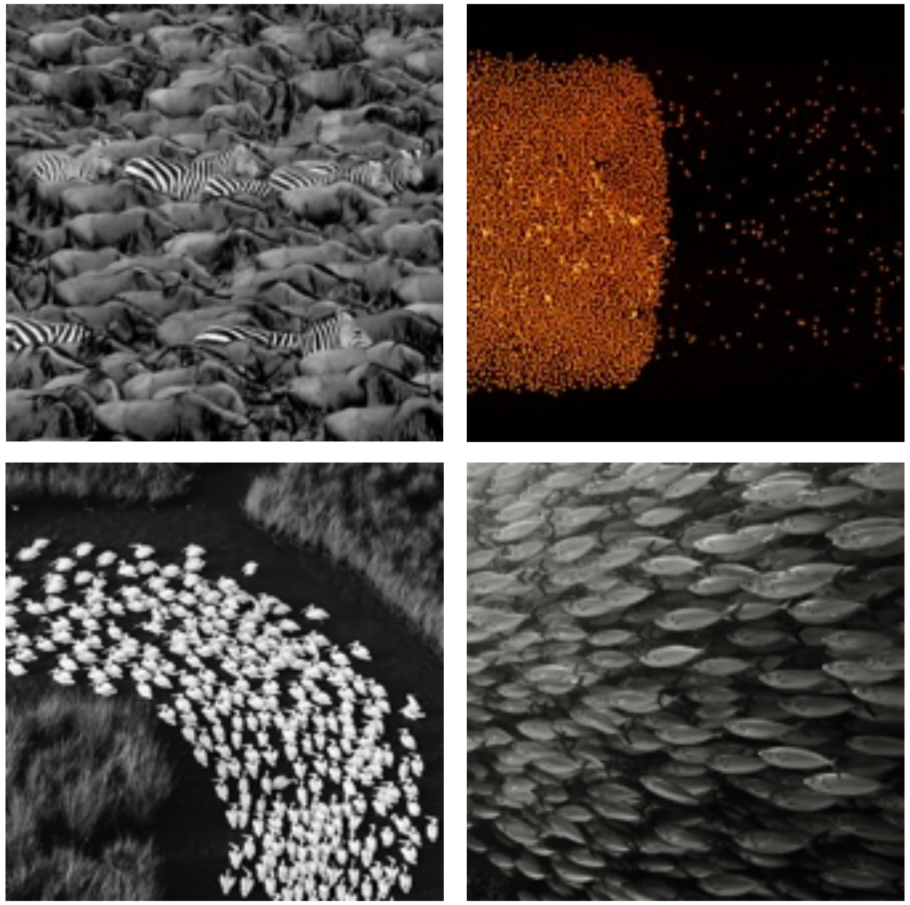
Collective Motion in Populations of Colloidal Bots



Denis **B**artolo

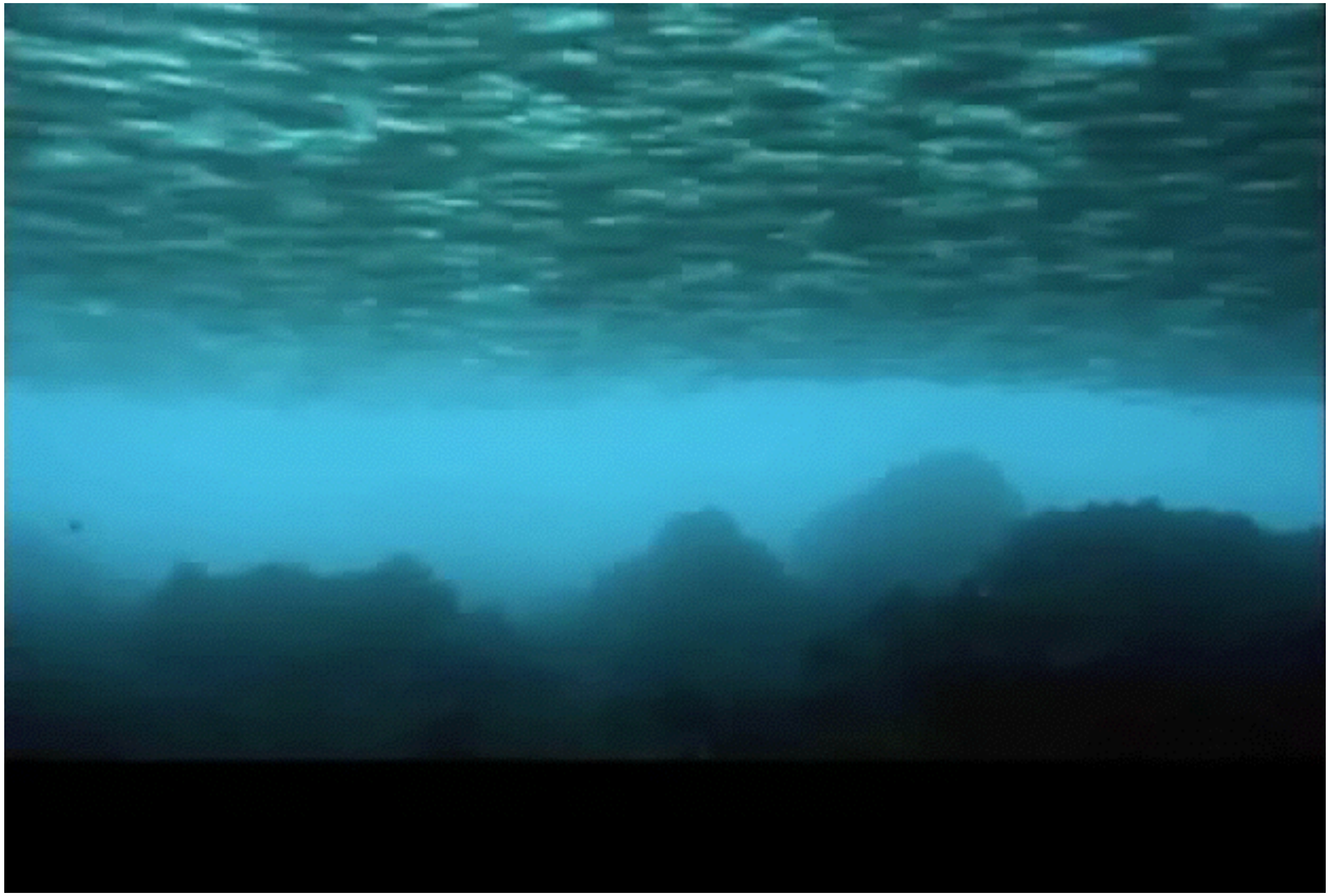
Antoine Bricard (PhD), Jean-Baptiste Caussin (PhD), Nicolas Desreumaux (PhD), Olivier Dauchot (EC2M, ESPCI)

