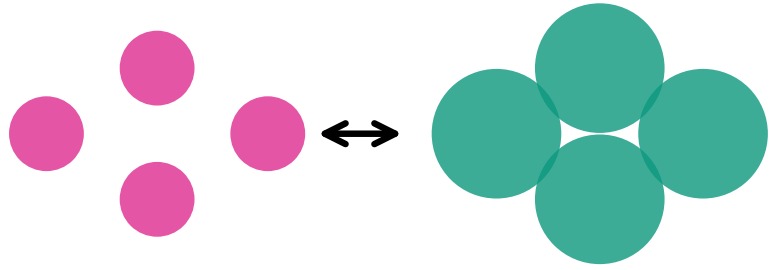
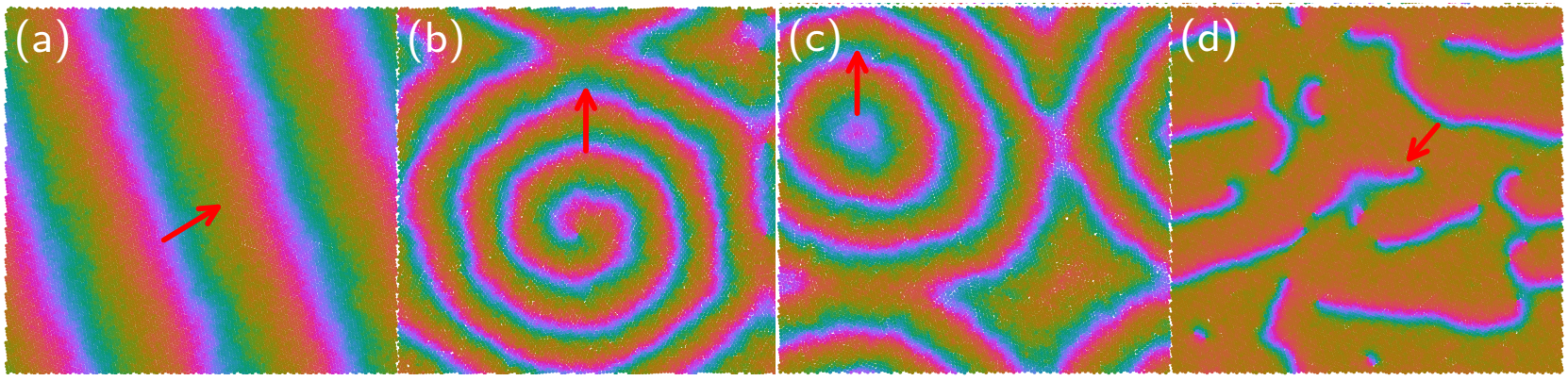
Pulsating active matter

Etienne Fodor

University of Luxembourg





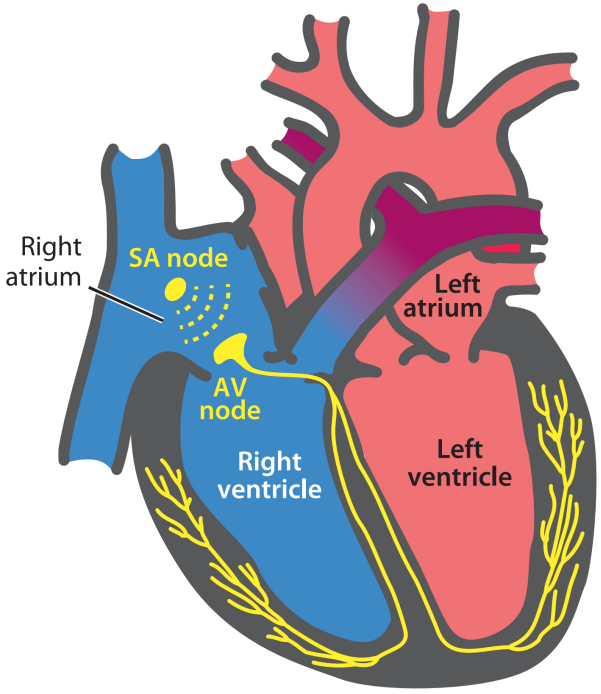
Nonequilibrium Statistical Physics of Complex Systems

