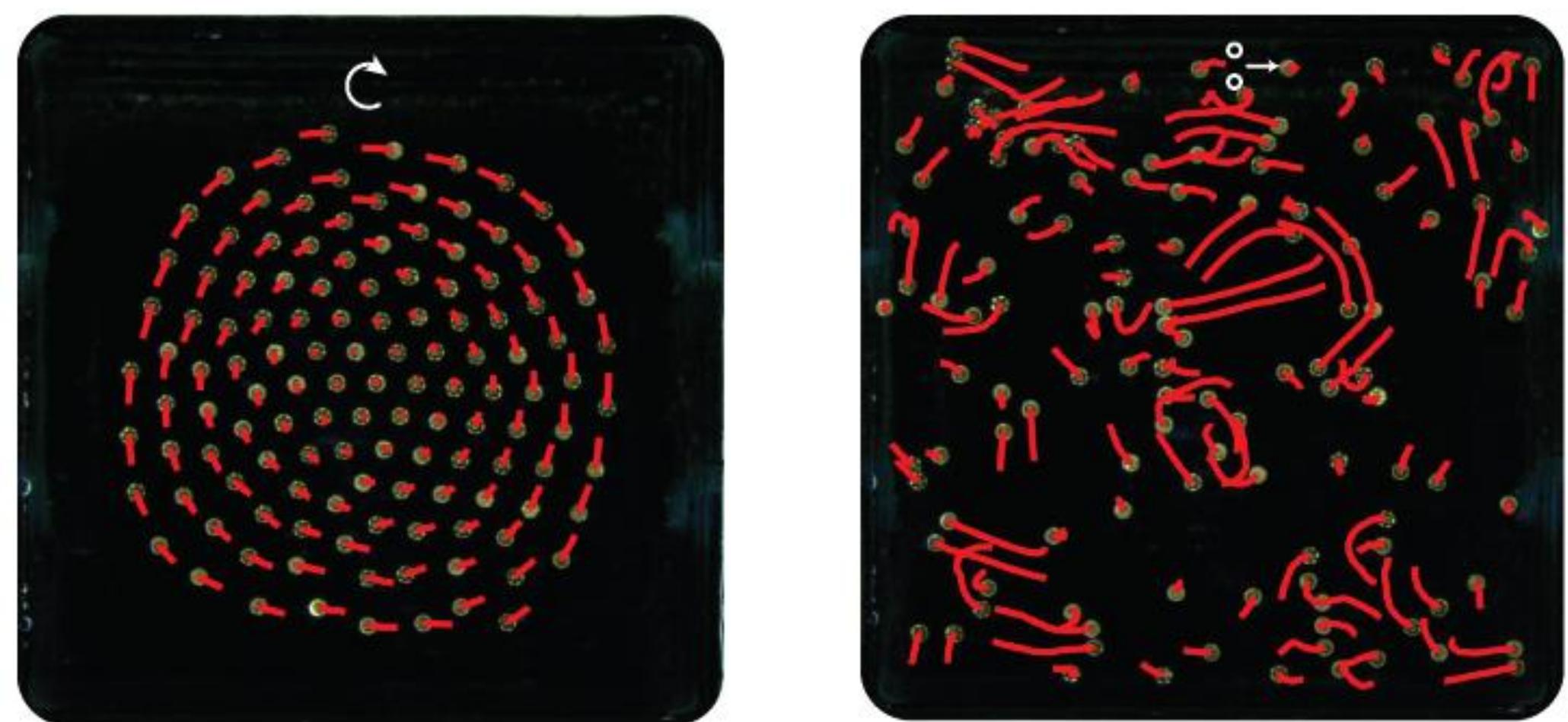


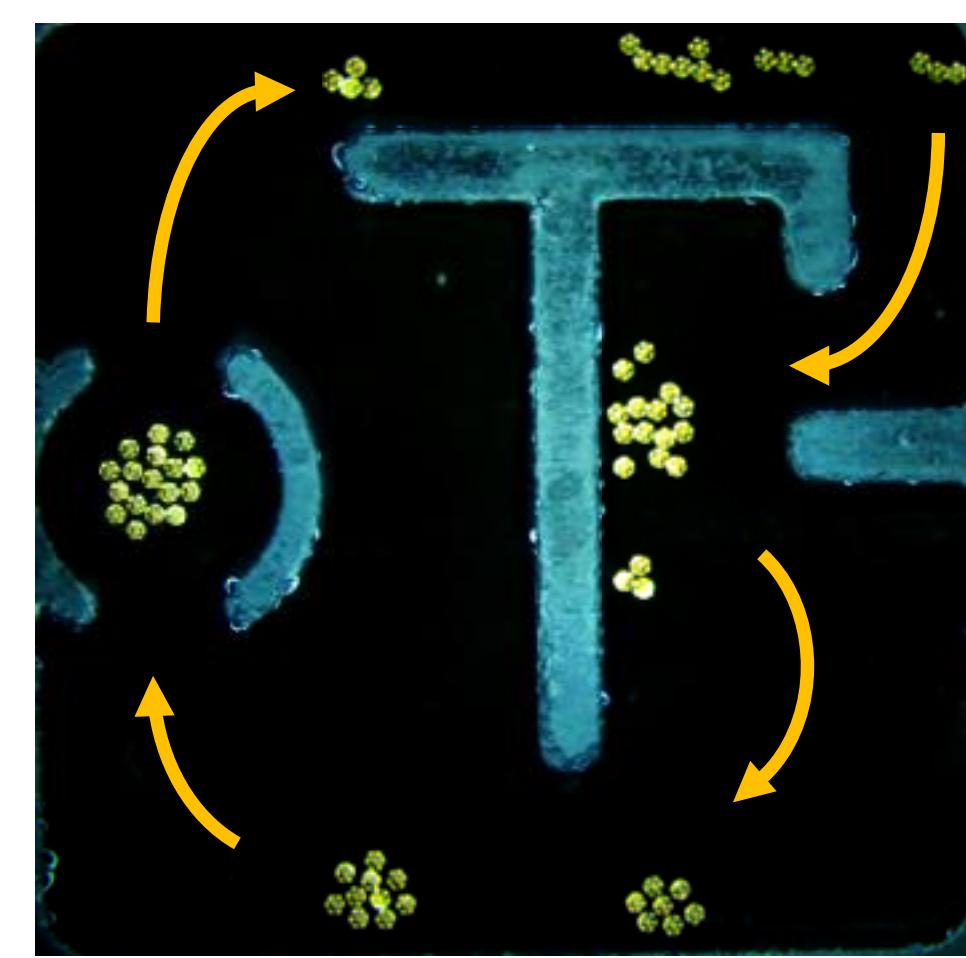
Steven Ceron

Sync and Swarm Behaviors