ESPCI ParisTech

ENS DE LYON

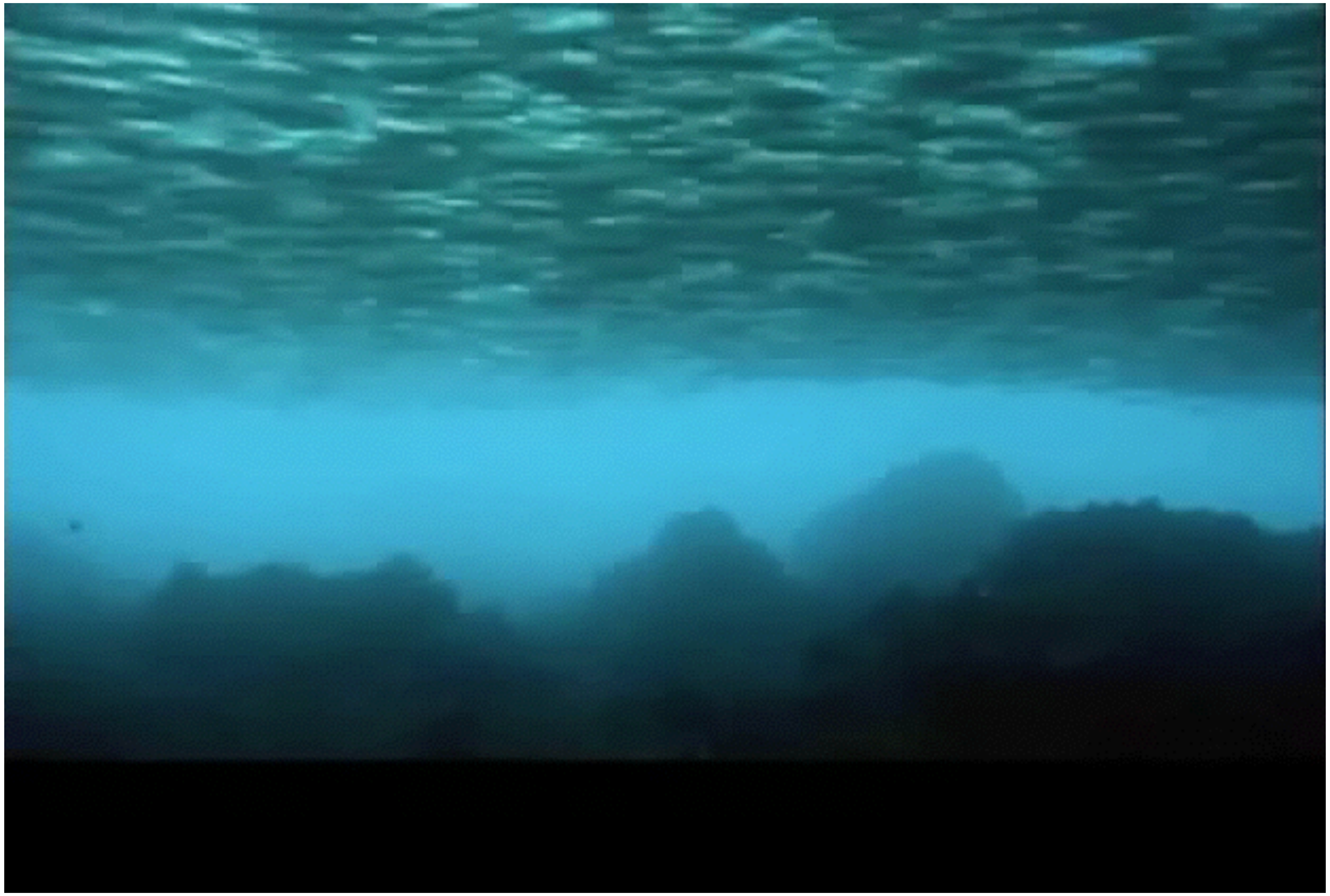
IUF

Coherent directed motion



Sardines: 7km-long school

Coherent directed motion



Sardines: 7km-long school

Coherent directed motion

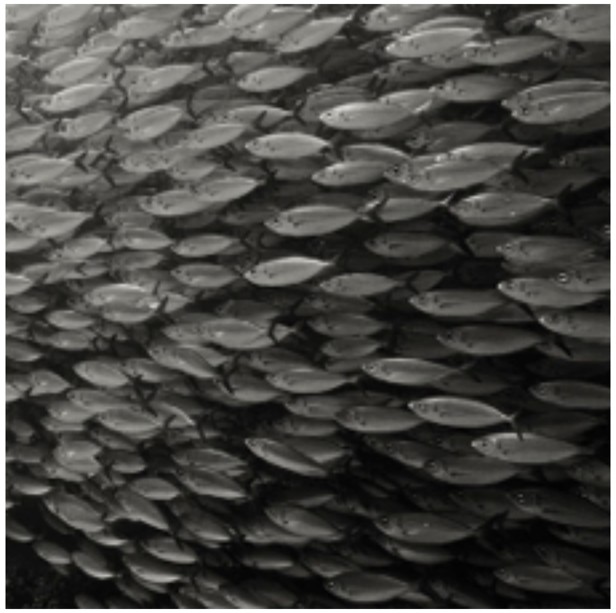
Locusts: 14km-long swarm

Coherent directed motion

Locusts: 14km-long swarm

Similar large-scale behavior

National geographic



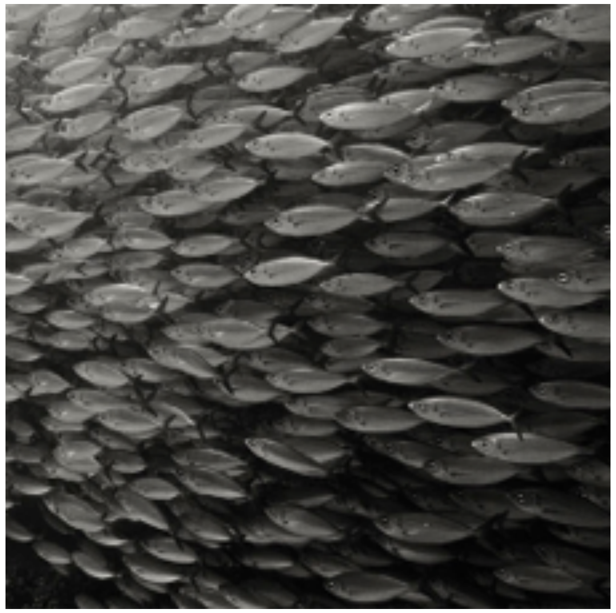
Steve Dunleavy

National geographic

National geographic

Different interactions at the individual level


National geographic

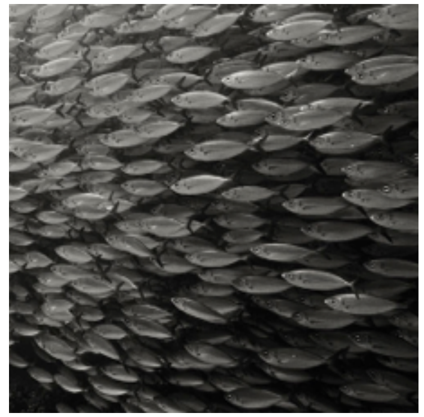

Steve Dunleavy

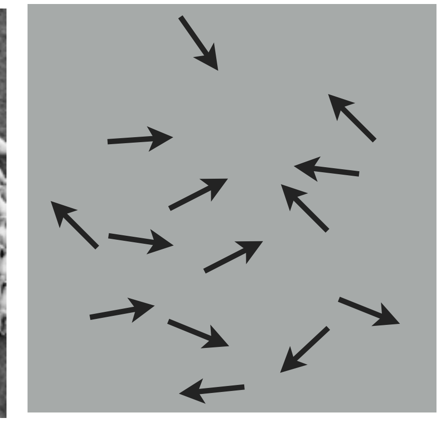

National geographic


National geographic

Physicists’ comfort zone

Flocking

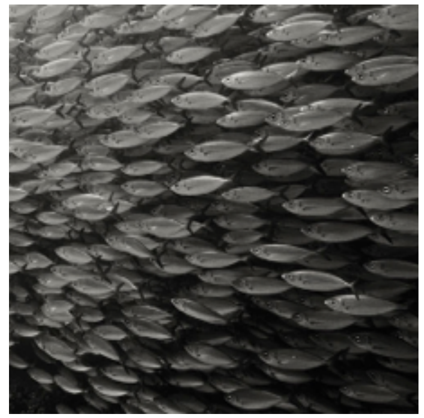
$\mathbf{v}_\mathbf{i}$ Emergence of directed motion?

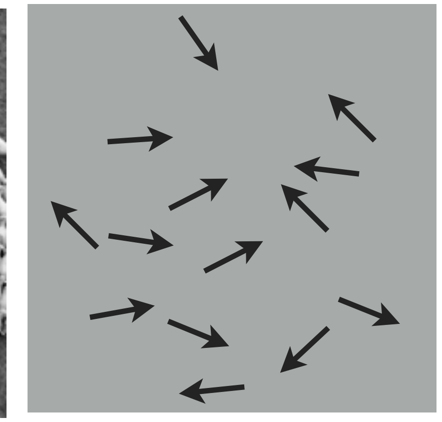
How is the rotational symmetry broken?

$\mathbf{r}_\mathbf{i}$ Self-organization into “localized” groups?

How is the translational symmetry broken?

Flocking

$\mathbf{v_i}$

Emergence of directed motion?
How is the rotational symmetry broken?

$\mathbf{r_i}$

Self-organization into “localized” groups?
How is the translational symmetry broken?

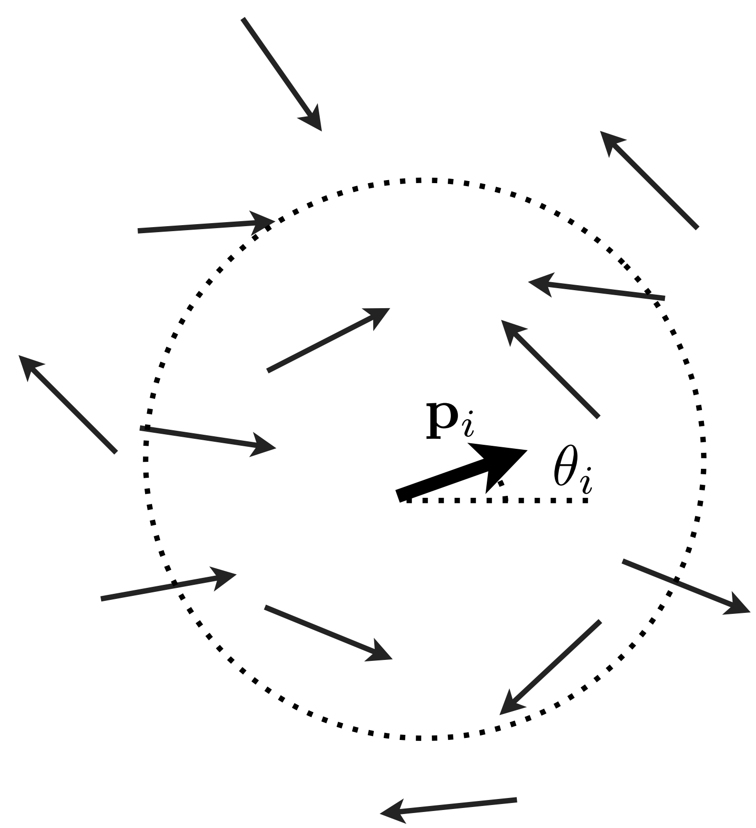
Vicsek model(s)

