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Multi-scale organization in communicating active matter

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The emergence of collective motion among interacting, self-propelled agents is a central paradigm in non-equilibrium physics. Examples of such active matter range from swimming bacteria and cytoskeletal motility assays to synthetic self-propelled colloids and swarming microrobots. Remarkably, the aggregation capabilities of many of these systems rely on a theme as fundamental as it is ubiquitous in nature: communication. Despite its eminent importance, the role of communication in the collective organization of active systems is not yet fully understood. Here we report on the multi-scale self-organization of interacting self-propelled agents that locally process information transmitted by chemical signals. We show that this communication capacity dramatically expands their ability to form complex structures, allowing them to self-organize through a series of collective dynamical states at multiple hierarchical levels. Our findings provide insights into the role of self-sustained signal processing for self-organization in biological systems and open routes to applications using chemically driven colloids or microrobots.

The Model

$$\frac{\mathrm{d}\mathbf{r}_i}{\mathrm{d}t} = v_0 \mathbf{n}_i + \sum_{j[r_{ij} < 2r_p]} f_{ij}$$

$$\mathbf{n}_i = (\cos\varphi_i, \sin\varphi_i)^\top, \ \varphi_i = \tan^{-1}\left(\frac{\partial_y c}{\partial_x c}\right)$$

$$\frac{d\varphi_i}{dt} = -\Gamma \sum_{j[r_{ij} < r_c]} \frac{\sin(\varphi_i - \varphi_j)}{|\mathbf{r}_i - \mathbf{r}_j|} + \omega \sin(\varphi_c - \varphi_i) + \xi_i$$

$$\partial_t c(r,t) = D_c \Delta c - \alpha c + \beta \sum_{i=1}^{N} f(|\mathbf{r} - \mathbf{r}_i|)\phi(s_i, c)$$

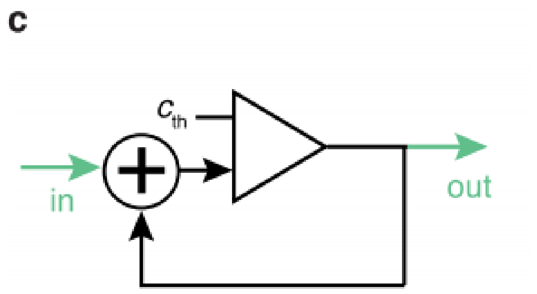
$$f \sim \exp\left[\frac{-x^2 - y^2}{2\omega^2}\right]$$

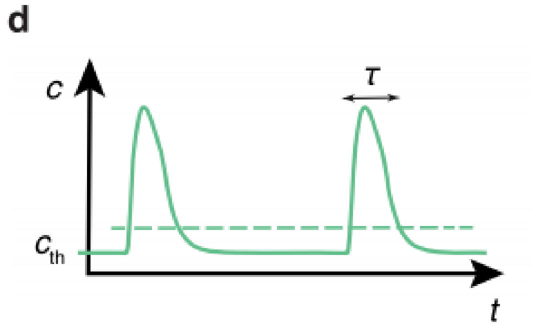
$$\beta\phi(s_i, c) = \beta(1 - s_i)\Theta(c - c_{th})$$

