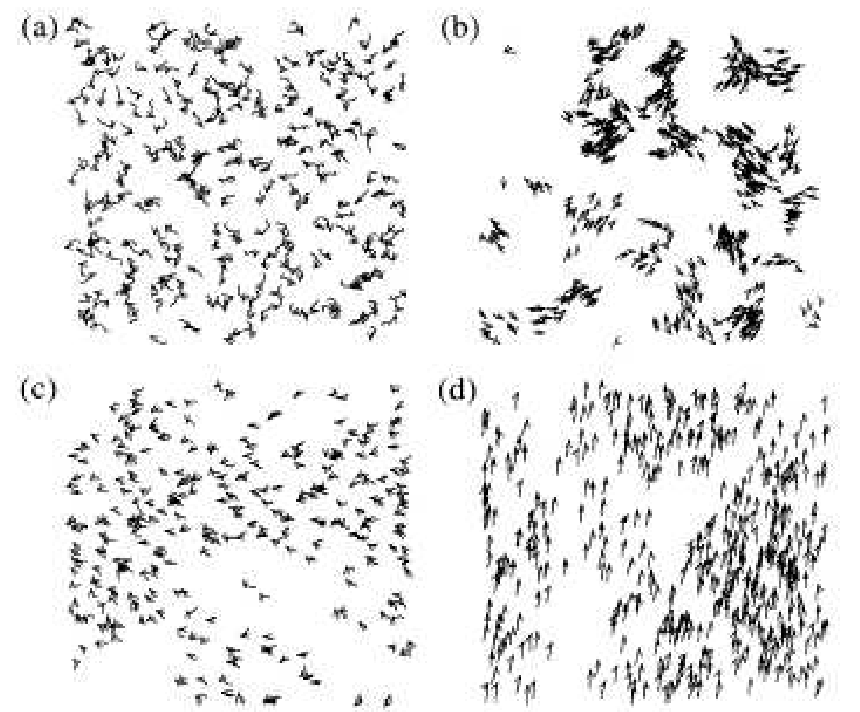
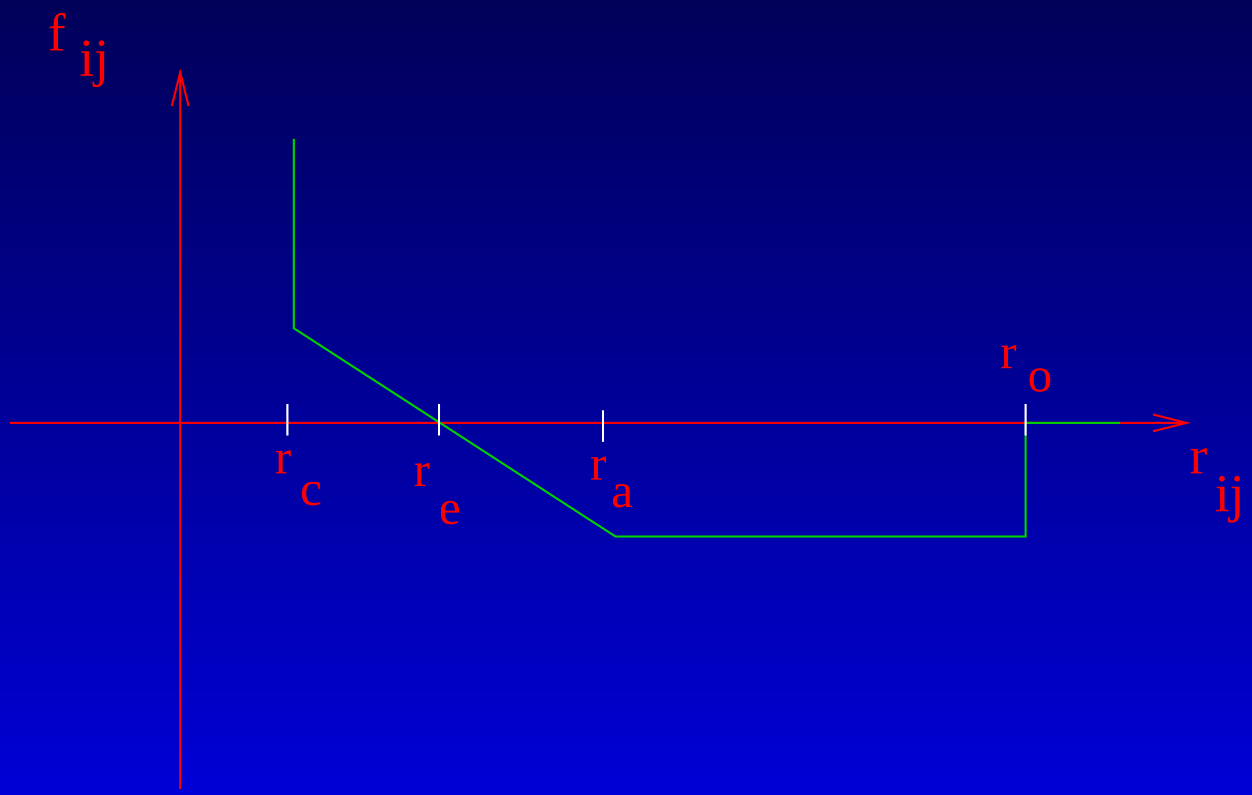