Self-propelled

$$\mathbf{v}_i = v_0 \mathbf{p}_i$$

Polar/Alignment interaction

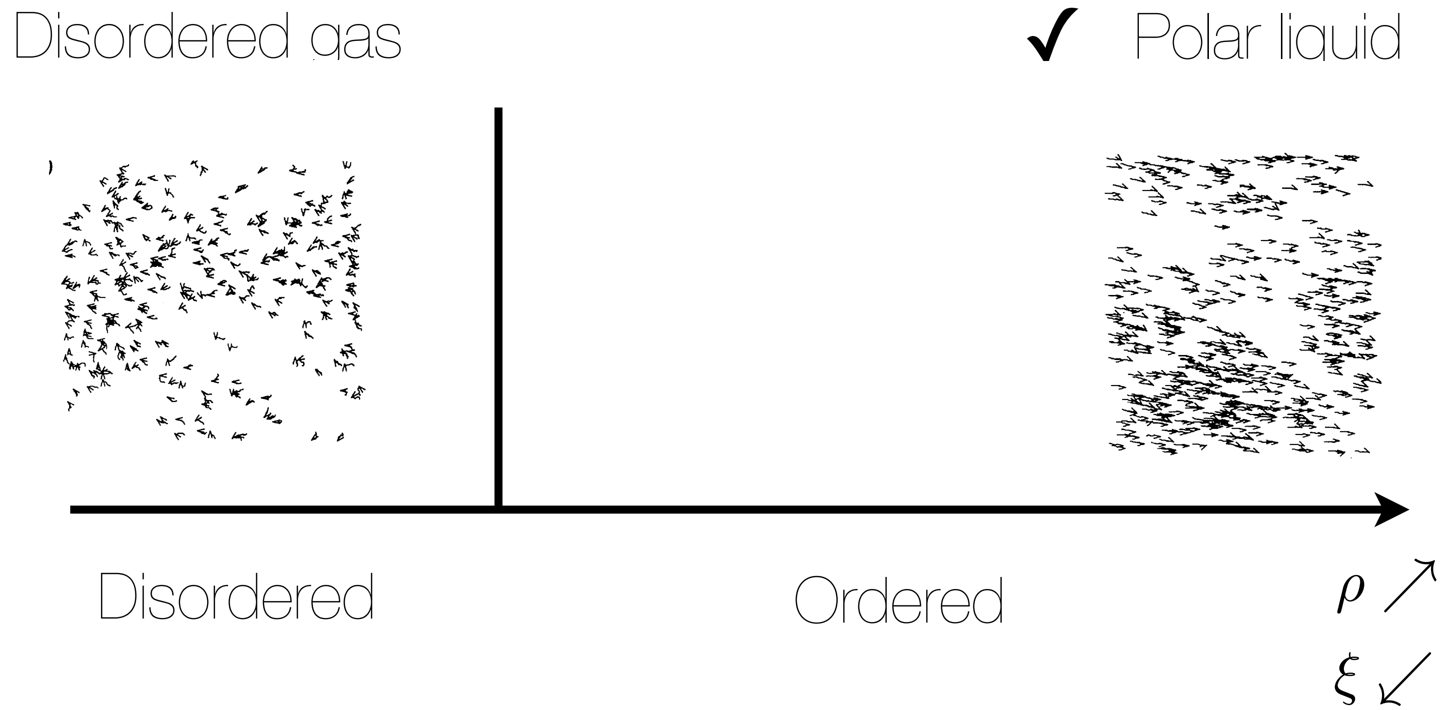
$$\theta_i(t+1) = \langle \theta_i(t) \rangle_R + \xi_i(t)$$



Polar active matter

Hallmarks of polar active matter

1



see e.g. Vicsek and Zafeiris Physics 2012
Toner, Tu and Ramaswamy 2005

Hallmarks of polar active matter

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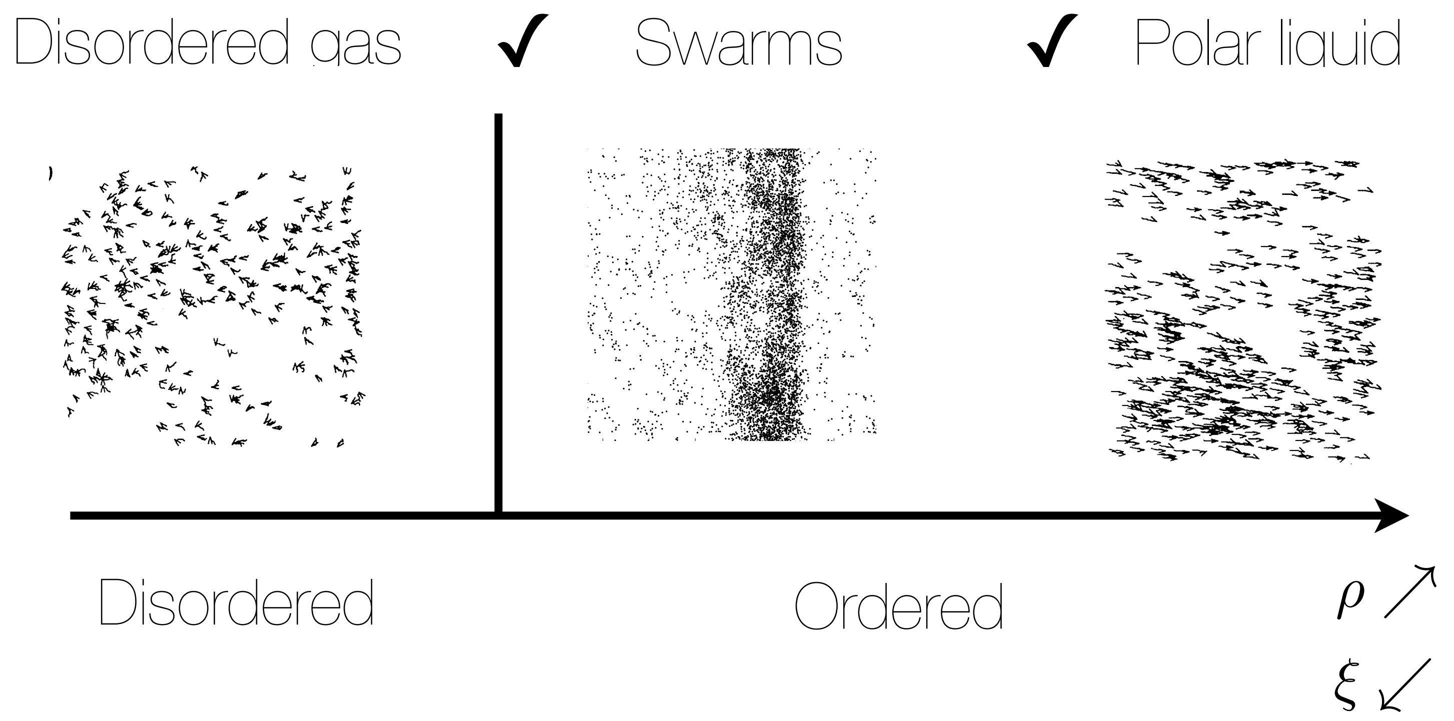