$$\frac{\mathrm{d}s_i}{\mathrm{d}t} = \epsilon(c - s_i)$$

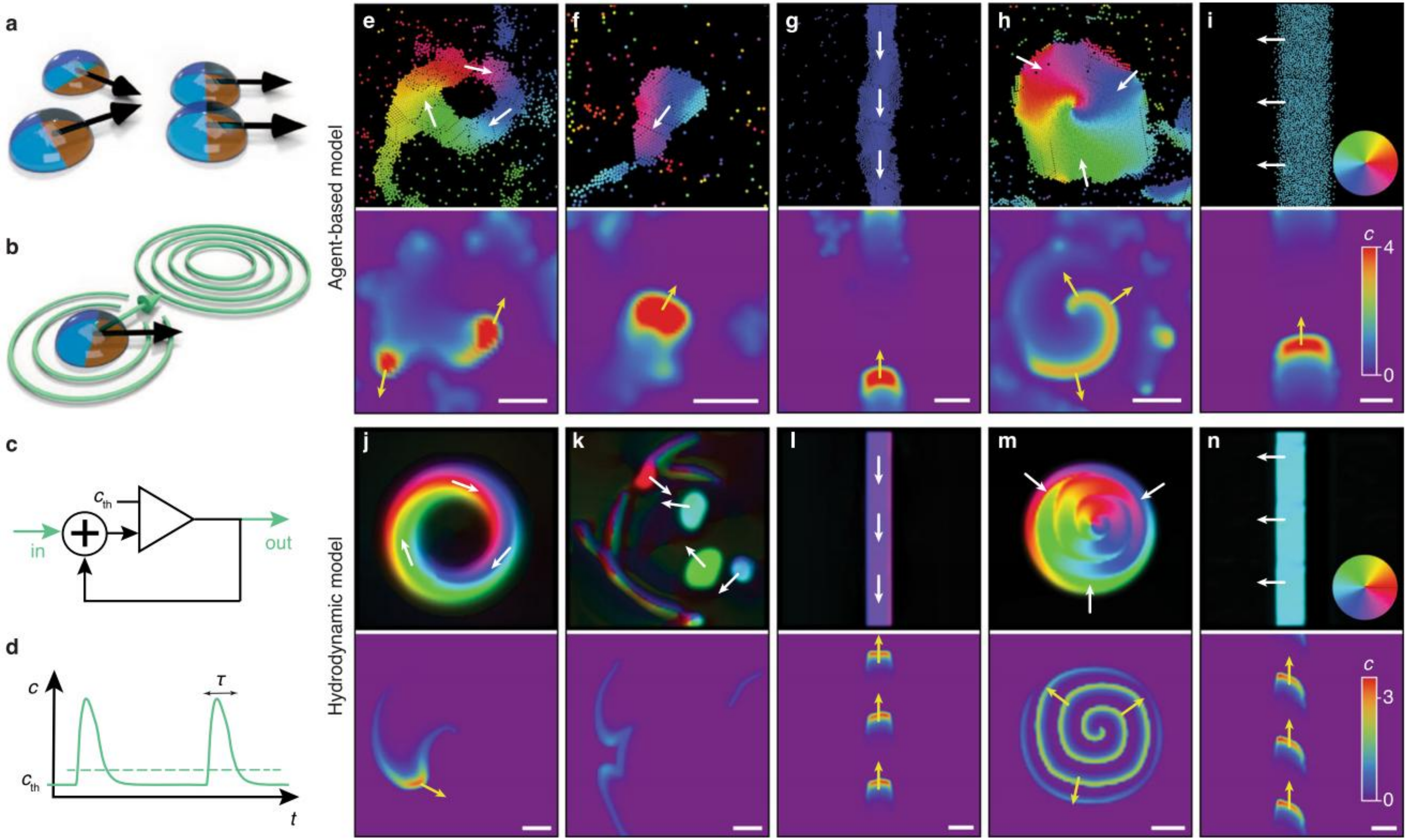
The hydrodynamic model:

$$\partial_t \rho(\mathbf{r},t) = -v_0 \nabla \cdot \mathbf{p} + D_\rho \Delta\rho,$$
$$\partial_t \mathbf{p}(\mathbf{r},t) = \sigma(\rho - 1)\mathbf{p} - \delta|\mathbf{p}|^2\mathbf{p} + D_p \Delta\mathbf{p} - \chi\mathbf{p}\cdot\nabla\mathbf{p} - Q(\rho)\nabla\rho + \rho\omega\nabla c,$$
$$\partial_t c(\mathbf{r},t) = D_c \Delta c - \alpha c + \rho\beta\Theta(c - c_{\mathrm{th}})(1 - s),$$
$$\partial_t s(\mathbf{r},t) = D_\rho \Delta s + \epsilon(c - s) - \bar{v}\mathbf{p}\cdot\nabla s.$$