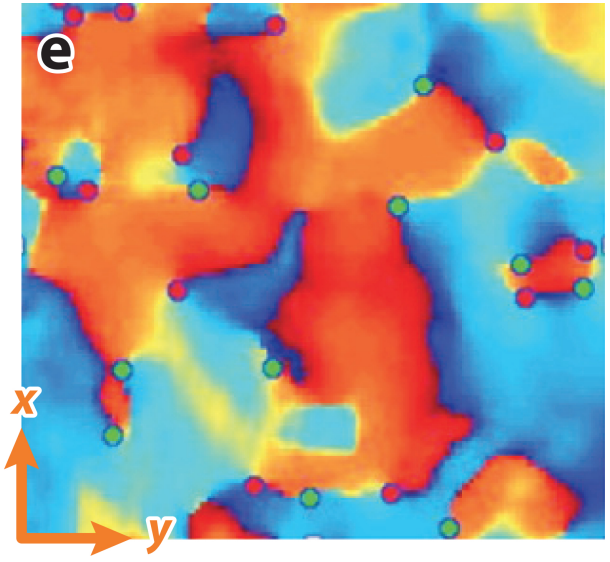
Biological tissues as active matter

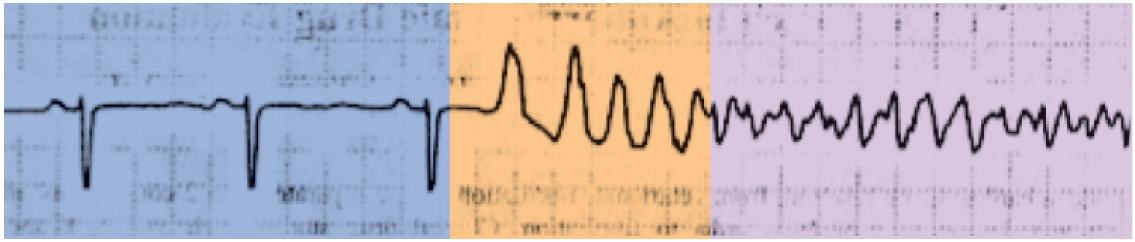
Waves of contracting cells in cardiac tissues

Spirals and topological defects

Karma, Annu Rev CMP **4**, 313 (2013)