Reconfigurable Microrobot Collectives



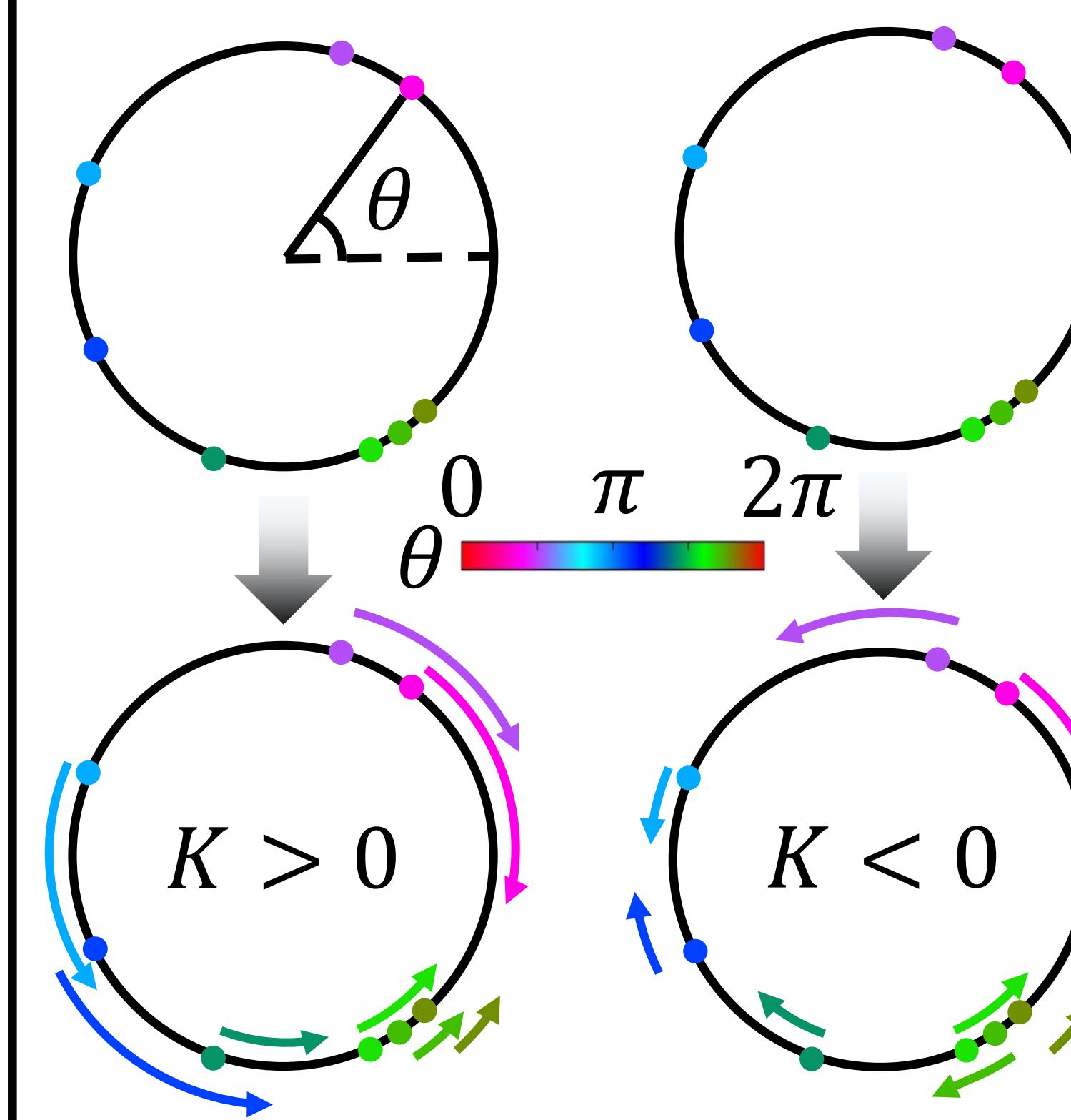
Synchronization
temporal self-organization
Swarming
spatial self-organization