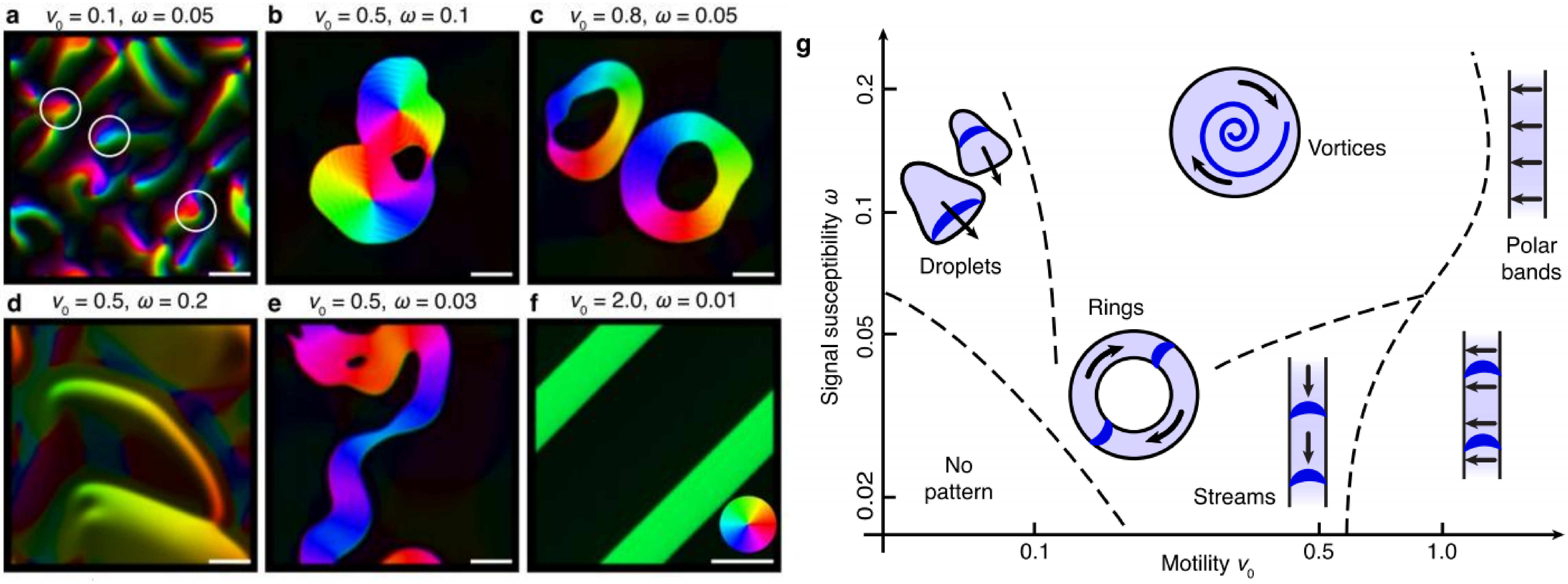


Results



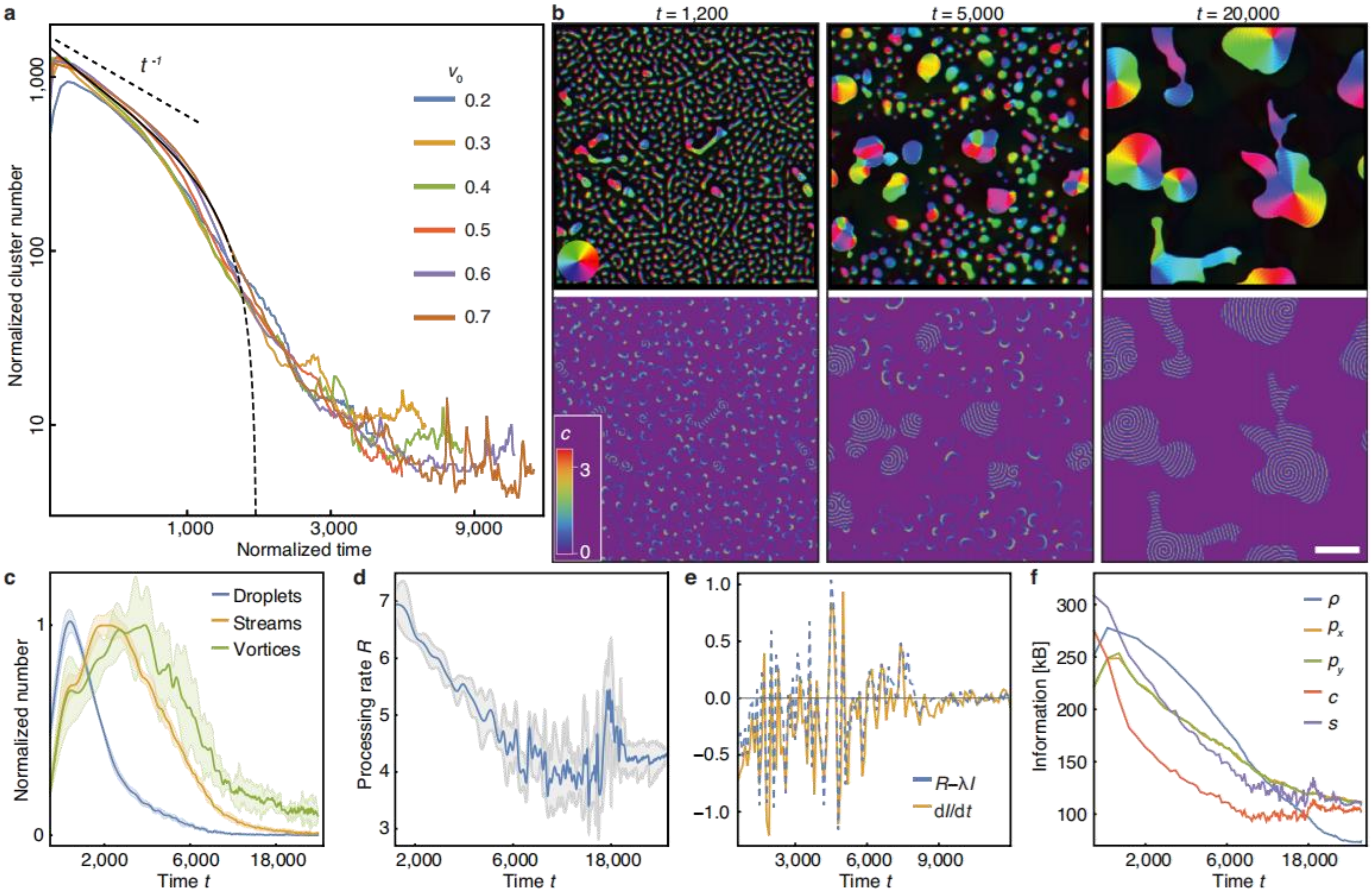
a
b
c
d
e
f
g
h
i
j
k
l
m
n
Agent-based model
Hydrodynamic model
c_{th}
in
out
c
τ
t
4
0
3