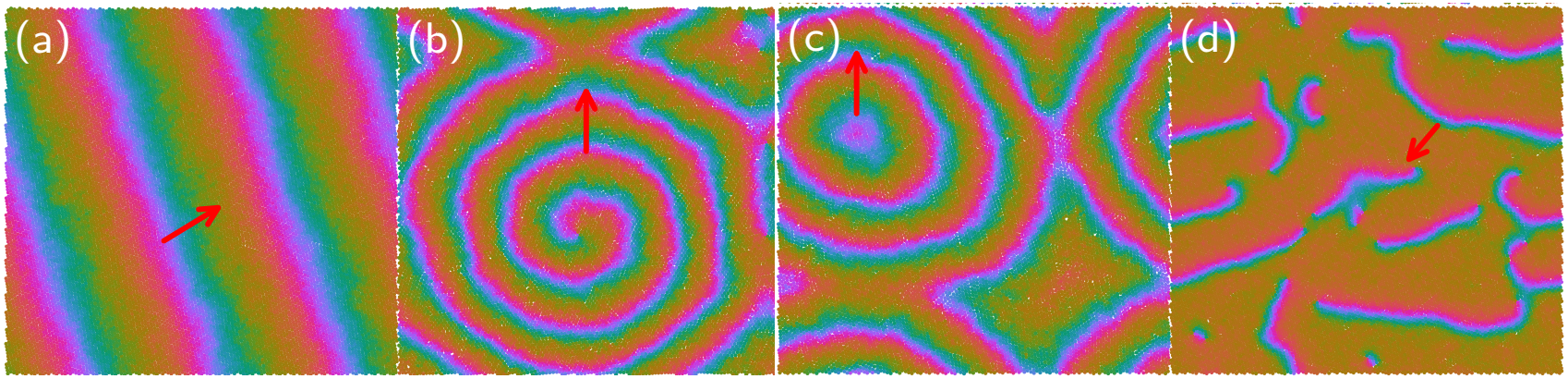




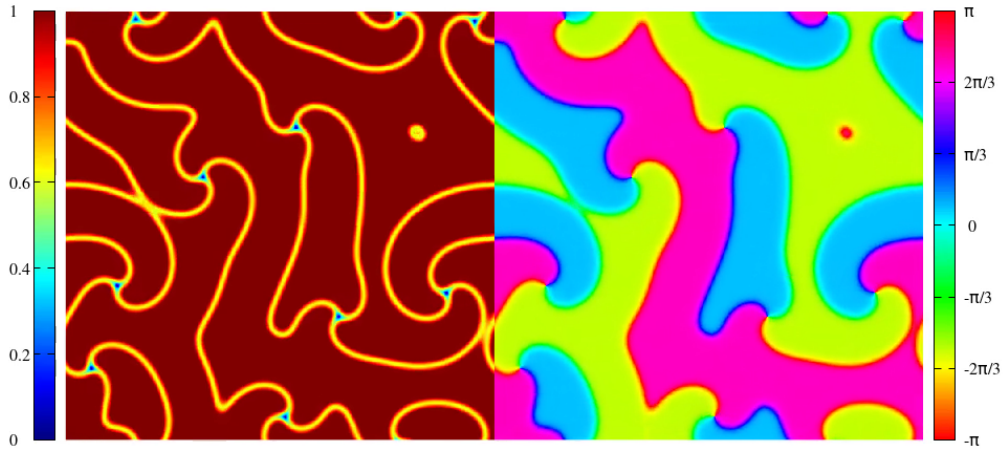
Pulsating active matter

Propagating waves emerge from individual pulsation

1. Pulsating deformable particles [Zhang, EF, PRL **131**, 238302 (2023)]



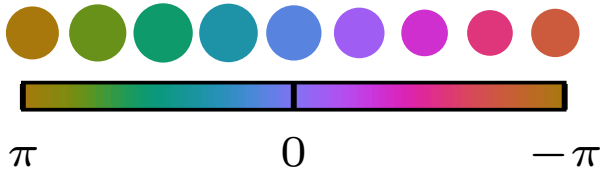
2. Pulsating with discrete symmetry [Manacorda, EF, arXiv:2310.1437]



Pulsating deformable particles [Zhang, EF, PRL **131**, 238302 (2023)]

Fluctuating dynamics of positions and phases

Particle size $\sigma_i = \sigma_0 \dfrac{1+\lambda \sin\theta_i}{1+\lambda}$



Main ingredients: repulsion, synchronisation, drive

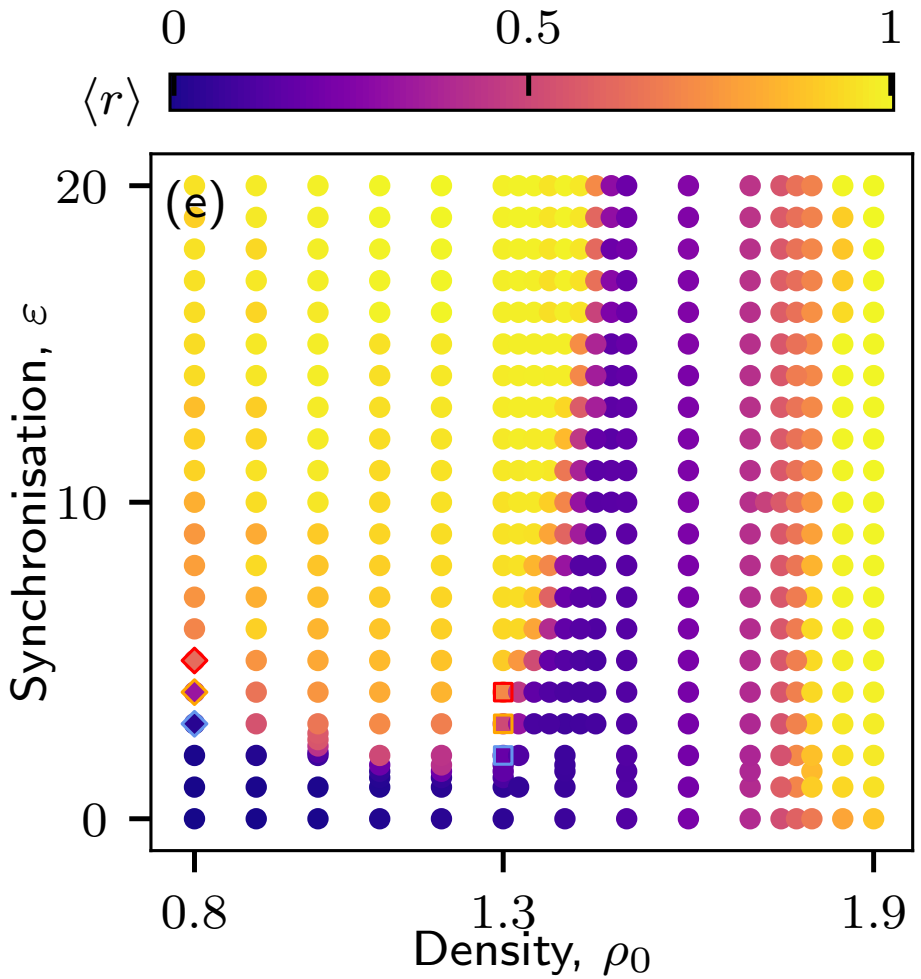
$$\dot{x}_i = -\sum_{j\wedge i} \nabla_i U\left(\frac{x_{ij}}{\sigma_i+\sigma_j}\right) + \xi_i$$

$$\dot{\theta}_i = \omega - \sum_{j\wedge i} \left[\varepsilon \sin(\theta_i-\theta_j) + \partial_{\theta_i} U\left(\frac{x_{ij}}{\sigma_i+\sigma_j}\right)\right] + \eta_i$$

Pulsating deformable particles [Zhang, EF, PRL **131**, 238302 (2023)]

