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## FIELD-CONTROLLED SELF-ORGANIZATION IN AN ACTIVE SPIN SYSTEM

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## Fish schools



Becco et al., Physica A (2006)

## Bird flocks



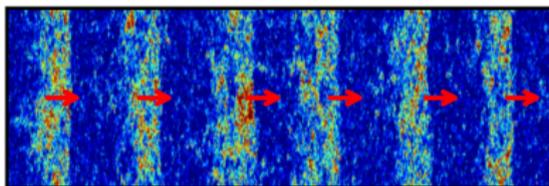
Ballerini et al., PNAS (2008)

- ▶ Collective motion: out-of-equilibrium phenomenon with internal energy consumption to self-propel.
- ▶ Flocking transition: spontaneous emergence of synchronized motion of large clusters (large densities, low noise).
- ▶ First theoretical model: the Vicsek model (1995), where particles follow the ferromagnetic alignment:

$$\theta_i(t+1) = \langle \theta(t) \rangle_r + \eta \xi_i(t)$$

$$\mathbf{x}_i(t+1) = \mathbf{x}_i(t) + v \mathbf{e}_i(t+1)$$

with  $\mathbf{e}_i(t+1)$  in the direction  $\theta_i(t+1)$ ,  $\xi_i(t)$  a white noise.



- ▶ Spontaneous breaking of the continuous symmetry, via a liquid-gas phase transition.

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

A. P. Solon et al., PRL **114**, 068101 (2015).

- ▶  $N$  particles in a periodic 2d lattice of size  $L_x \times L_y$ . Average density:  $\rho_0 = N/L_x L_y$ .
- ▶  $j^{\text{th}}$  particle on site  $i$  equipped with a spin  $\sigma_i^j \in \{1, 2, \dots, q\}$ .
- ▶ External field on site  $i$ : strength  $h_i = h$  and direction  $\alpha_i \in \{1, 2, \dots, q\}$ .
- ▶ Local Hamiltonian (Potts interaction) on site  $i$ :

$$\mathcal{H}_i = -\frac{J}{2\rho_i} \sum_{j=1}^{\rho_i} \sum_{k \neq j} \left( q \delta_{\sigma_i^j, \sigma_i^k} - 1 \right) - h_i \sum_{j=1}^{\rho_i} \left( q \delta_{\sigma_i^j, \alpha_i} - 1 \right),$$

- ▶ Flipping rate for  $\sigma \rightarrow \sigma'$ :

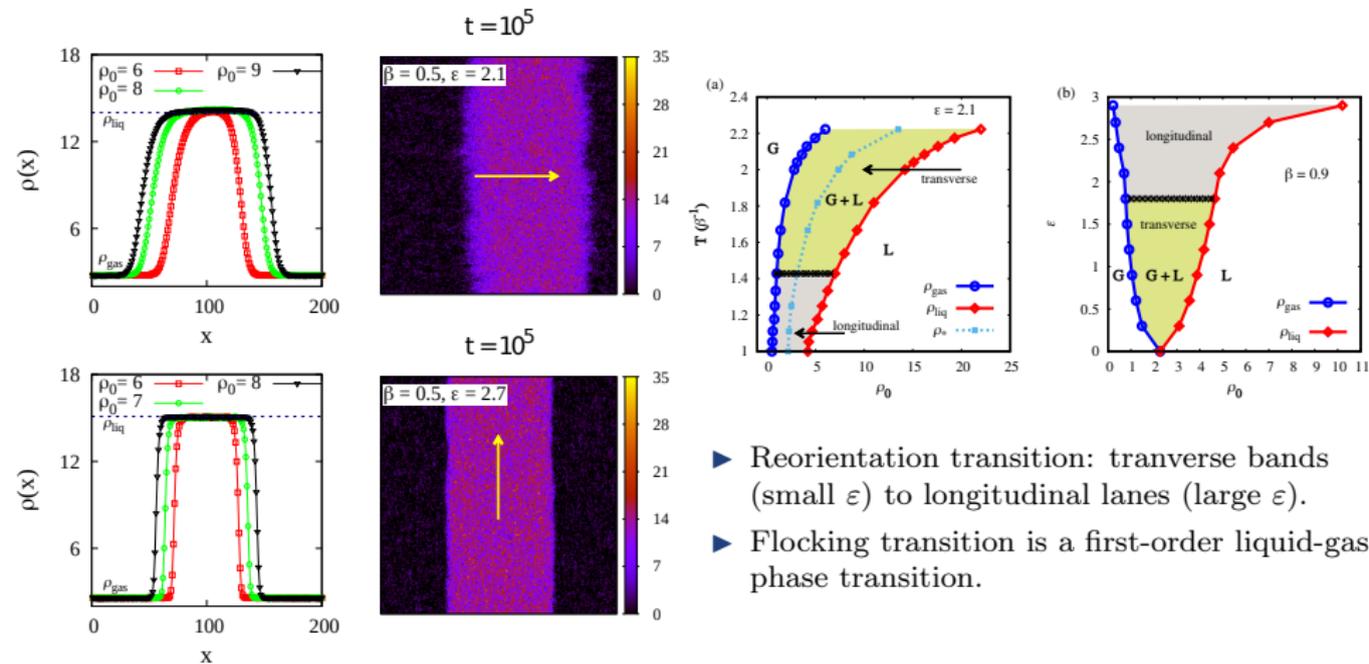
$$W_{\text{flip}} = \exp \left[ -\frac{q\beta J}{\rho_i} \left( n_i^\sigma - n_i^{\sigma'} - 1 \right) - q\beta h_i \left( \delta_{\sigma, \alpha_i} - \delta_{\sigma', \alpha_i} \right) \right],$$