Results



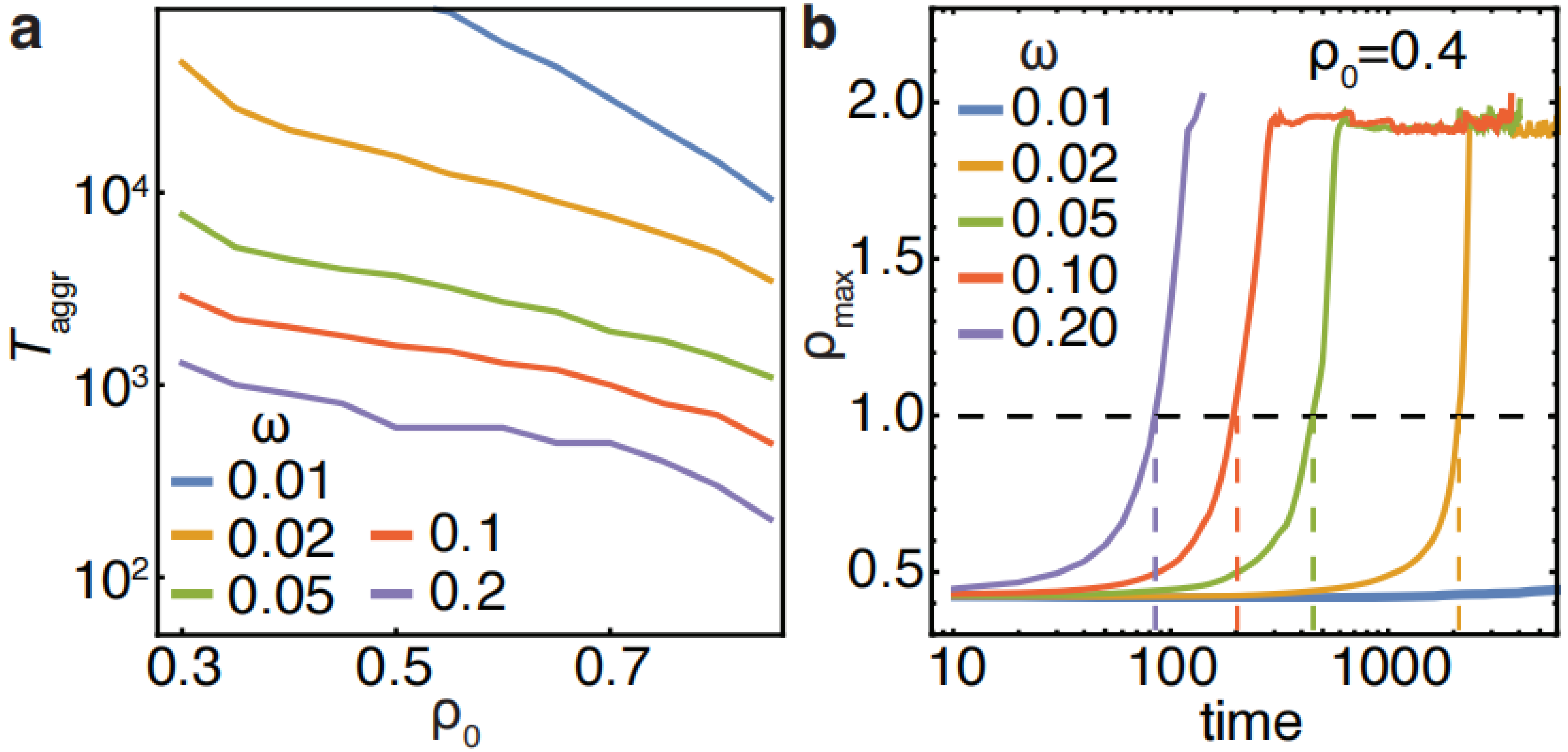
a $v_0 = 0.1,\ \omega = 0.05$
b $v_0 = 0.5,\ \omega = 0.1$
c $v_0 = 0.8,\ \omega = 0.05$
d $v_0 = 0.5,\ \omega = 0.2$
e $v_0 = 0.5,\ \omega = 0.03$
f $v_0 = 2.0,\ \omega = 0.01$
g
Signal susceptibility ω
0.2
0.1
0.05
0.02
Motility v_0
0.1
0.5
1.0
Droplets
Vortices
Polar bands
Rings
No pattern
Streams