**Swarming Oscillators (Swarmalators)**

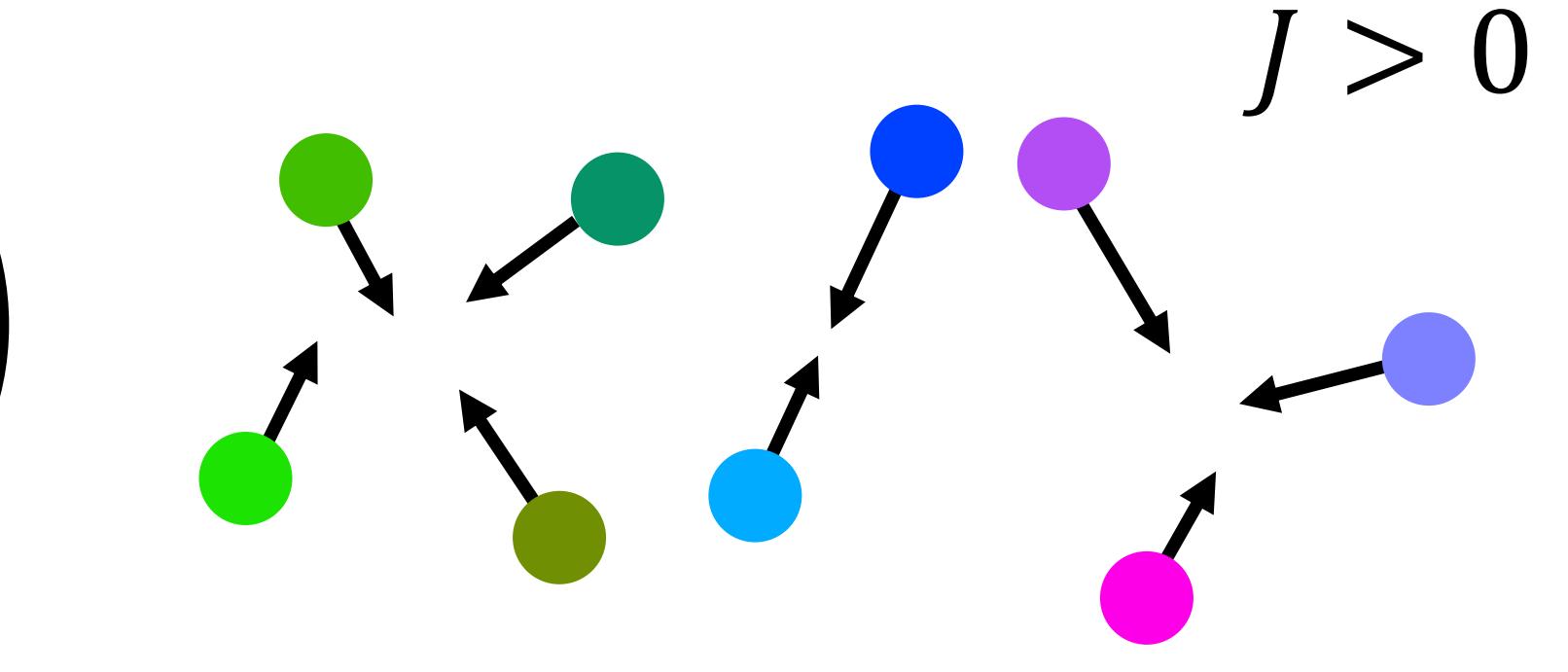
$$\dot{x}_i = c_i \mathbf{n}_i + \frac{1}{N} \sum_{j \neq i}^N \frac{\mathbf{x}_j - \mathbf{x}_i}{|\mathbf{x}_j - \mathbf{x}_i|} (A + J \cos(\theta_j - \theta_i - Q_x)) - B \frac{\mathbf{x}_j - \mathbf{x}_i}{|\mathbf{x}_j - \mathbf{x}_i|^2}$$

$$\dot{\theta}_i = \omega_i + \frac{K}{N} \sum_{j \neq i}^N \frac{\sin(\theta_j - \theta_i - Q_\theta)}{|\mathbf{x}_j - \mathbf{x}_i|}$$