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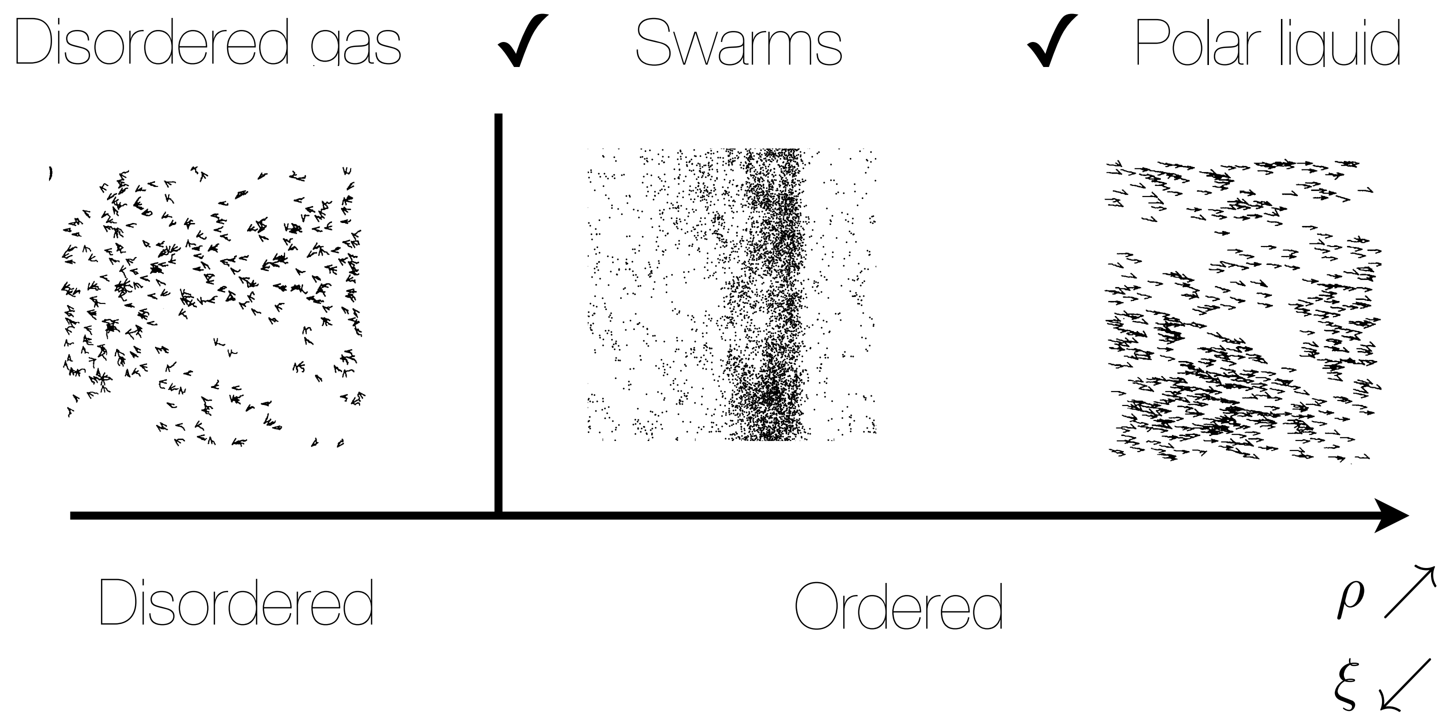
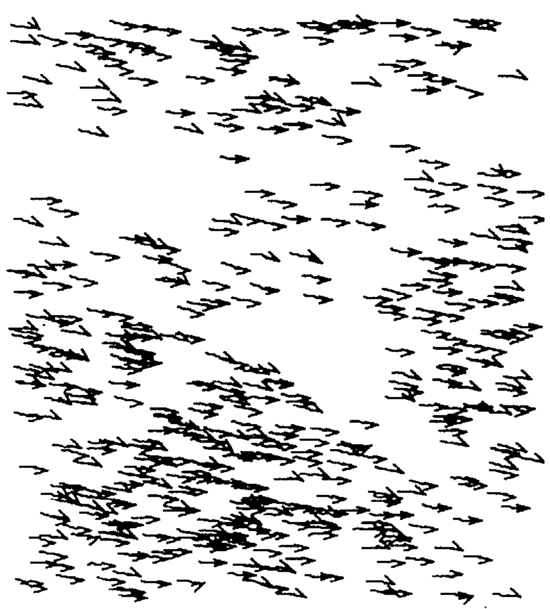


2



Giant Number Fluctuations

$$\Delta N \sim \langle N \rangle^{\alpha}$$

$$\alpha > 1$$

see e.g. Vicsek and Zafeiris Physics 2012
Toner, Tu and Ramaswamy 2005

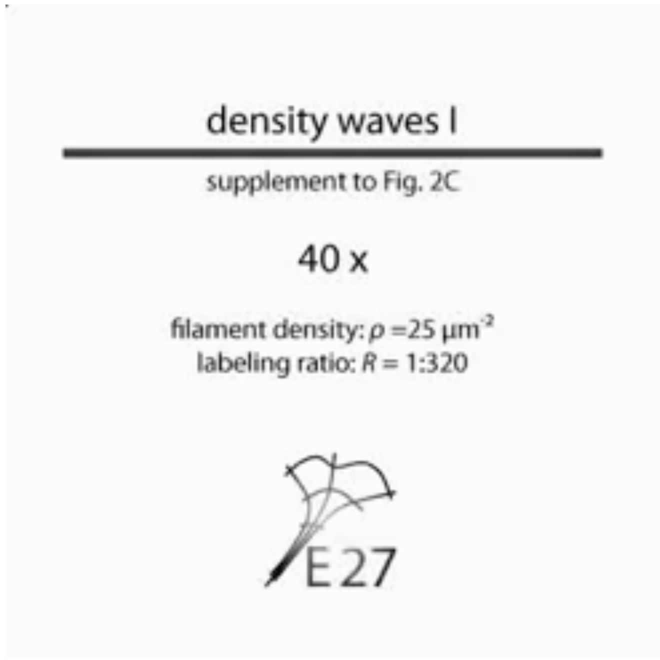
The hallmarks of active matter

3

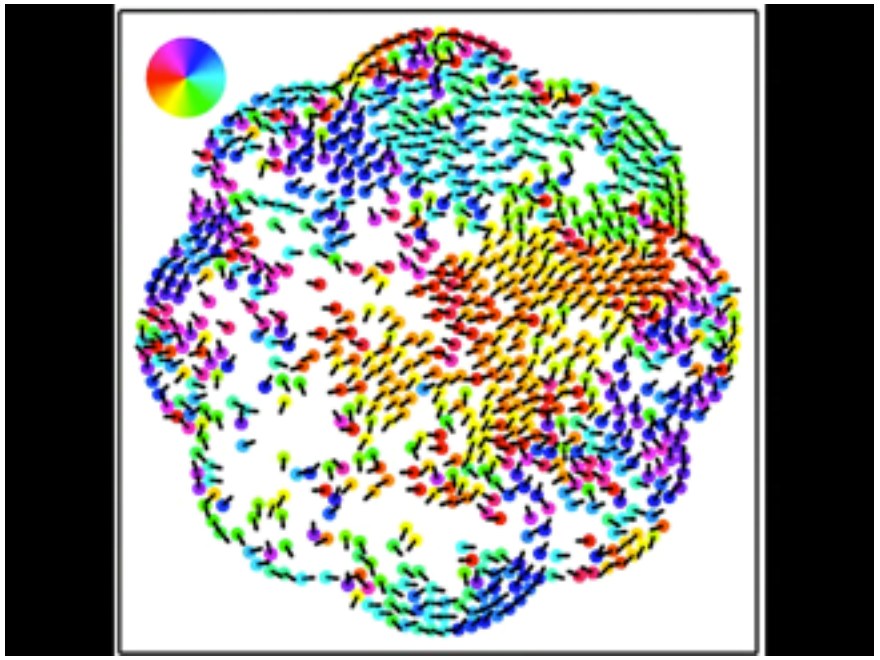
$$N_{\text{Theories}} \gg N_{\text{Experiments}}$$

The hallmarks of active matter

3 $$N_{\text{Theories}} \gg N_{\text{Experiments}}$$



Baush's group Nature 2010

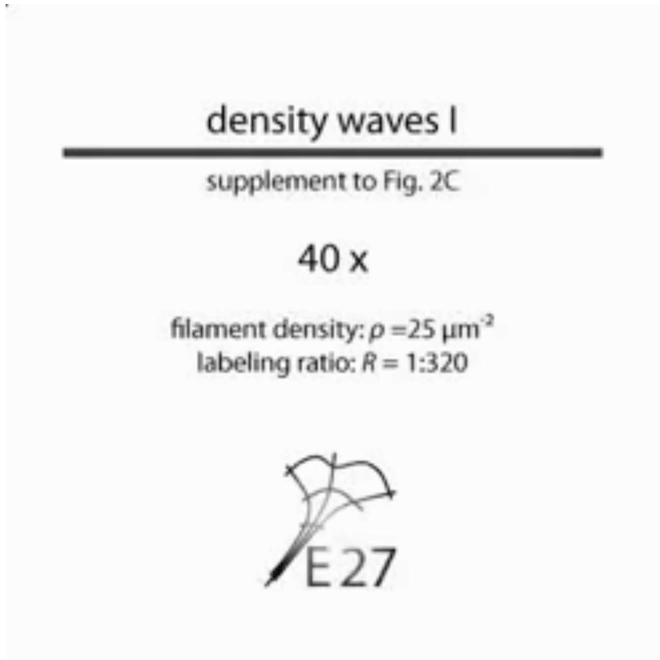


Dauchot's group PRL 2010

The hallmarks of active matter

3 $$N_{\mathrm{Theories}} \gg N_{\mathrm{Experiments}}$$

~0 model system until 2010



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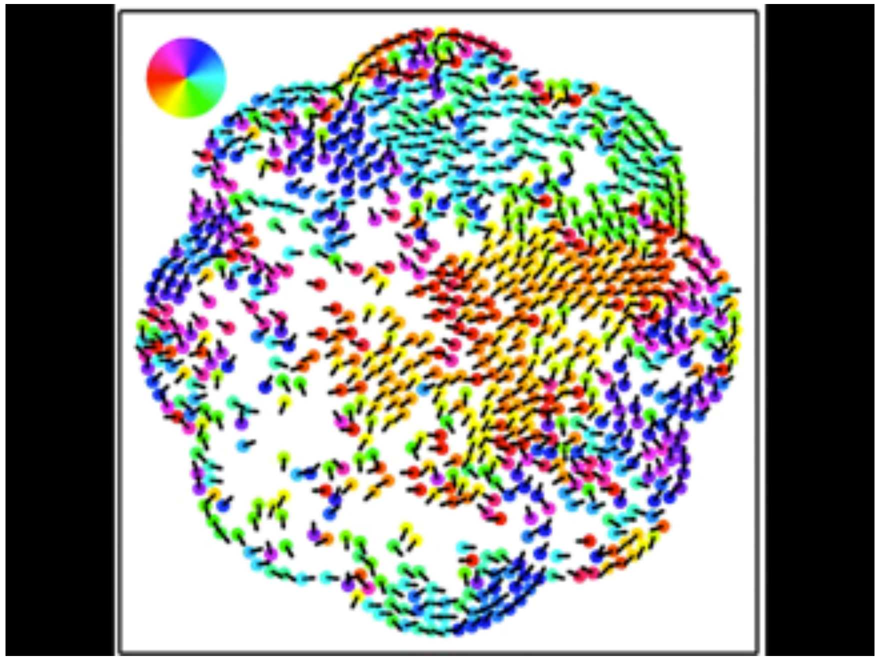


Dauchot's group PRL 2010

Polar-liquid phase?