Results



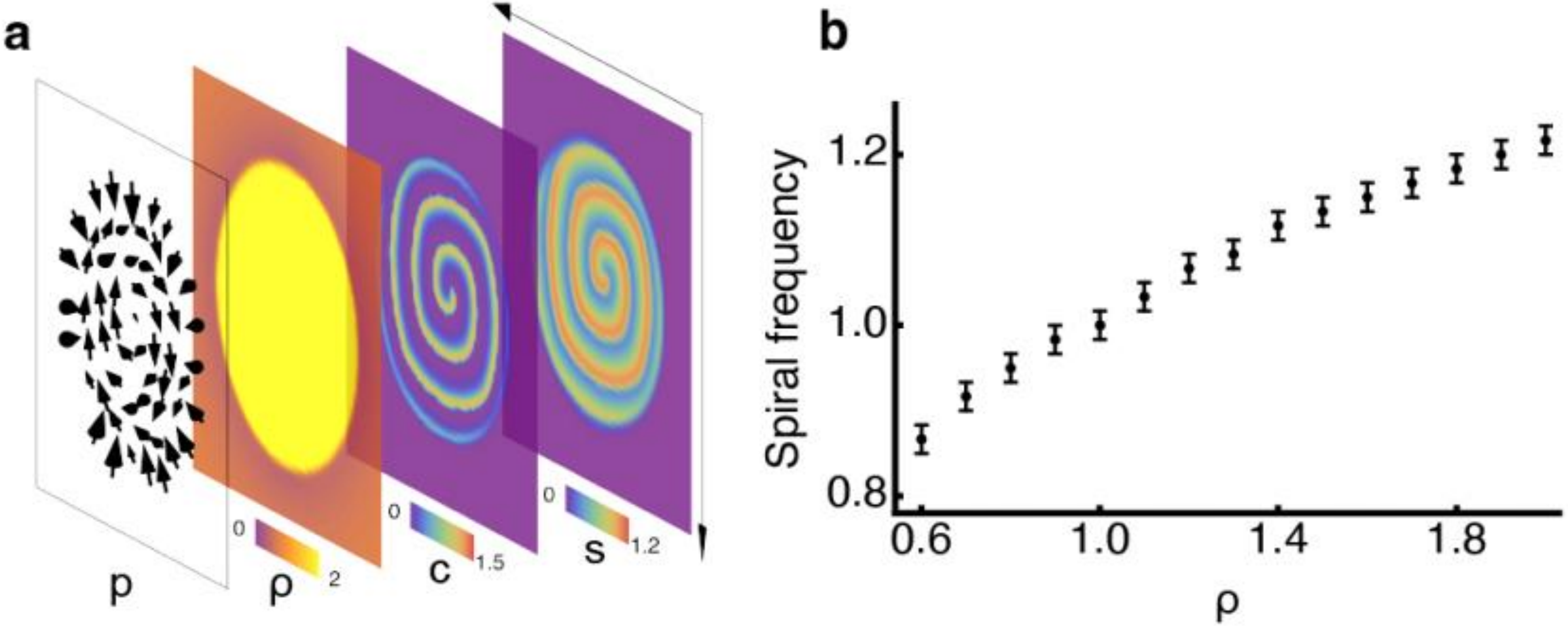
a
b
t = 1,200
t = 5,000
t = 20,000
t^{-1}
v_0
0.2
0.3
0.4
0.5
0.6
0.7
Normalized cluster number
1,000
100
10
1,000
3,000
9,000
Normalized time
c
3
0
c
Droplets
Streams
Vortices
Normalized number
1
0
2,000
6,000
18,000
Time t
d
Processing rate R
7
6
5
4
3
2,000
6,000
18,000
Time t
e
1.0
0.5
0.0
−0.5
−1.0
R−λI
dI/dt
3,000
6,000
9,000
Time t
f
Information [kB]
300
250
200
150
100
ρ
p_x
p_y
c
s
2,000
6,000
18,000
Time t