FIG. 1. In this figure the velocities of the particles are displayed for varying values of the density and the noise. The actual velocity of a particle is indicated by a small arrow, while their trajectory for the last 20 time steps is shown by a short continuous curve. The number of particles is $N = 300$ in each case. (a) $t = 0$, $L = 7$, $\eta = 2.0$. (b) For small densities and noise the particles tend to form groups moving coherently in random directions, here $L = 25$, $\eta = 0.1$. (c) After some time at higher densities and noise ($L = 7$, $\eta = 2.0$) the particles move randomly with some correlation. (d) For higher density and *small noise* ($L = 5$, $\eta = 0.1$) the motion becomes ordered. All of our results shown in Figs. 1–3 were obtained from simulations in which v was set to be equal to 0.03.

Vicsek's Model Generalization

$$\theta_i^{t+1} = arg(\alpha \sum_{j \sim i} \vec{v}_j + \beta \sum_{j \sim i} \vec{f}_{i,j} + \mathcal{N}_i \eta \vec{u}_i)$$



G. Gregoire, H. Chaté and Yuhai Tu, Physica D 181 (2003) 157.

Gregoire-Chaté-Tu results - I

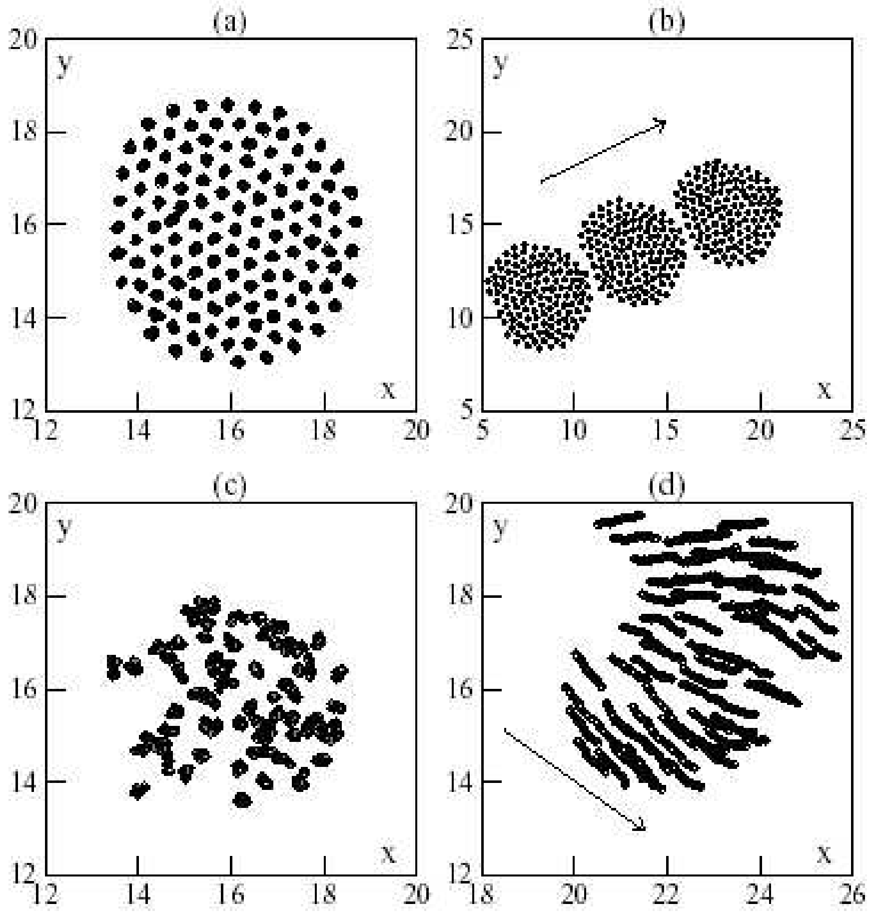


Figure 1. Cohesive flocks of 128 particles in a square box of linear size 32 with periodic boundary conditions (for parameters see Table I). (a): immobile "solid" at $\alpha = 1.0$ and $\beta = 100.0$ (20 timesteps superimposed). (b): 3 snapshots, separated by 120 timesteps, of a "flying crystal" at $\alpha = 3.0$ and $\beta = 100.0$. (c): fluid droplet ($\alpha = 1.0$, $\beta = 2.0$, 20 consecutive timesteps). (d): moving droplet ($\alpha = 3.0$, $\beta = 3.0$, 20 consecutive timesteps). In (b) and (d), the arrow indicates the (instantaneous) direction of motion.

Gregoire-Chaté-Tu results - II

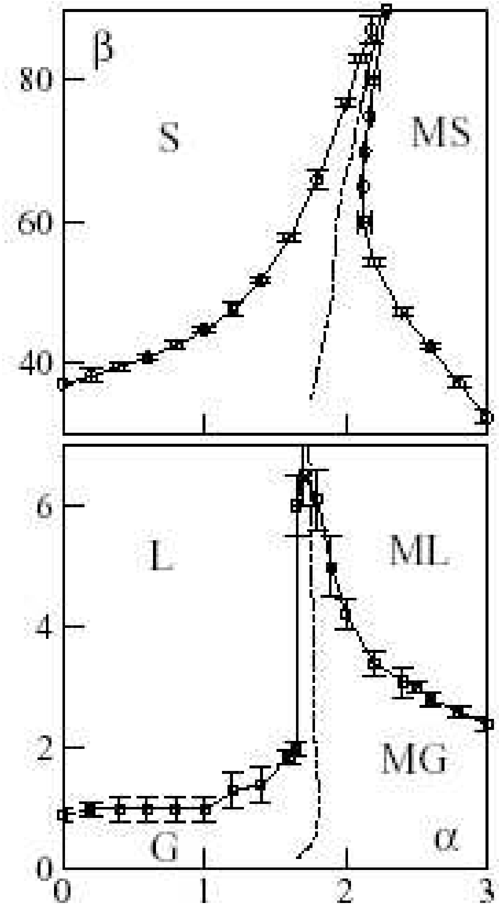
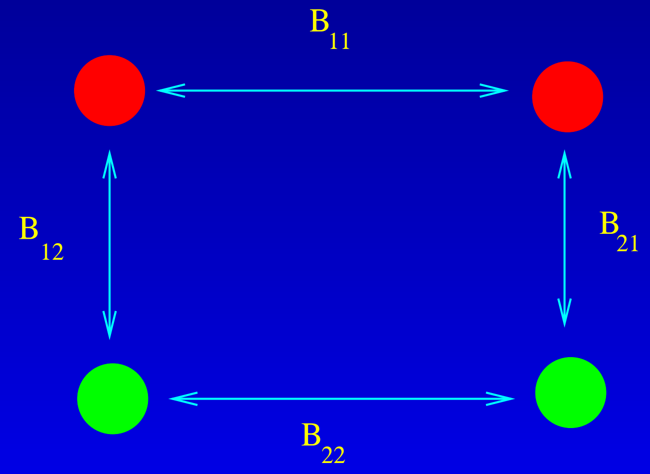


Figure 7. Phase diagram at $\rho = 1/16$, $L = 180$ (other parameters as in Table 1). S : solid, MS : moving solid, L : liquid, ML : moving liquid, G : gas, MG : moving gas. Dashed line : transition line of collective motion.