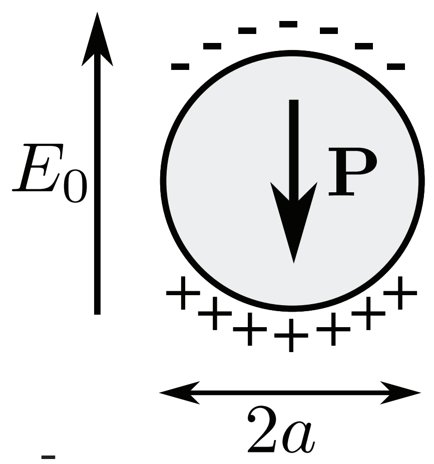
Requirements

- N>>>1 Small (Paris: 12 000 €/m²)
- Quantitative measurements (tracking)
- Known polar interactions

Self-propelled particles: 1st trick

Quincke Rotation

G. Quincke, Ann. Phys. Chem. **59**, 417 (1896).



Self-propelled particles: 1st trick

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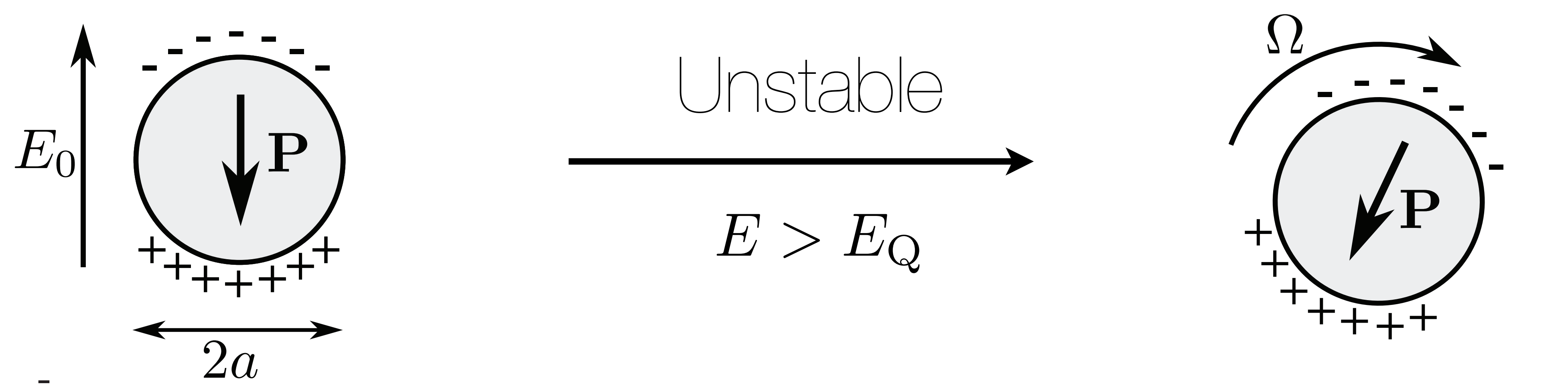
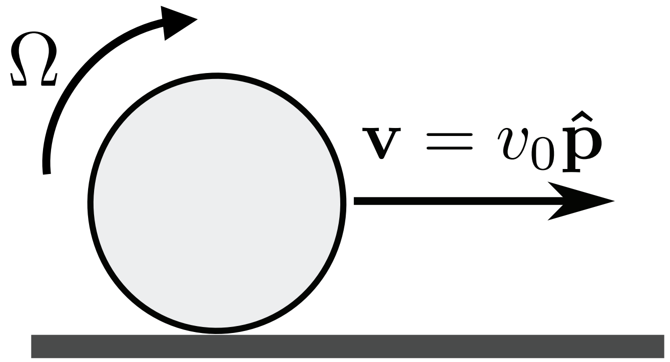
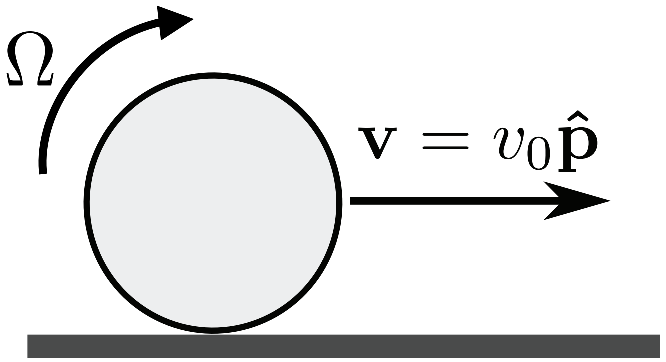