Multiple order-disorder transitions

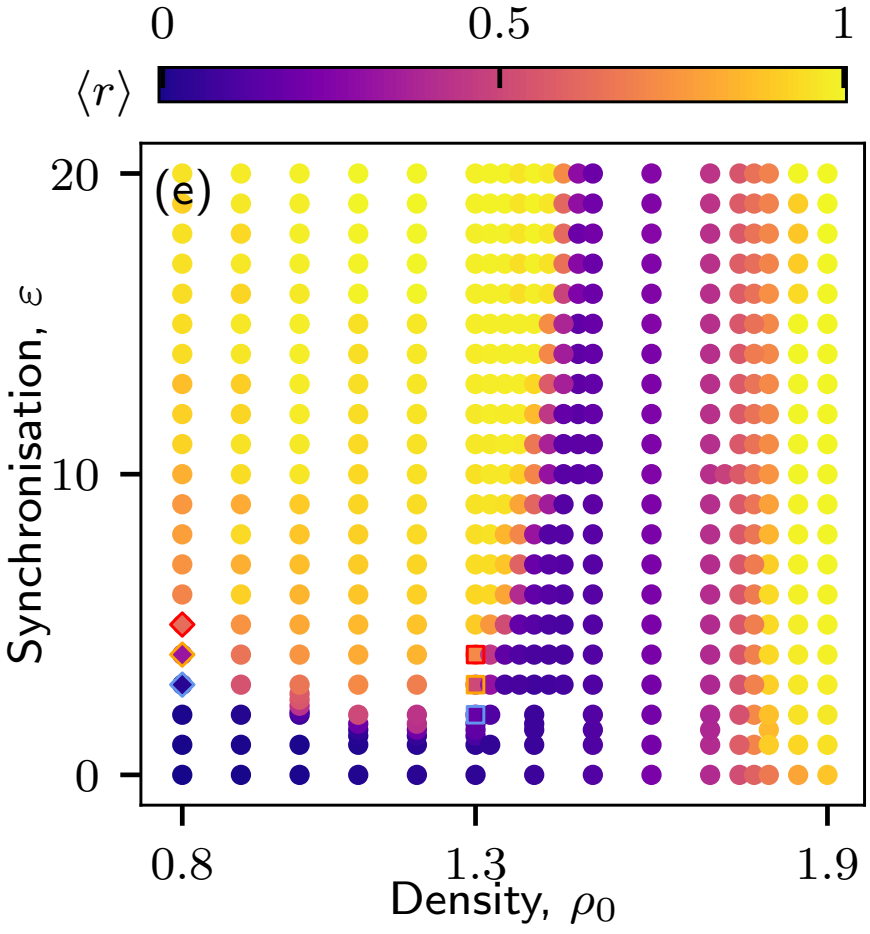
Synchronisation parameter $r = \frac{1}{N}\left|\sum_j e^{i\theta_j}\right|$



Pulsating deformable particles [Zhang, EF, PRL **131**, 238302 (2023)]

Multiple order-disorder transitions

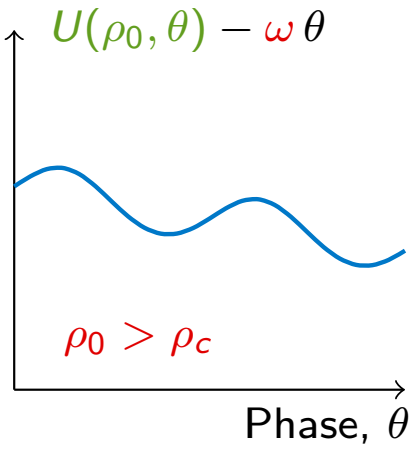
Synchronisation parameter $r = \frac{1}{N}\left|\sum_j e^{\mathrm{i}\theta_j}\right|$

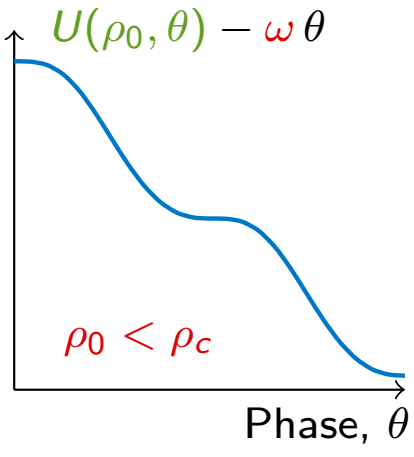


High synchronisation ($\rho_0\varepsilon \gg D_\theta$)

$$\dot{\theta} = \omega - \partial_\theta U$$

$$U = U\left(\frac{r(\rho_0)}{2\sigma(\theta)}\right) \qquad r(\rho_0) \sim \frac{1}{\sqrt{\rho_0}}$$