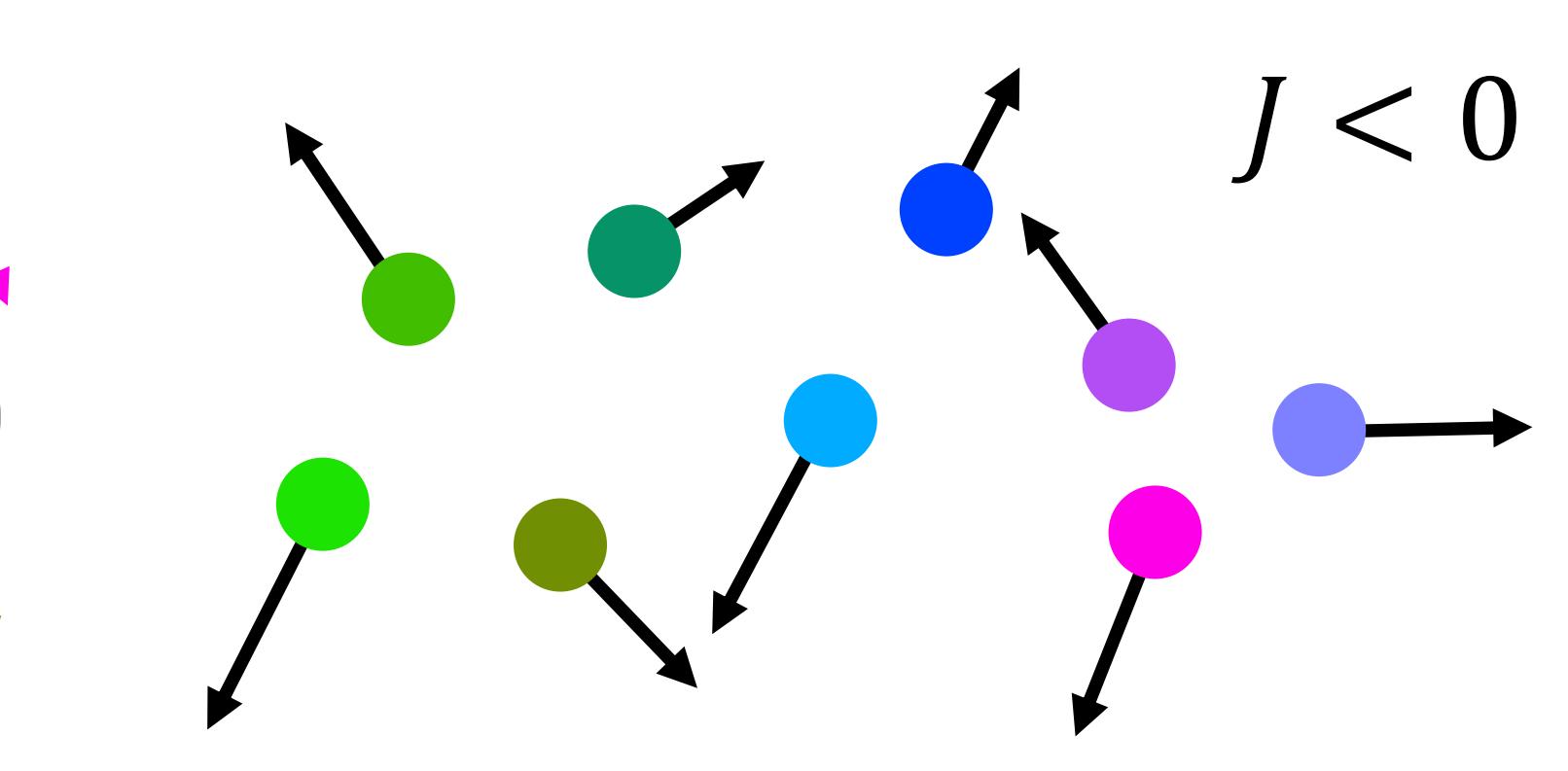
Phase Interactions



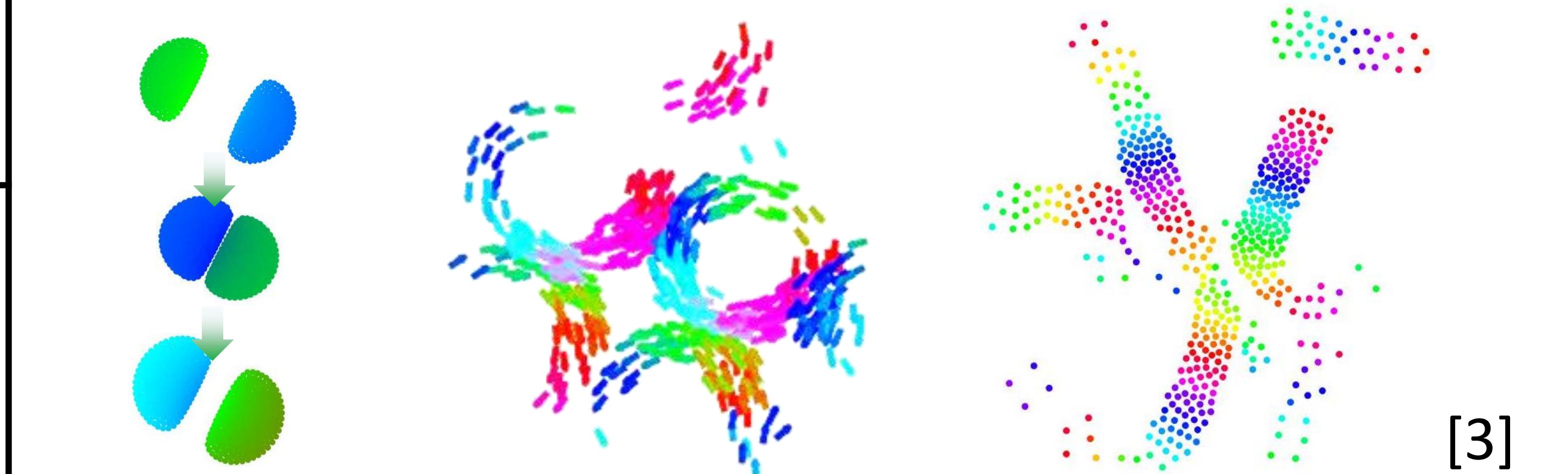
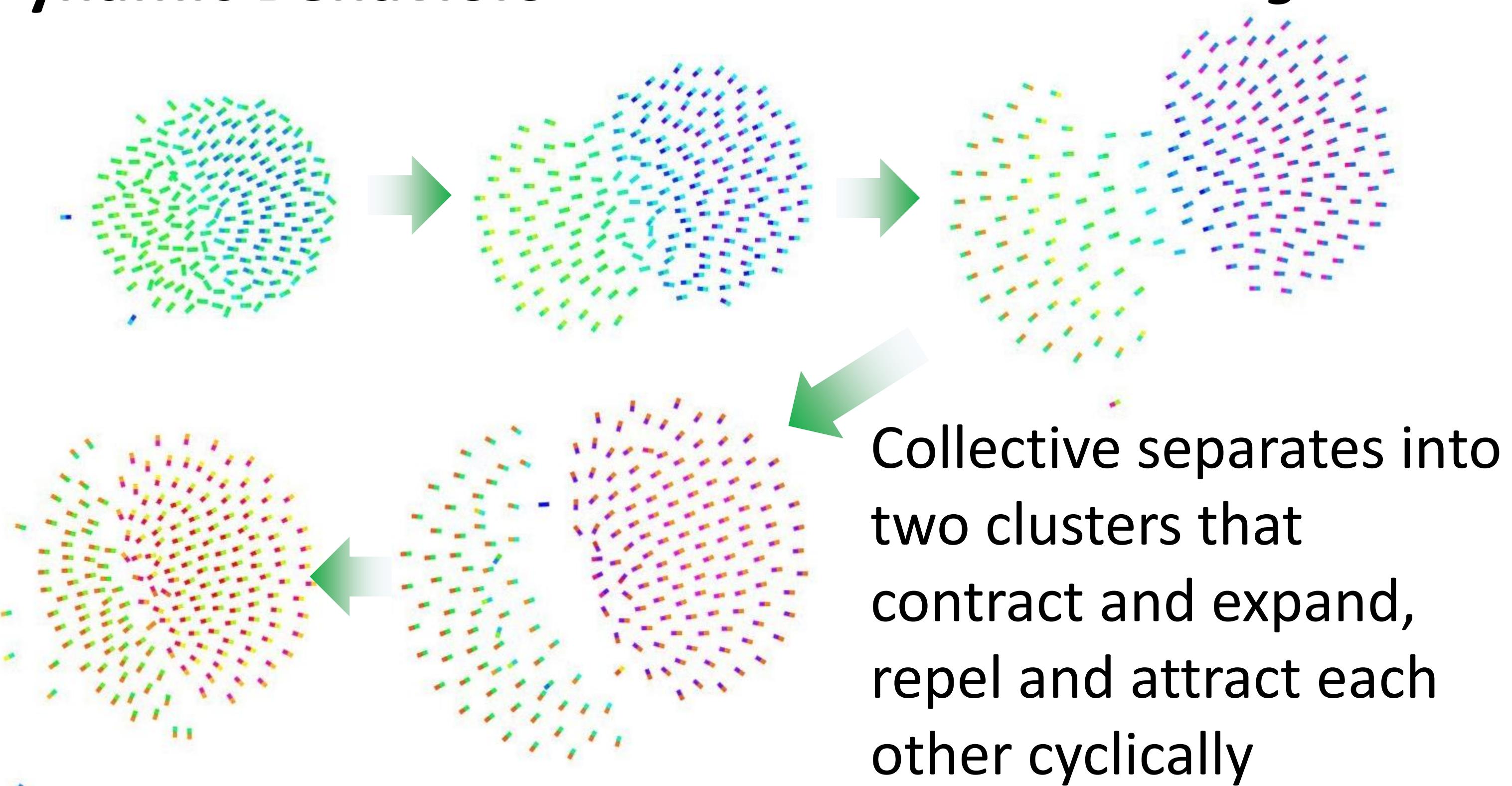
Spatial Interactions