Cell segregation using boids

- Two kinds of boids, 1 and 2, representing two different kinds of cells.
- Three different force parameters: $\beta_{11} > \beta_{12} = \beta_{21} > \beta_{22}$ and null inertial term $\alpha = 0$.
- Typical values: $\beta_{11} = 75$ (solid); $\beta_{12} = \beta_{21} = 40$ (solid-liquid); $\beta_{22} = 30$ (liquid).



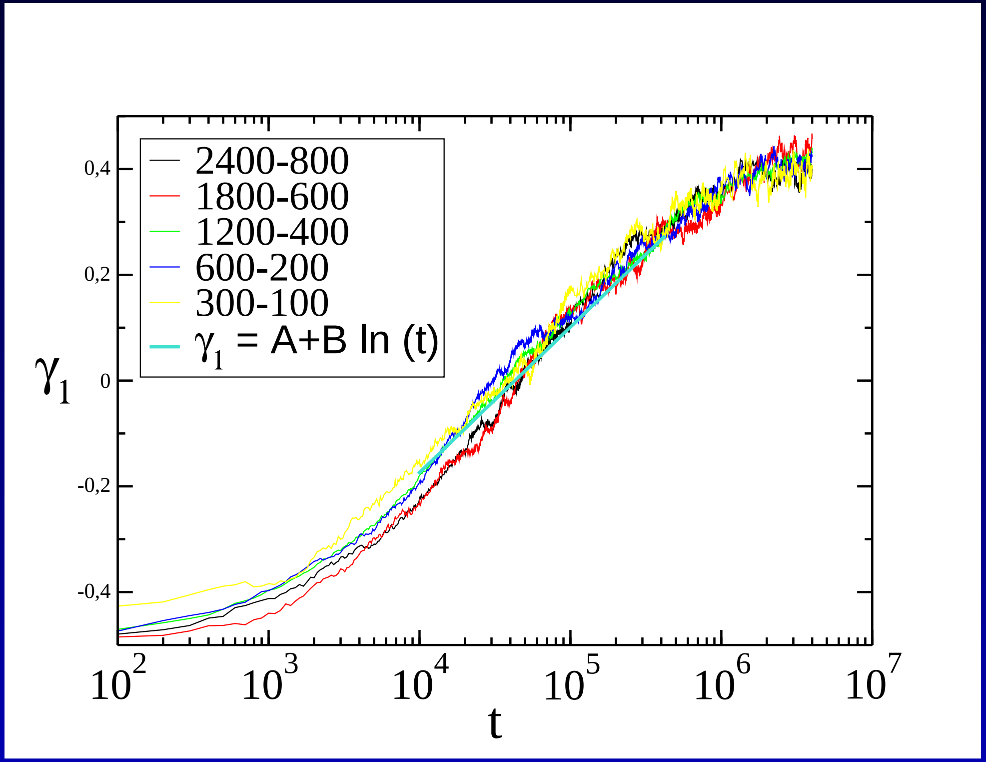
- (Film 400 boids)

Segregation Time Evolution

- Four different sample sizes (N) with $1/4$ of boids 1 and $3/4$ of boids 2: $N = 400, 800, 1600, 3200$.
- Measure of the average fraction of equal neighbors less the different ones.