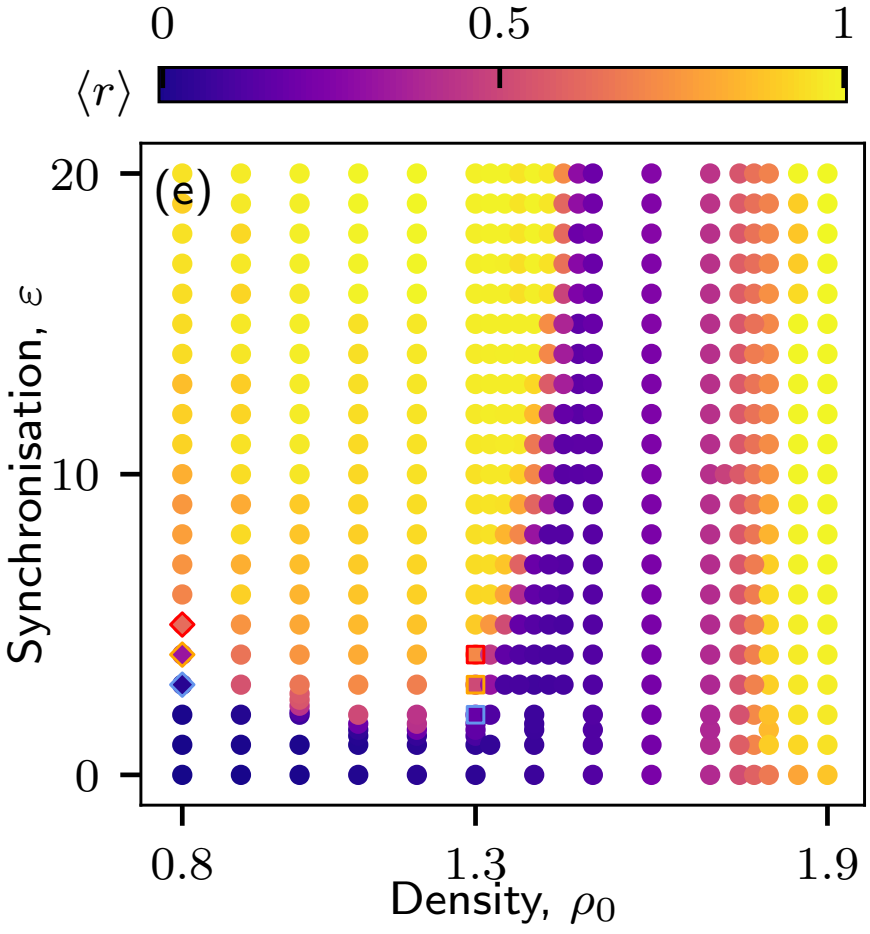




Pulsating deformable particles [Zhang, EF, PRL **131**, 238302 (2023)]

Multiple order-disorder transitions

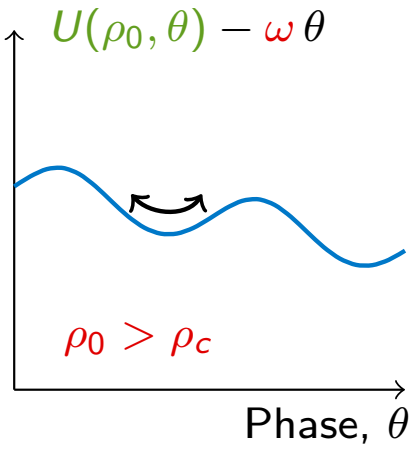
Synchronisation parameter $r = \frac{1}{N}\left|\sum_j e^{\mathrm{i}\theta_j}\right|$

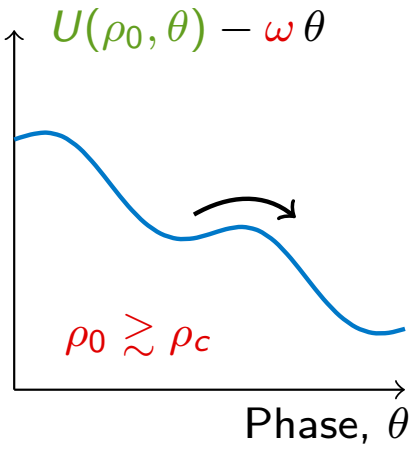


High synchronisation ($\rho_0\varepsilon \gg D_\theta$)

$$\dot\theta = \omega - \partial_\theta U + \text{noise}$$

$$U = U\left(\frac{r(\rho_0)}{2\sigma(\theta)}\right) \qquad r(\rho_0) \sim \frac{1}{\sqrt{\rho_0}}$$