$$J > 0$$



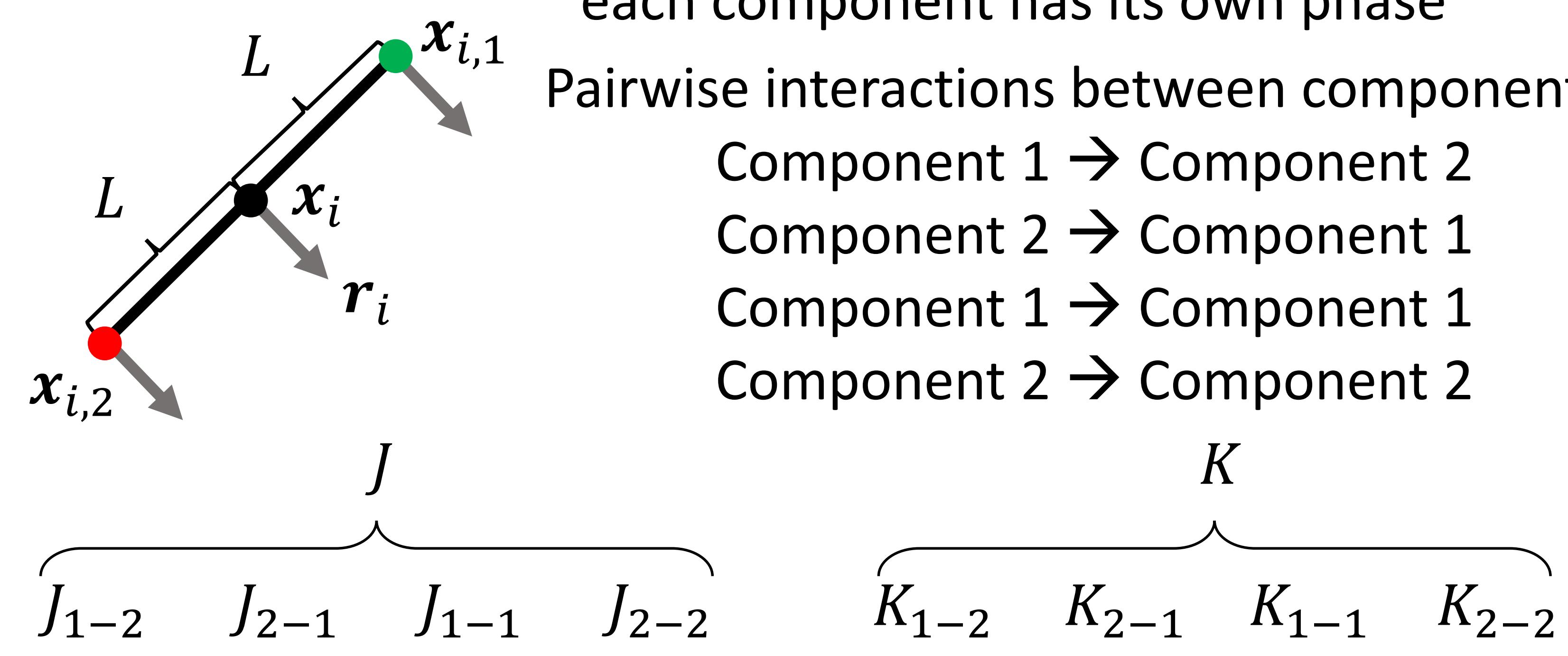
$$J < 0$$

**Bouncing Clusters**

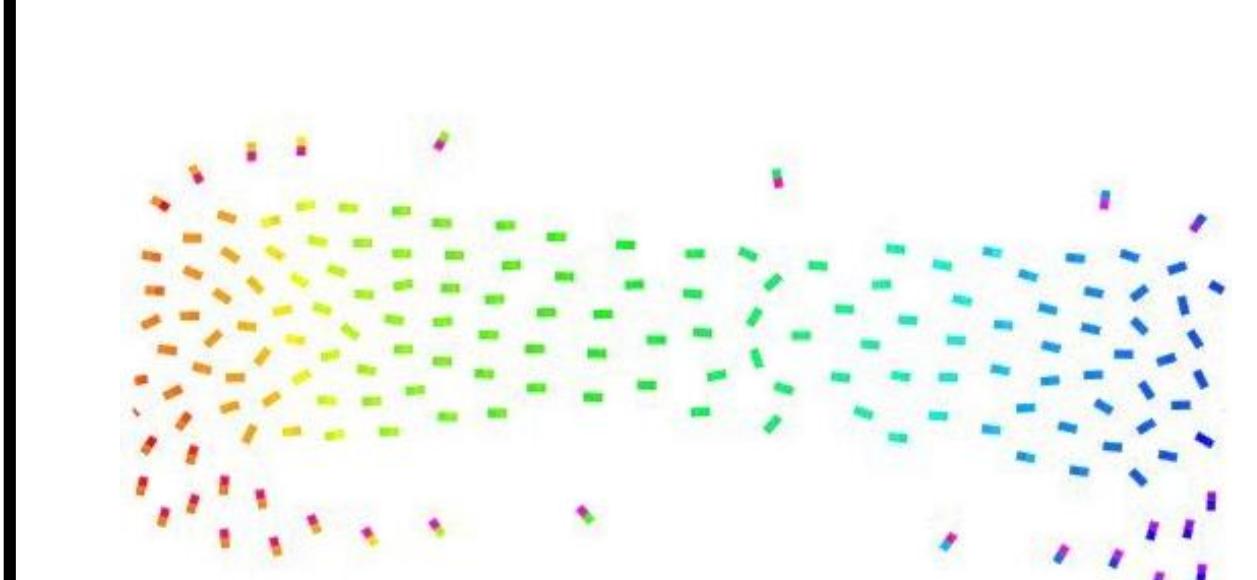
Collective separates into two clusters that contract and expand, repel and attract each other cyclically