where  $n_i^\sigma$  is the number of particles in state  $\sigma$  on site  $i$ .

- ▶ Nearest-neighbor biased hopping in  $p$  direction:

$$W_{\text{hop}}(\sigma) = \begin{cases} D(1 + \varepsilon) & p = \sigma \\ D[1 - \varepsilon/(q - 1)] & p \neq \sigma \end{cases}$$

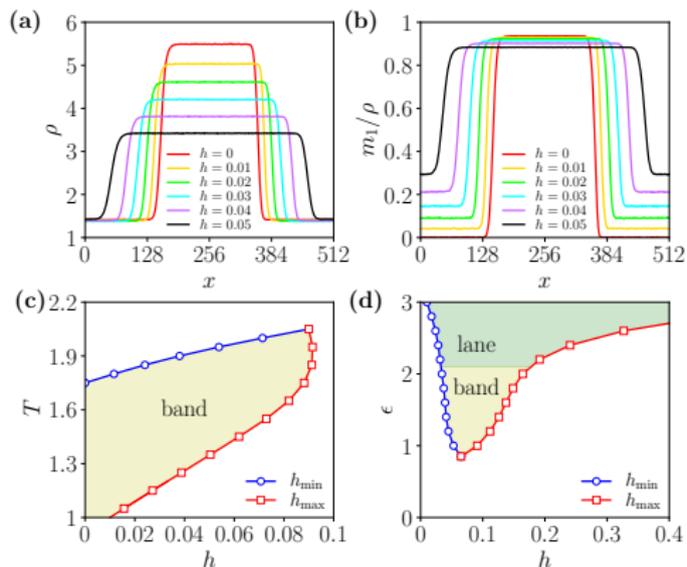
# Without the external field ( $h=0$ )



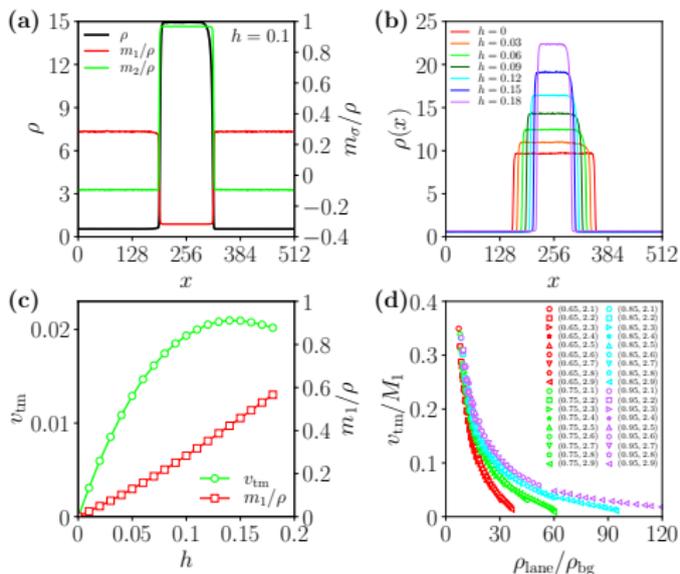
- ▶ Reorientation transition: transverse bands (small  $\epsilon$ ) to longitudinal lanes (large  $\epsilon$ ).
- ▶ Flocking transition is a first-order liquid-gas phase transition.