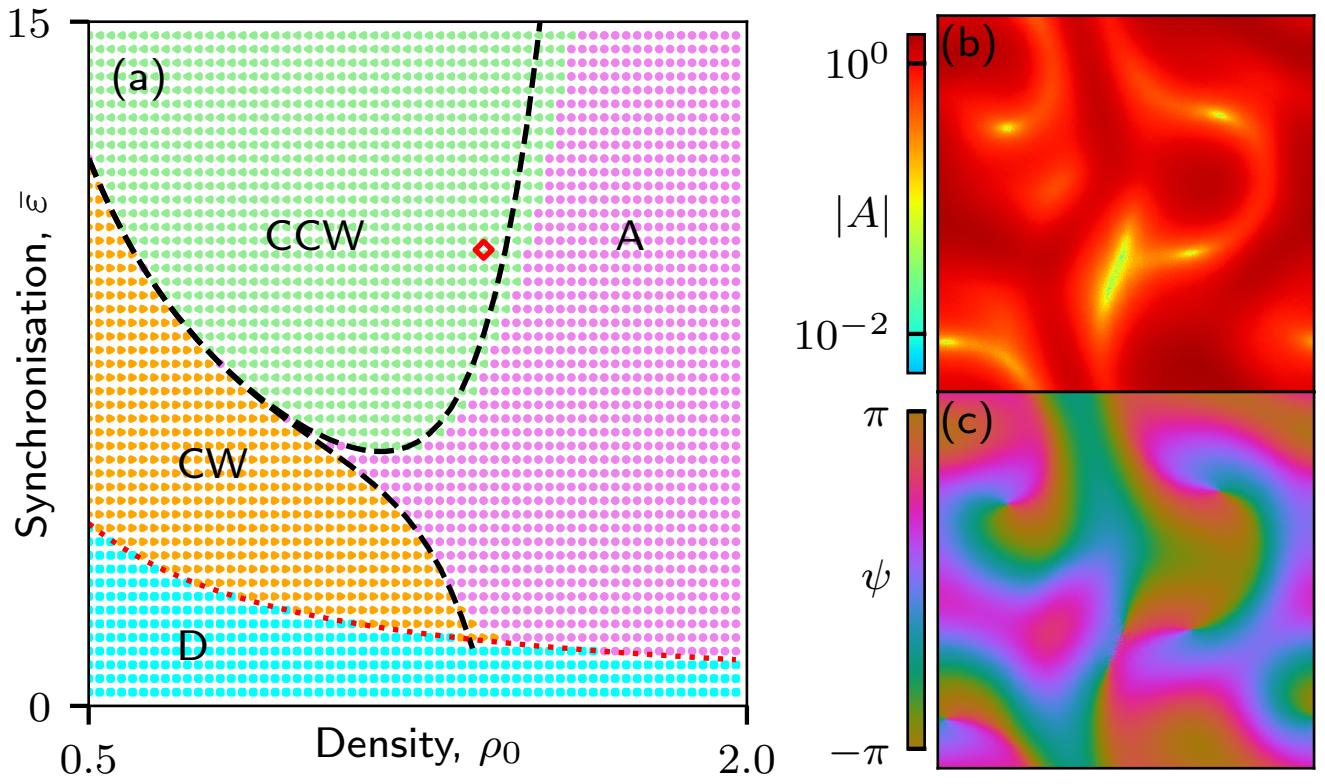


Pulsating deformable particles [Zhang, EF, PRL **131**, 238302 (2023)]

Coarse-grained field $A(\mathrm{x},t) = \sum_j e^{\mathrm{i}\theta_j}\,\delta(\mathrm{x}-\mathrm{x}_j(t)) = |A|\,e^{\mathrm{i}\Psi}$

$$\partial_t A = (a + D\nabla^2)\,A + b\,A|A|^2 + A\left[c_1\mathrm{Re}(A) + c_2\mathrm{Im}(A^2)\right] + \text{noise}$$

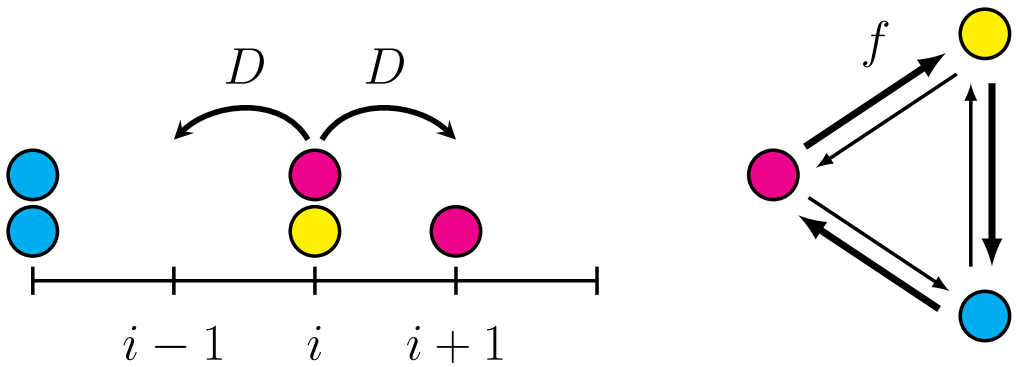
Breakdown of invariance $A \to A\,e^{\mathrm{i}\Phi}$



Pulsating with discrete symmetry [Manacorda, EF, arXiv:2310.1437]