Janus Swarmalators

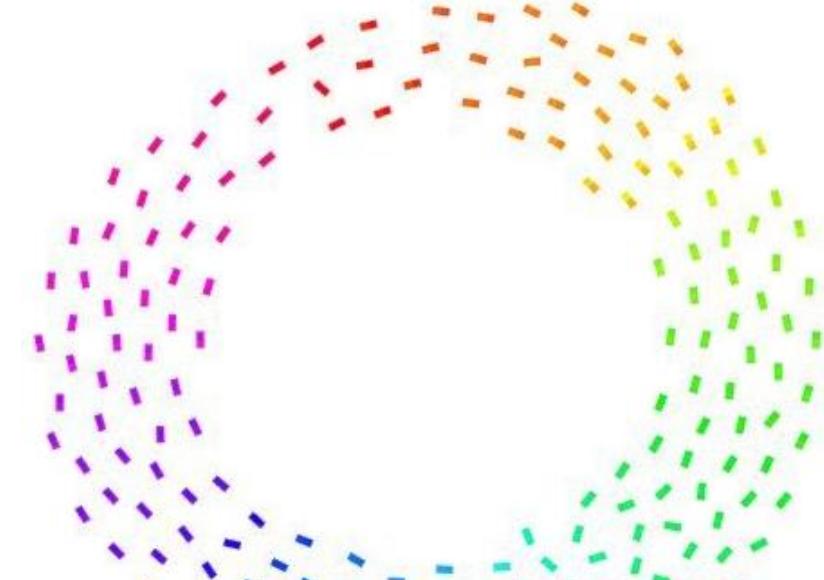
Each agent is made up of two components; each component has its own phase



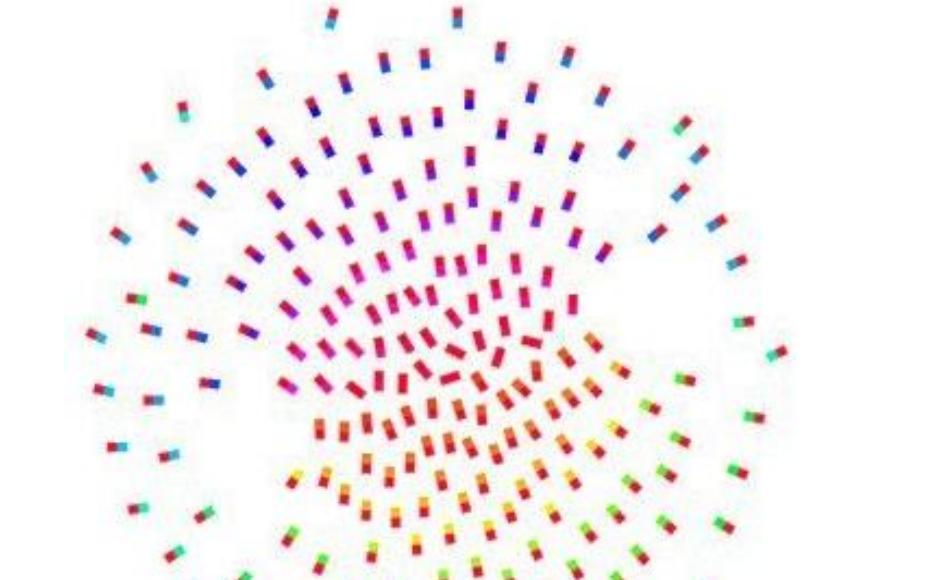
Pairwise interactions between components:
Component 1 → Component 2
Component 2 → Component 1
Component 1 → Component 1
Component 2 → Component 2