S. Chatterjee, M. Mangeat, R. Paul, and H. Rieger, EPL **130**, 66001 (2020)

M. Mangeat, S. Chatterjee, R. Paul, and H. Rieger, Phys. Rev. E **102**, 042601 (2020)

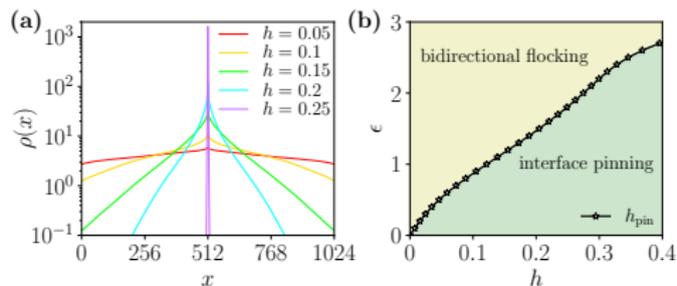


- ▶ Only polar phases for  $h > 0$  ( $m > 0$  and  $R^2(t) \sim t^2$ ).
- ▶ Phase separation between two polar phases both moving along the field.
- ▶ When  $h$  increases the band becomes wider.
- ▶ Reorientation transition present for  $h \geq 0$ .

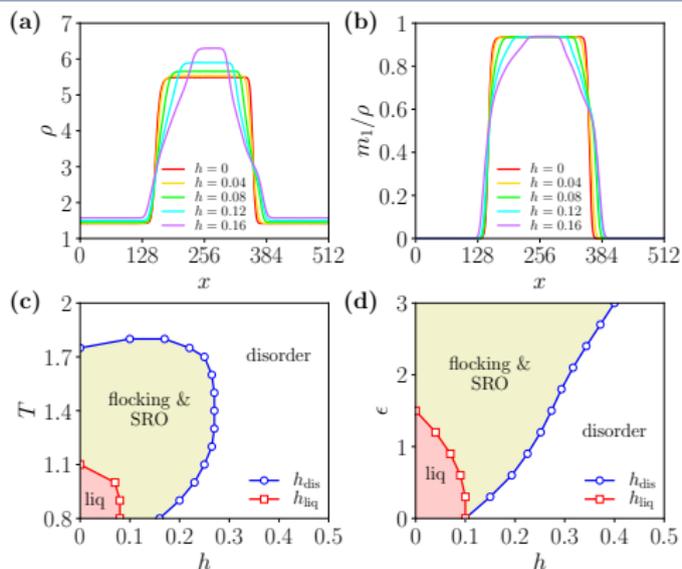


- ▶ Longitudinal lane, transverse to the field, treads against the field.
- ▶ When  $h$  increases the lane becomes denser.
- ▶ Treadmilling velocity:

$$v_{tm} \simeq \frac{m_1}{\rho_{bg}} \mathcal{F} \left( \frac{\rho_{lane}}{\rho_{bg}}, \beta \right).$$



- ▶  $\alpha_i = 1$  in the left,  $\alpha_i = 3$  in the right.
- ▶ For  $0 < h < h_{\text{pin}}$ , bidirectional flocking of state  $\sigma = 1$  and  $\sigma = 3$ .
- ▶ For  $h > h_{\text{pin}}$ , field-induced interface pinning.
- ▶ Particles are trapped at the interface executing a back-and-forth motion.



- ▶ Uniformly distributed  $\alpha_i \in \{1, 2, 3, 4\}$ .
- ▶ Destruction of the flocking into pinned regions (disordered state with  $R^2(t) \sim t$ ).
- ▶ When  $h$  increases the band becomes denser.
- ▶ In the disordered state  $\langle m \rangle \sim L^{-\xi}$ ,  $\xi < 1$  (consistent with Imry–Ma arguments).
- ▶ First-order signatures cancelled (consistent with Aizenman–Wehr theorem).

- ▶ Homogeneous field:
  - ▶ Phase separation between two polar phases both moving along the field.
  - ▶ Longitudinal lane, transverse to the field, treadmills against the field.
- ▶ Bidirectional field: field-induced interface pinning.
- ▶ Random orientational field: destruction of the flocking into pinned regions (disordered state), analogous to random field theories.

**Thank you for your attention !**