$$\mathbf{\Omega} \sim \mathbf{P} \times \mathbf{E}$$

Self-propelled particles: 2nd trick



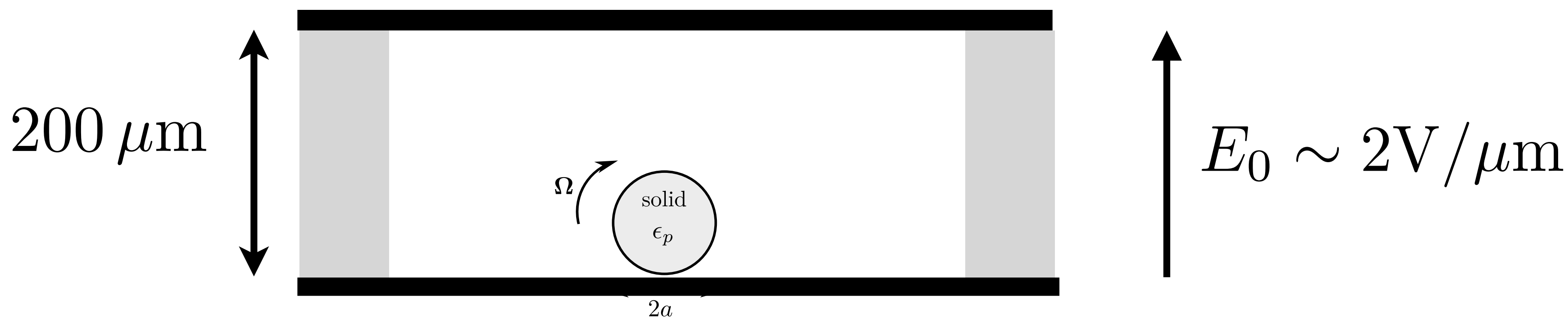
Self-propelled particles: 2nd trick



Self-propelled colloids

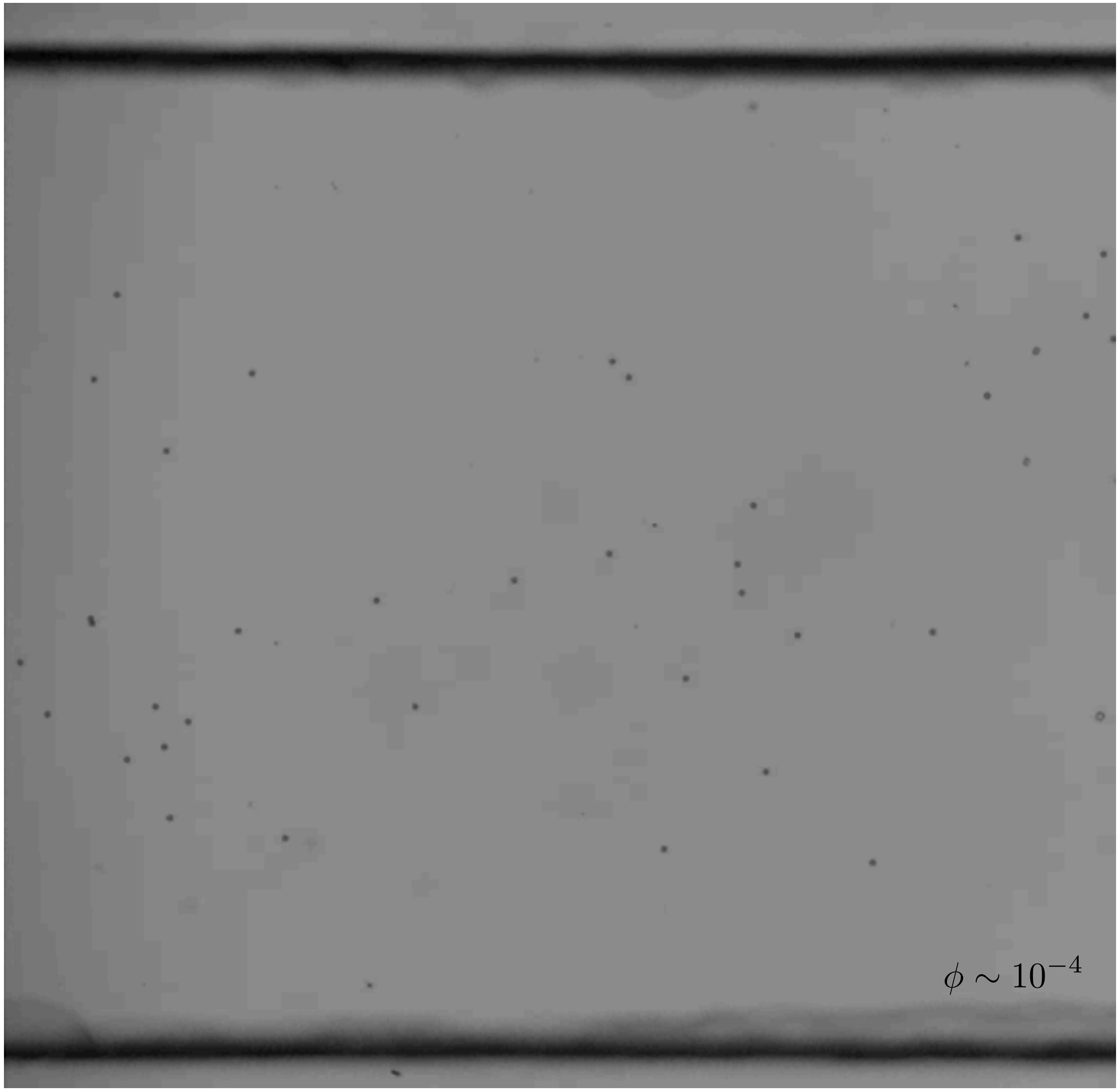
PMMA colloids
Hexadecane oil+AOT salt

Microfluidic channel:
ITO coated glass

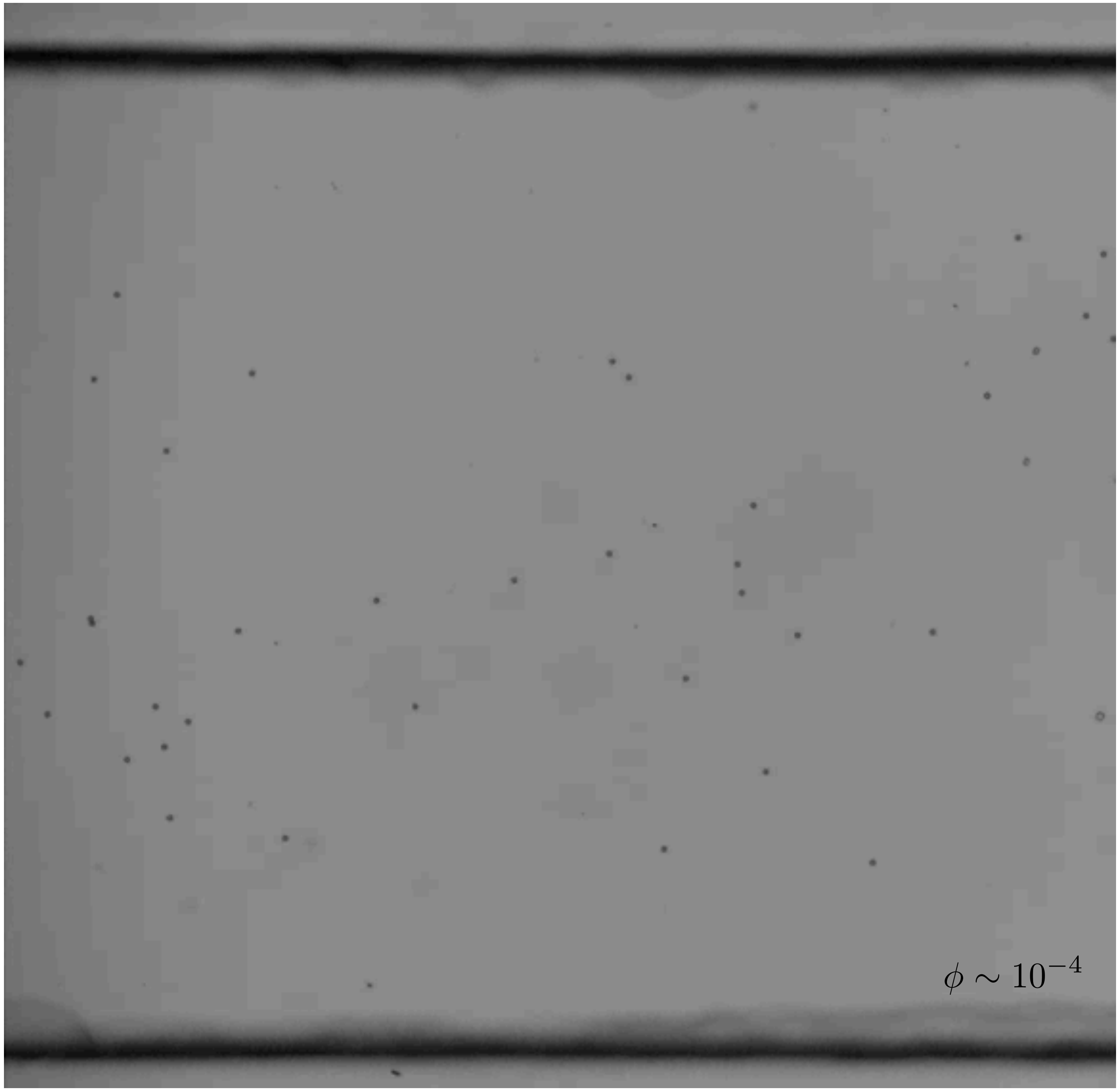