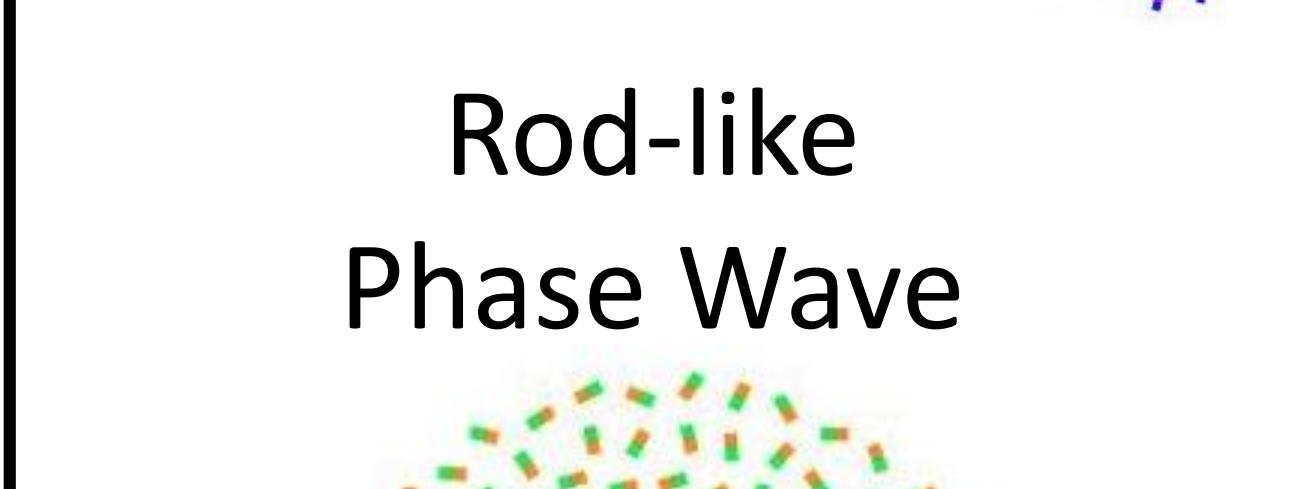
Rod-like Phase Wave



Phase Wave



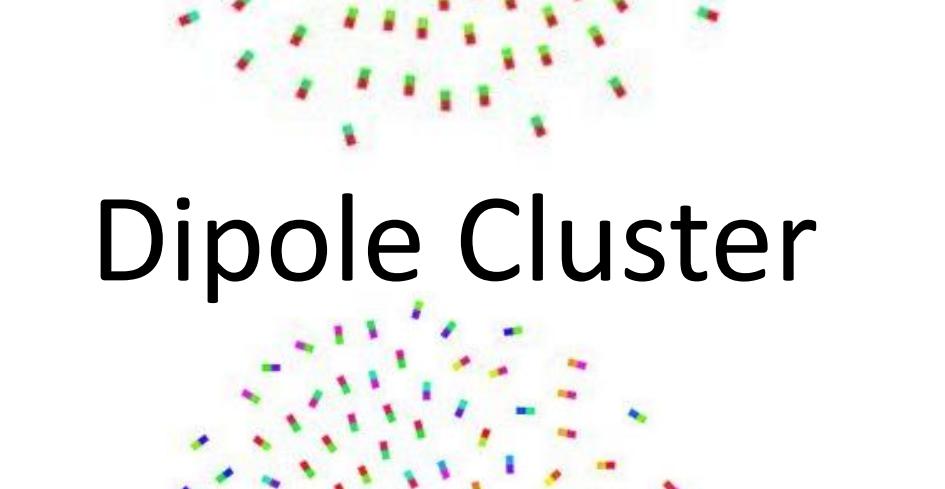
Dipole Cluster



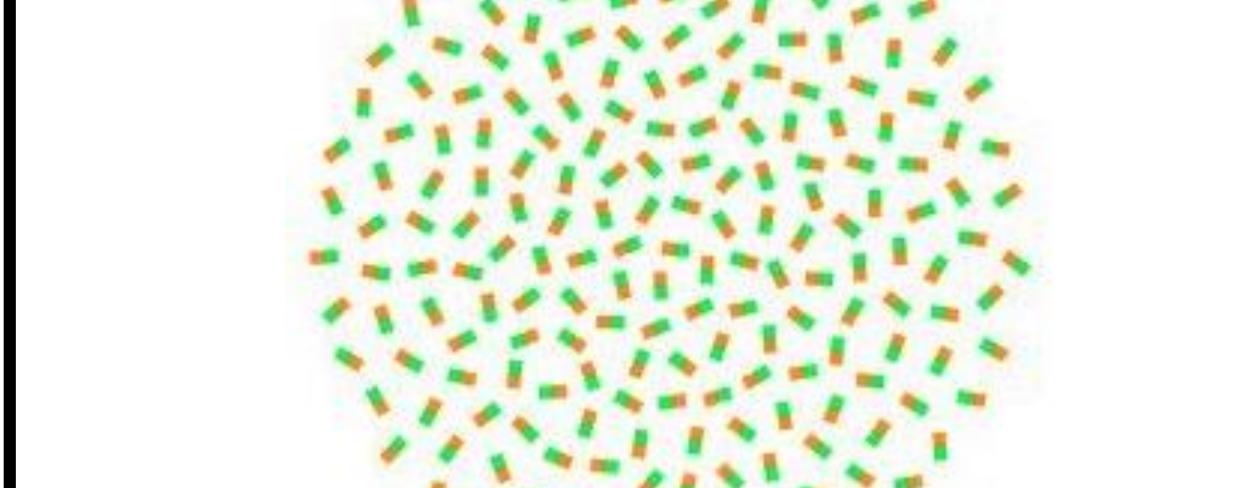
Orientation-Disordered Double Sync Cluster