Results



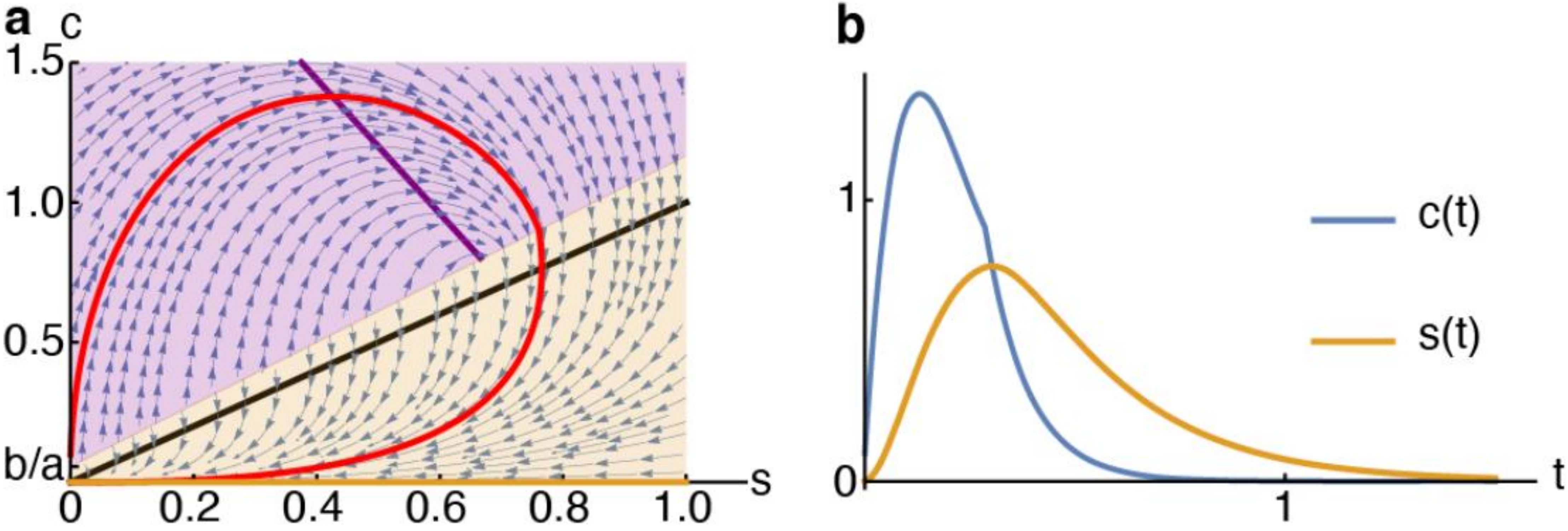
Supplementary Figure 1: Signaling-enhanced aggregation capabilities. a, Aggregation times T_{aggr} of the hydrodynamic system, main text Eqs. (6)-(9), reaching the polar-order transition at $\rho = 1$ from a homogeneous initial density ρ_0. We observe faster aggregation for higher initial densities as well as larger signaling susceptibilities ω. b, Corresponding temporal evolution of the system's maximum density ρ_{max} evolving from a homogeneous initial density $\rho_0 = 0.4$ for different values of ω. We determine the aggregation times T_{aggr} (dashed colored lines) as the first times at which the critical density (dashed black line) is reached, $\rho_{\text{max}} = \rho_c = 1$. Other parameters as given in SI section 3.

Results



Supplementary Figure 2: Spiral waves and vortex solution in the hydrodynamic model. a, Vortex solution with persistent spiral wave activity in the hydrodynamic model, see Methods. The composite image containing layers representing the orientation vector field $\boldsymbol{p}(\boldsymbol{r})$ (arrows), the local density profile $\rho(\boldsymbol{r})$, concentration of signaling molecules $c(\boldsymbol{r})$, and field of state $s(\boldsymbol{r})$. b, Dependence of spiral frequency on spatially homogeneous density values ρ. Error bars indicate error ranges arising from the numerical measurement of spiral frequencies. Parameters as stated in SI section 3.