$2a = 5\,\mu\text{m}$

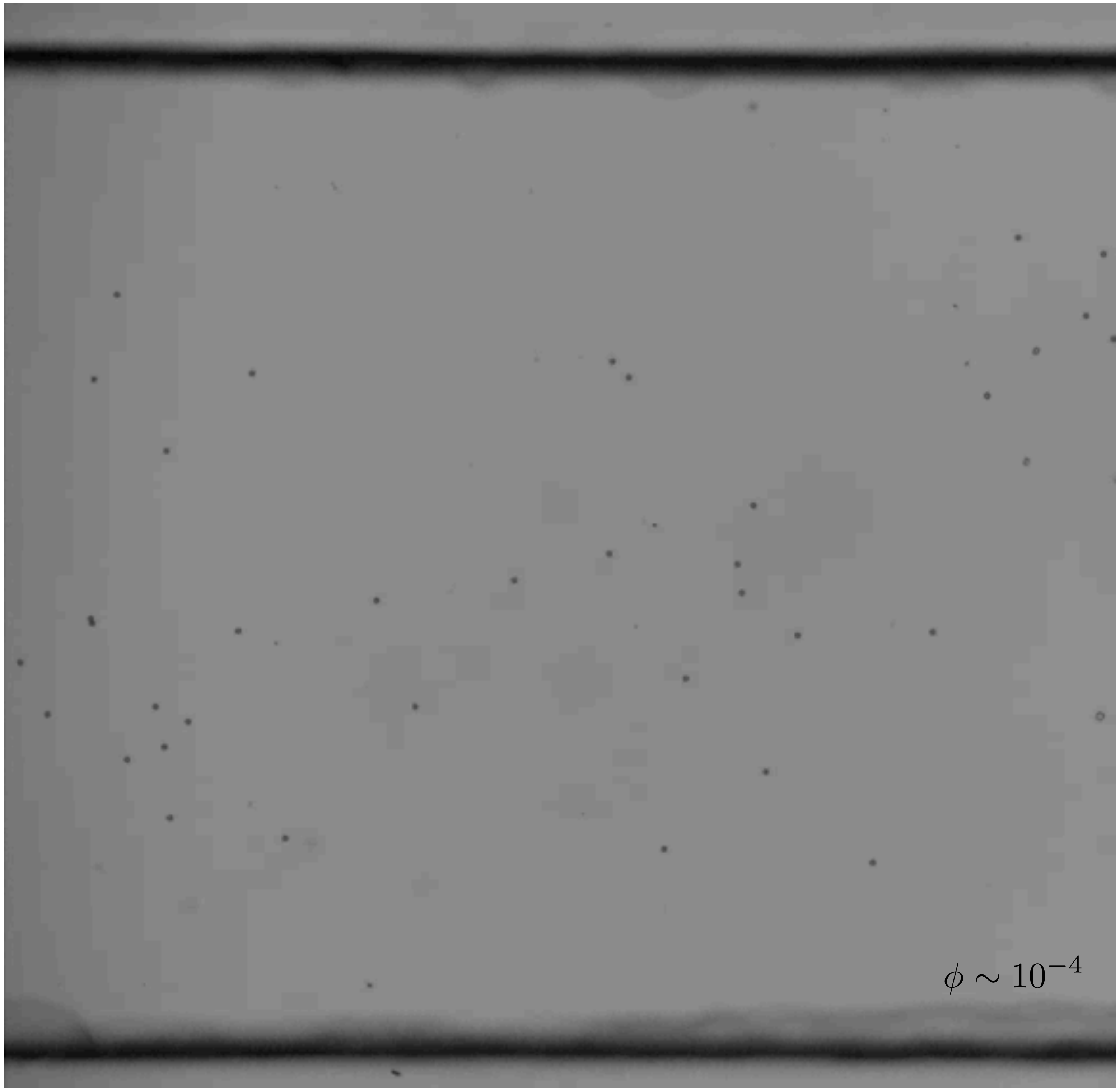
Colloidal rolling robots



Colloidal rolling robots

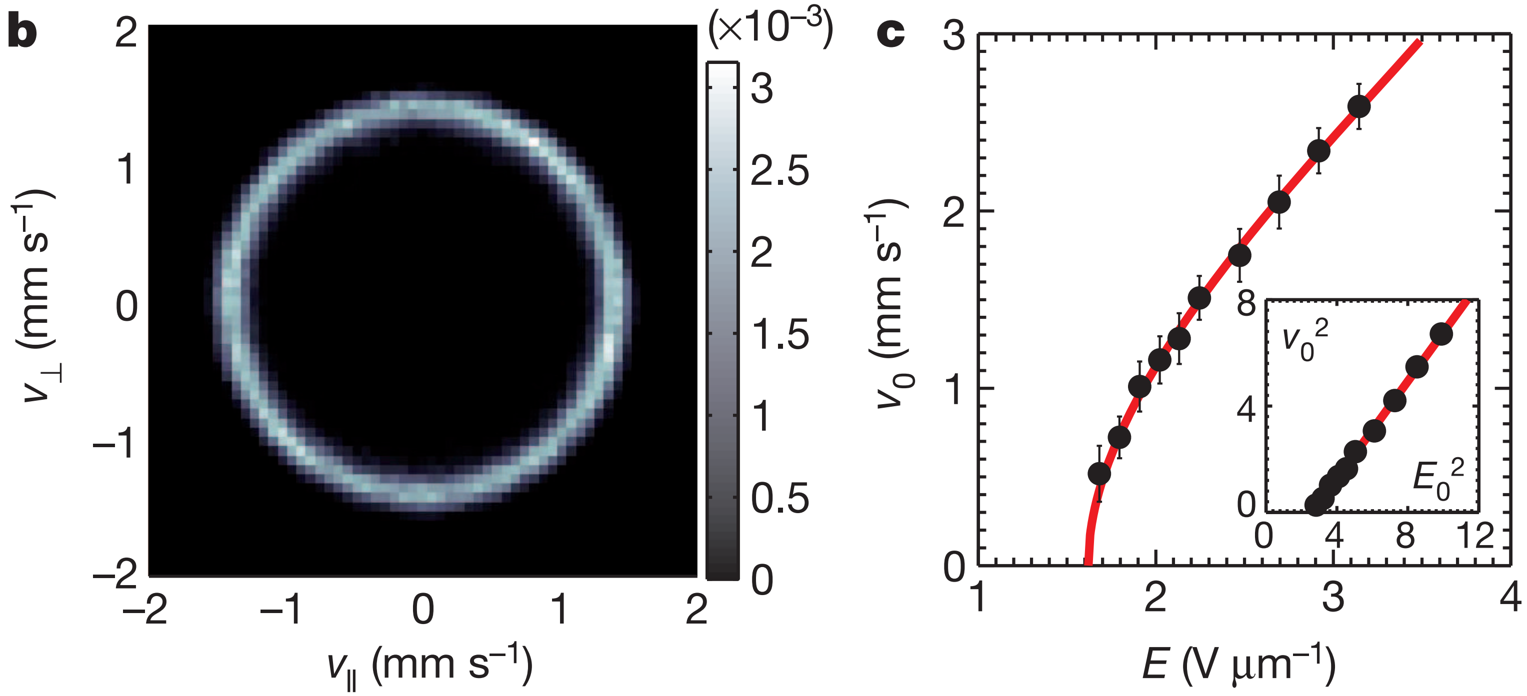


Colloidal rolling robots



$$v_0 = 1.5\,\mathrm{mm/s}$$

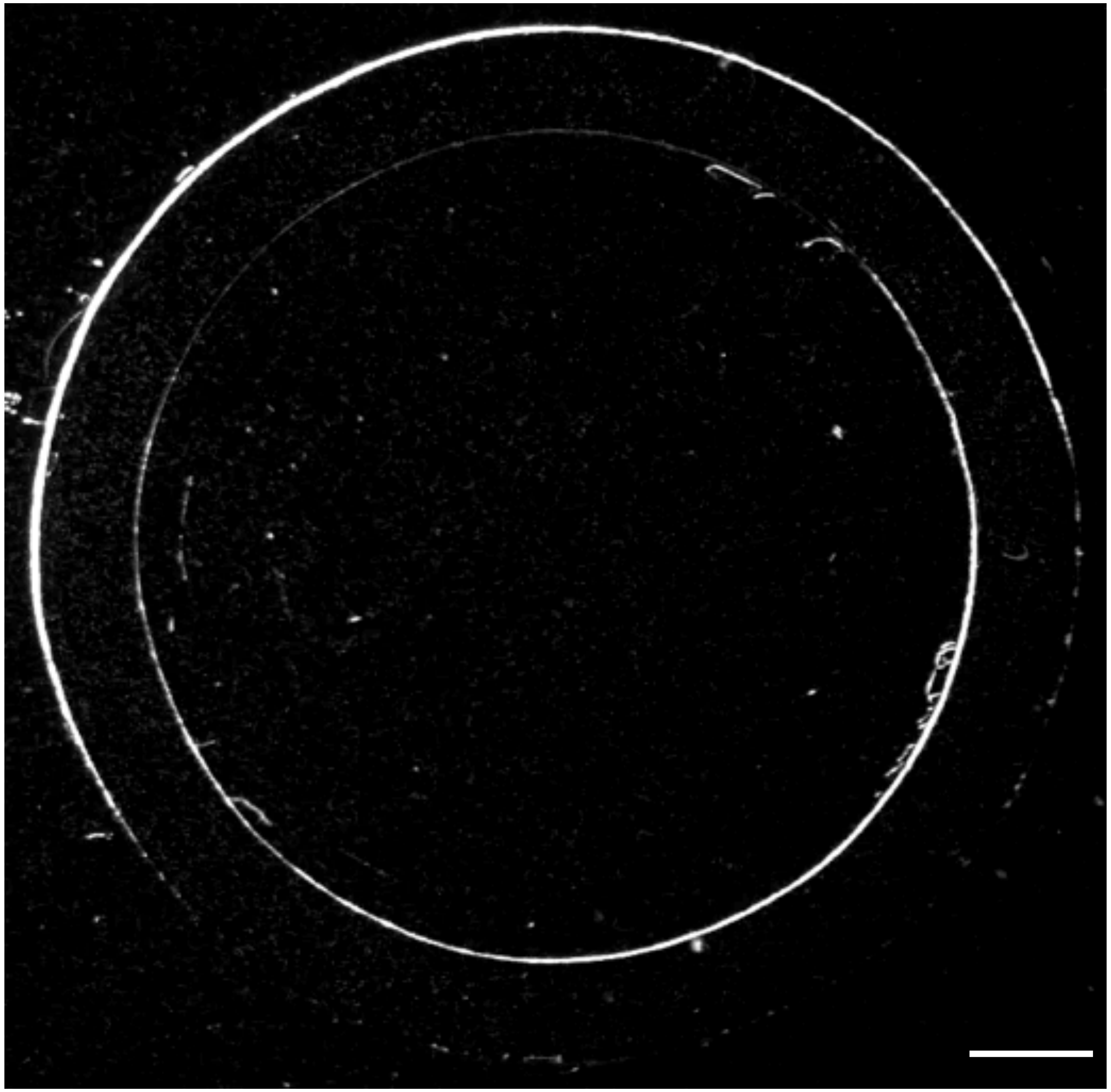
Self-propulsion: isotropic and tunable



✓

Collective motion?