Lattice model of pulsating particles

Free diffusion with driving of internal state



Main ingredients: diffusion, synchronisation, drive

- Transition between sites: Constant rate D
- Transition between states: Fully connected on-site

$$W_{ab} \sim \exp\left(\pm f + \varepsilon \frac{n_b - n_a}{\rho}\right)$$

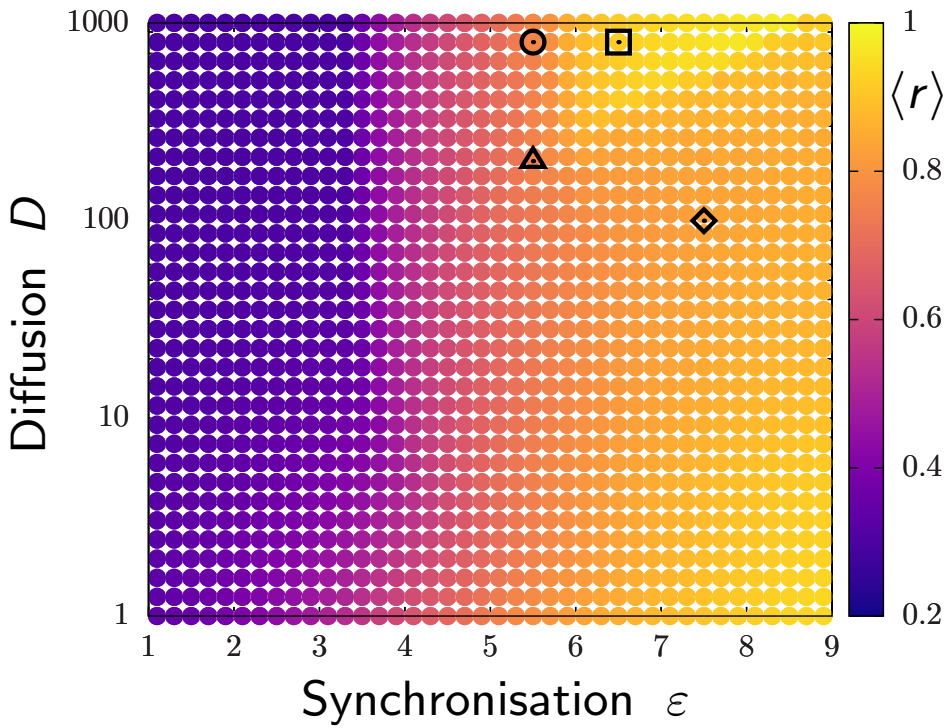
Pulsating with discrete symmetry [Manacorda, EF, arXiv:2310.1437]