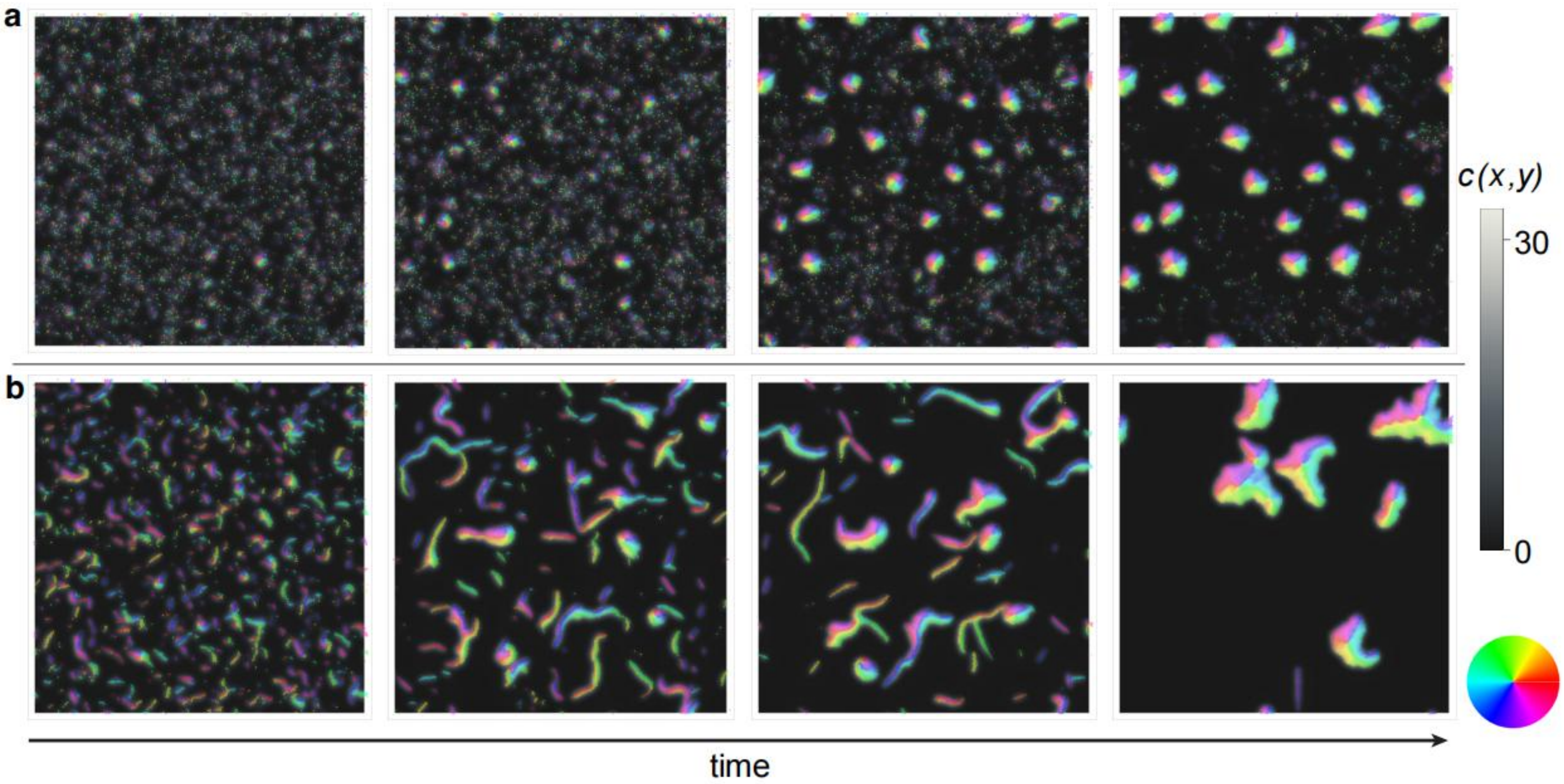
Results



$$\partial_t c(\mathbf{r},\mathbf{t}) = D_c \Delta c - \alpha c + \beta \sum_{i=1}^{N} f\left(|\mathbf{r}-\mathbf{r}_i|\right)\phi\left(s_i, c\right), \tag{3}$$

$$\frac{\mathrm{d}s_i}{\mathrm{d}t} = \epsilon\left(c - s_i\right). \tag{5}$$

Results



$$\frac{\mathrm{d}\varphi_i}{\mathrm{d}t} = -\Gamma \sum_{j[r_{ij}<r_c]} \frac{\sin(\varphi_i-\varphi_j)}{|\mathbf{r}_i-\mathbf{r}_j|} + \omega \sin(\varphi_c-\varphi_i) + \xi_i, \qquad (2)$$

By the way

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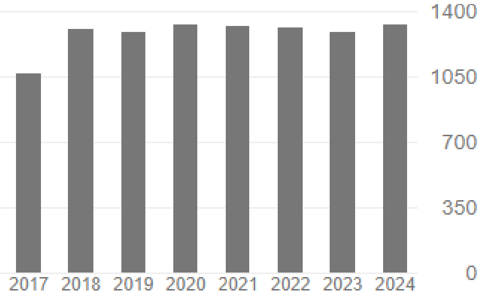

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