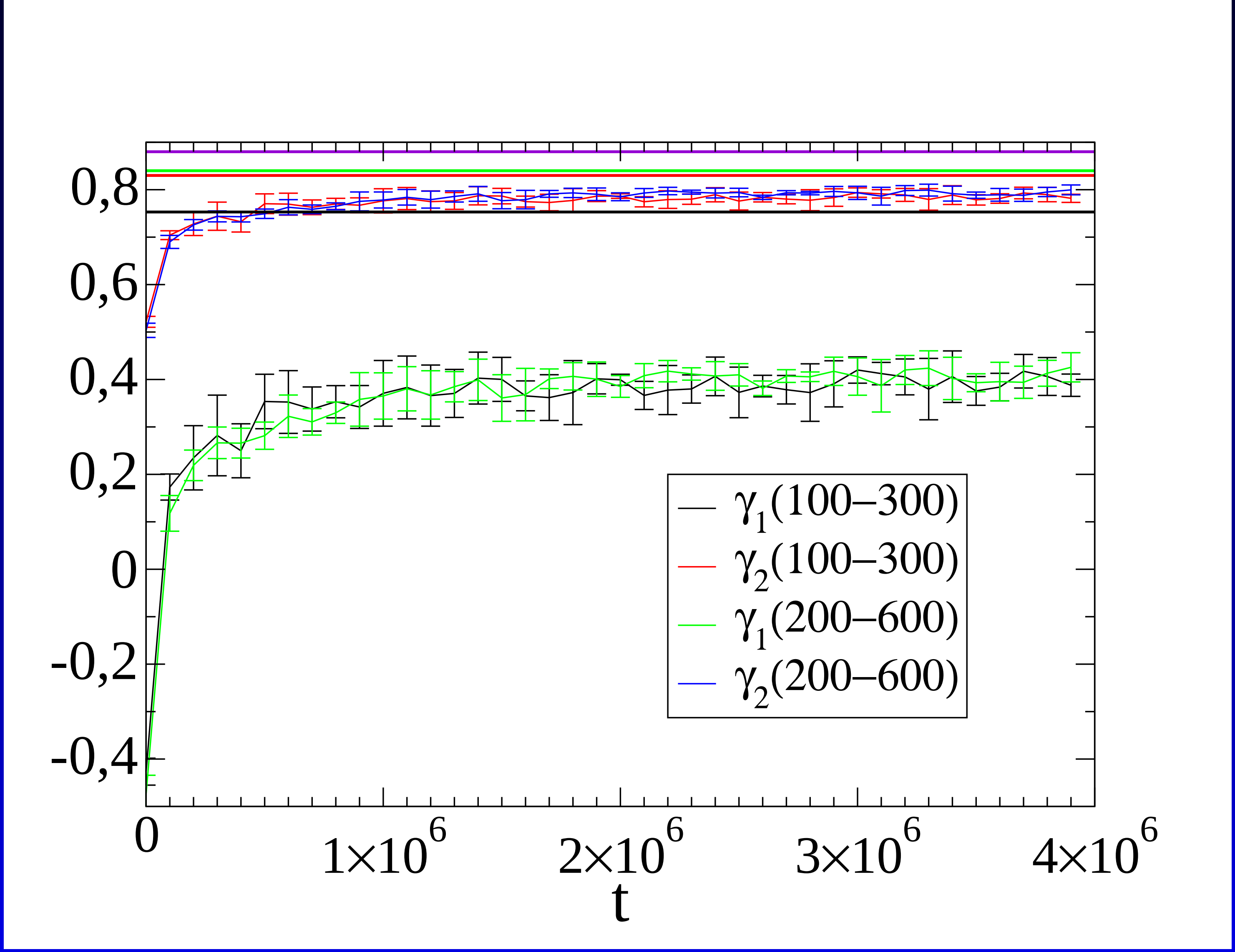
$$\gamma_{1,2} = \langle \frac{n_{eq} - n_{diff}}{n_{eq} + n_{diff}} \rangle$$