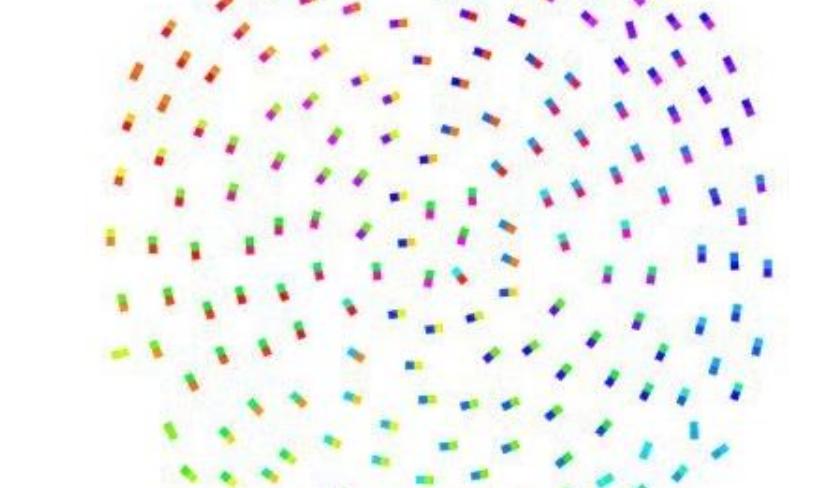
Static Vortex



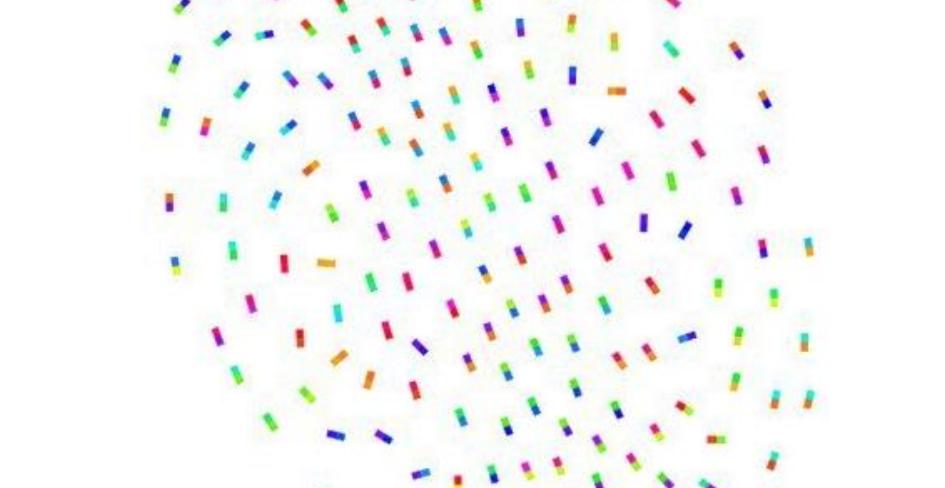
Phase-Disordered Dipole Cluster



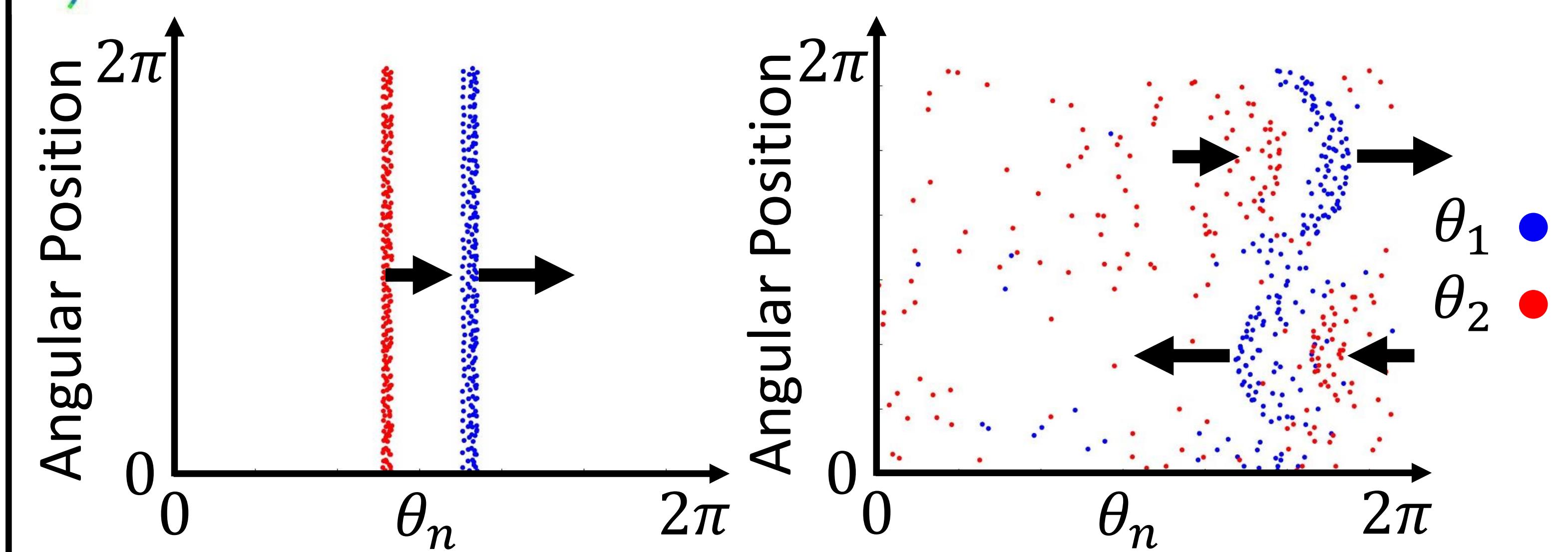
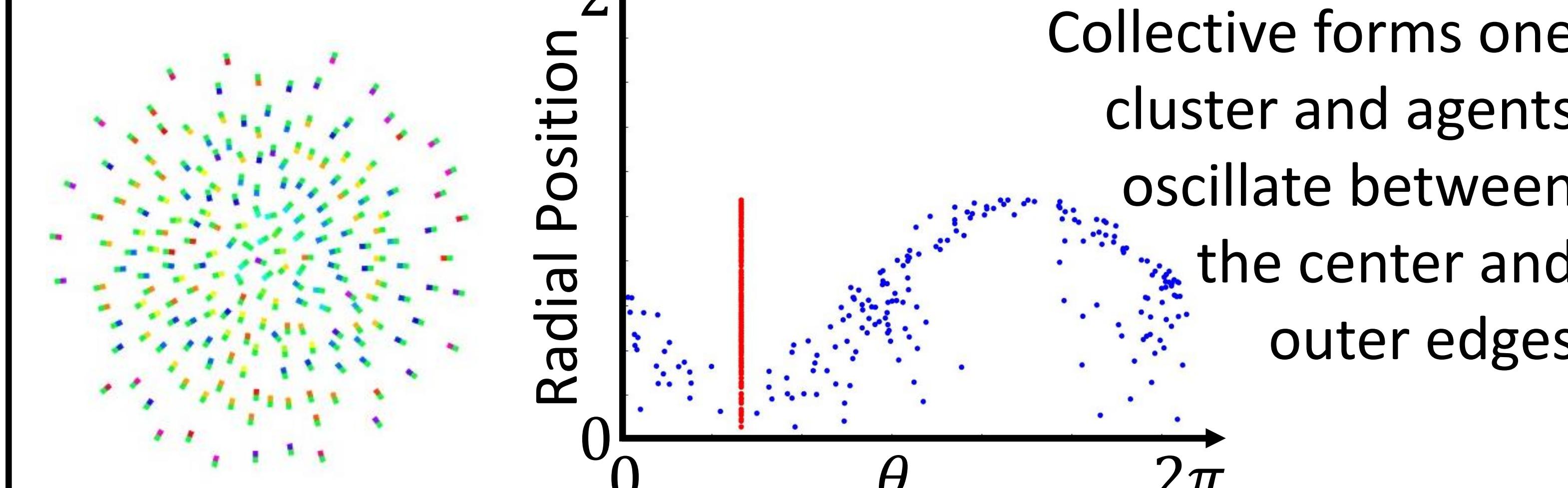
Orientation-Ordered Double Sync Cluster



Async Cluster



Vibrating Sync Cluster

Dynamic Behaviors**Radially Switching**

Collective forms one cluster and agents oscillate between the center and outer edges

References:

- [1] G. Gardi*, S. Ceron*, et al. Microrobot Collectives with Reconfigurable Morphologies, Behaviors, and Functions. *Nature Communications* (2022).
- [2] S. Ceron*, G. Gardi*, K. Petersen, M. Sitti. Programmable Self-Organization of Heterogeneous Microrobot Collectives. *PNAS* (2023).
- [3] S. Ceron, K. O'Keefe, K. Petersen. Diverse Behaviors in Non-Uniform Chiral and Non-Chiral Swarmalators. *Nature Communications* (2023).

* Equally contributing first authors

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