Lattice model of pulsating particles

Emergence of propagating waves: Role of diffusion

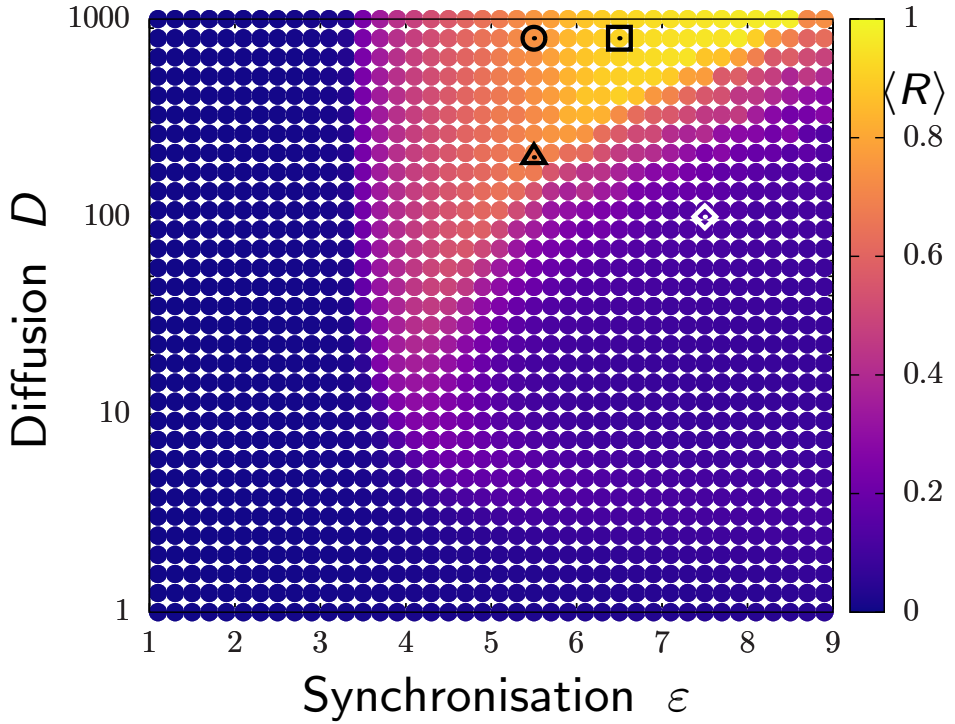
Local order

$$r(x) = \frac{1}{\rho(x)} \left| \sum_a e^{i\,2\pi a/3}\, n_a(x,t) \right|$$



Global order

$$R = \frac{1}{N} \left| \sum_a e^{i\,2\pi a/3} \int n_a(x,t)\,dx \right|$$



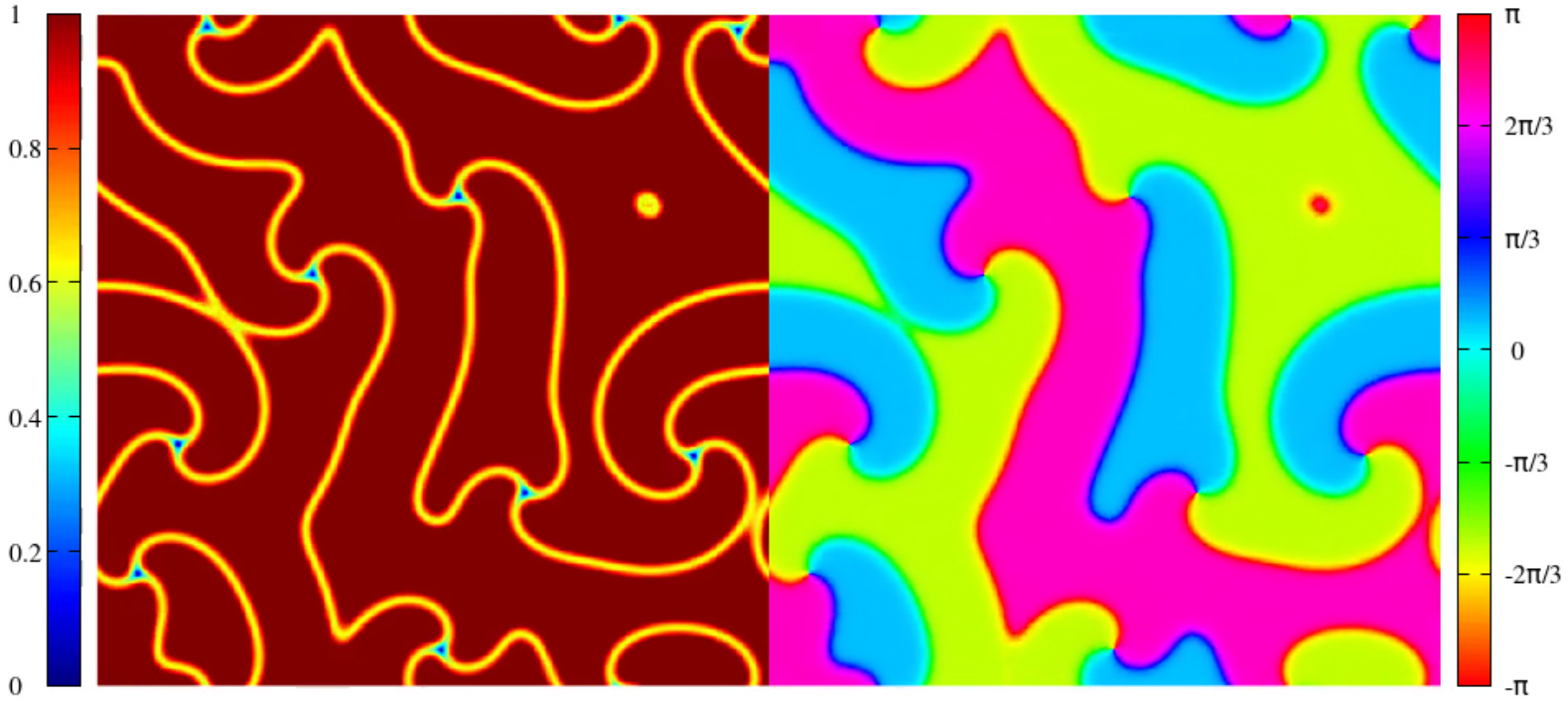
Pulsating with discrete symmetry [Manacorda, EF, arXiv:2310.1437]

Coarse-grained field $A(\mathrm{x},t) = \sum_{a=1}^{3} n_a(\mathrm{x},t)\, e^{i\,2\pi a/3} = |A|\, e^{i\Psi}$

$$\partial_t A = (a + D\nabla^2)\, A + b\, A^2 \bar{A} + c\bar{A}^2 + \text{noise}$$

No continuous invariance $A \to A\, e^{i\Phi}$

Discrete invariance $A \to A\, e^{i\frac{2\pi k}{3}}$



Pulsating active matter

Minimal ingredients

- Drive of internal states
- Arrest mechanism
- Local synchronisation

Pulsating deformable particles
Zhang, EF, PRL **131**, 238302 (2023)

Pulsating with discrete symmetry
Manacorda, EF, arXiv:2310.1437

Large deviations of pulsating particles
Piñeros, EF, arXiv:2403.16961

Field theory of pulsating liquids
Banerjee, Desaleux, Ranft, EF, in preparation


Y. Zhang


A. Manacorda


W. D. Piñeros


T. Banerjee


L. Casagrande