Time evolution

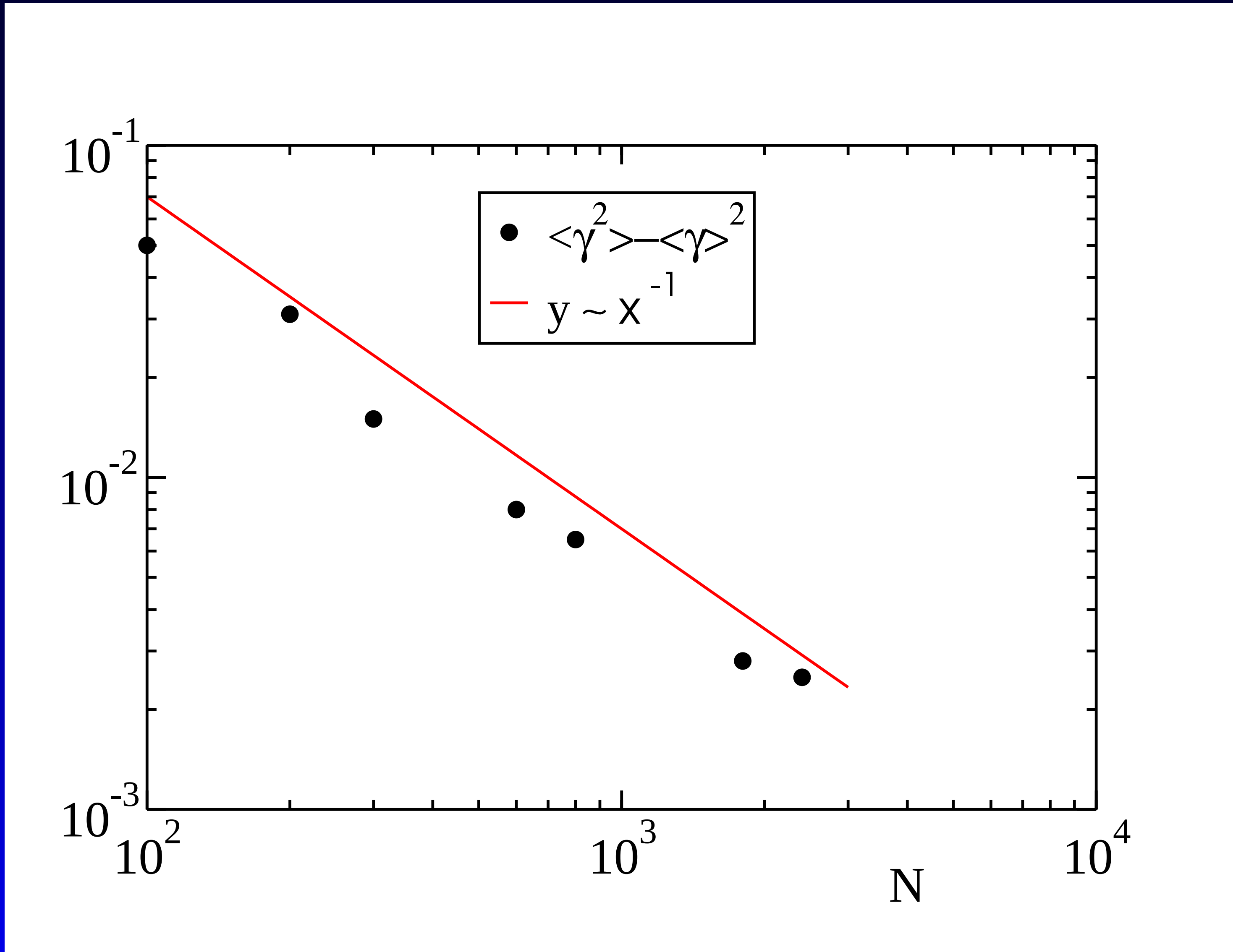


- Segregation saturates at the same value for different sample sizes.
- Before saturation, a log(t) can be fitted somewhere ;(.

Time evolution and fluctuations



Fluctuations and sample size



Conclusions

- There is segregation in a proper parameter range. (Not if all boids are in the liquid phase!)
- During the growing time segregation seems to follow $log(t)$ but ....
- Saturation at large t is independent of the sample size.
- Saturation happens well below the ideal value for zero noise.
- Fluctuations (of γ) scale with the inverse of the system size.
- Boids do have a path $\longrightarrow$ dynamical quantities.
- No pinning effect, no problems during collisions.