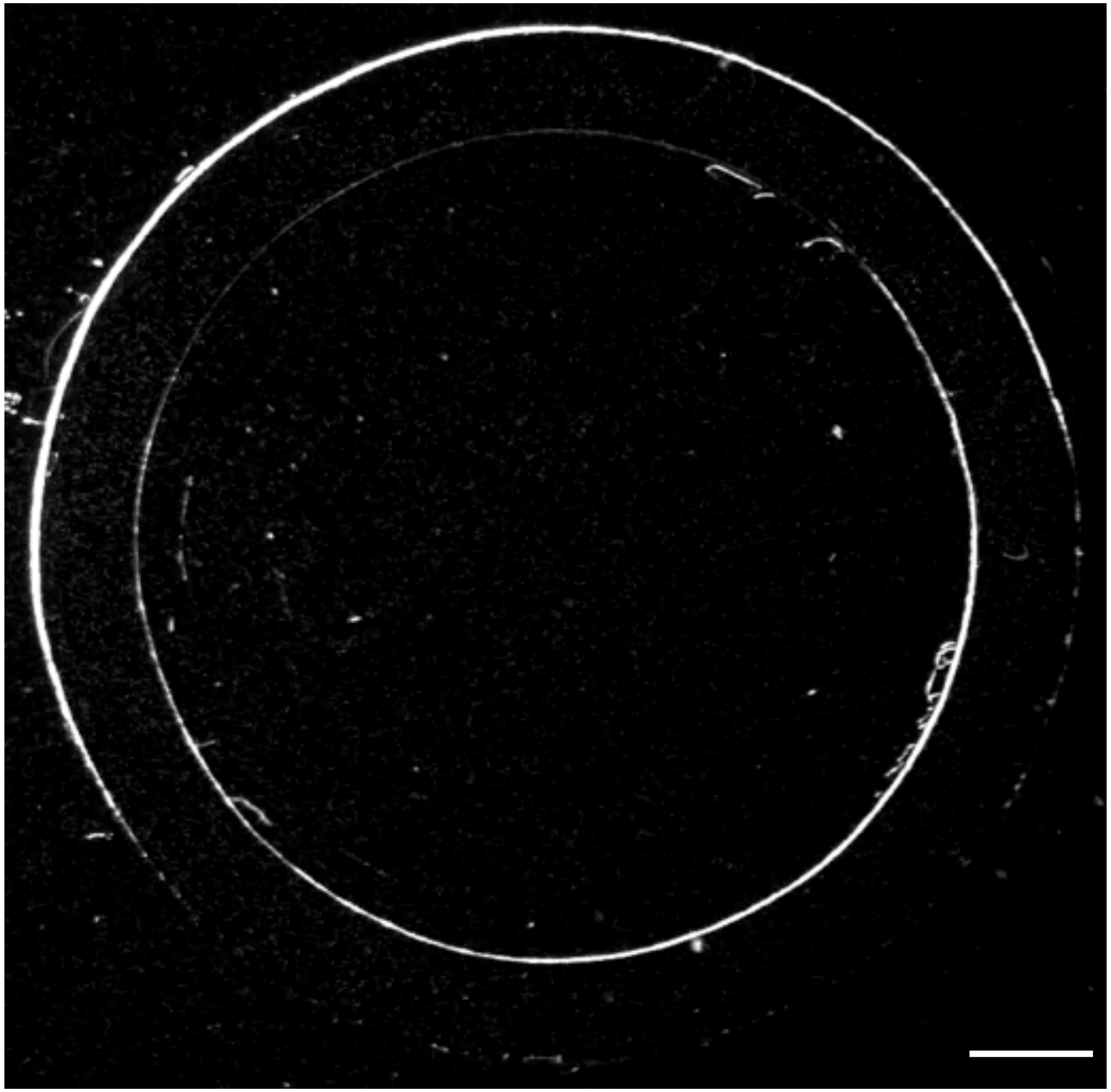
Periodic boundary conditions



1 mm

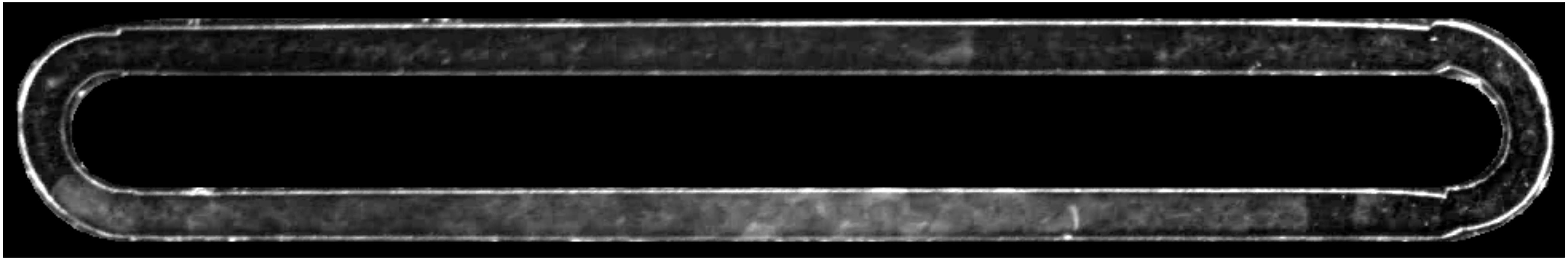
Collective motion?

Periodic boundary conditions



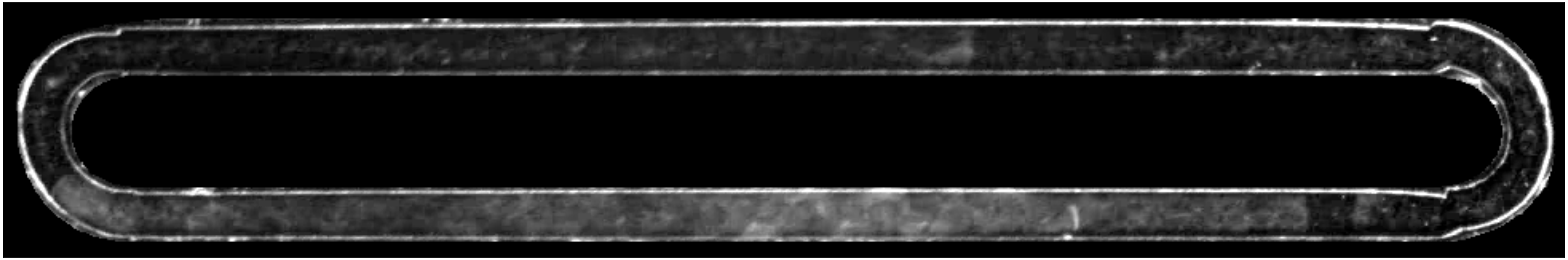
1 mm

Flocking



$\phi \sim 10^{-2}$

Flocking



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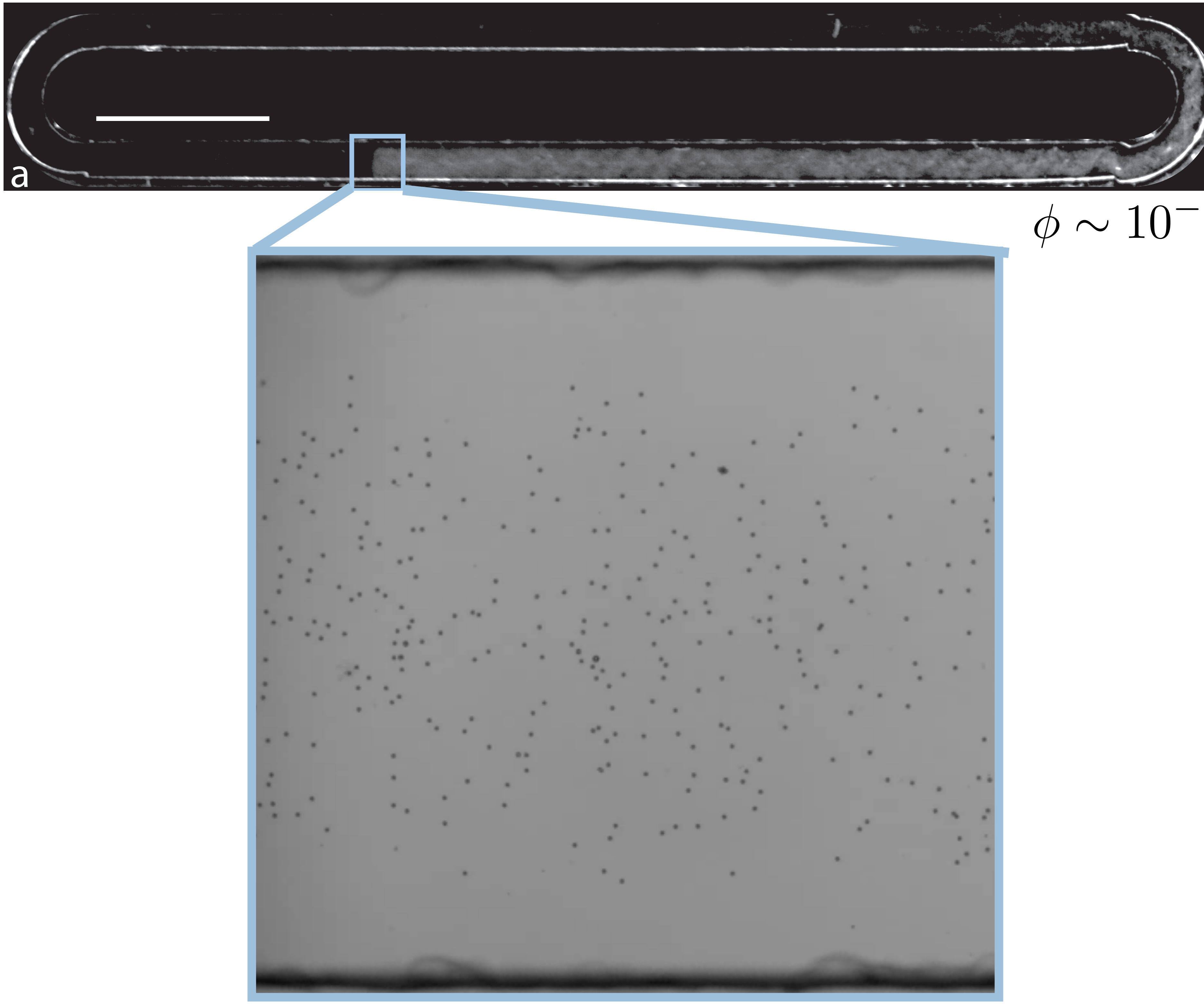
Flocking



$\phi \sim 10^{-2}$

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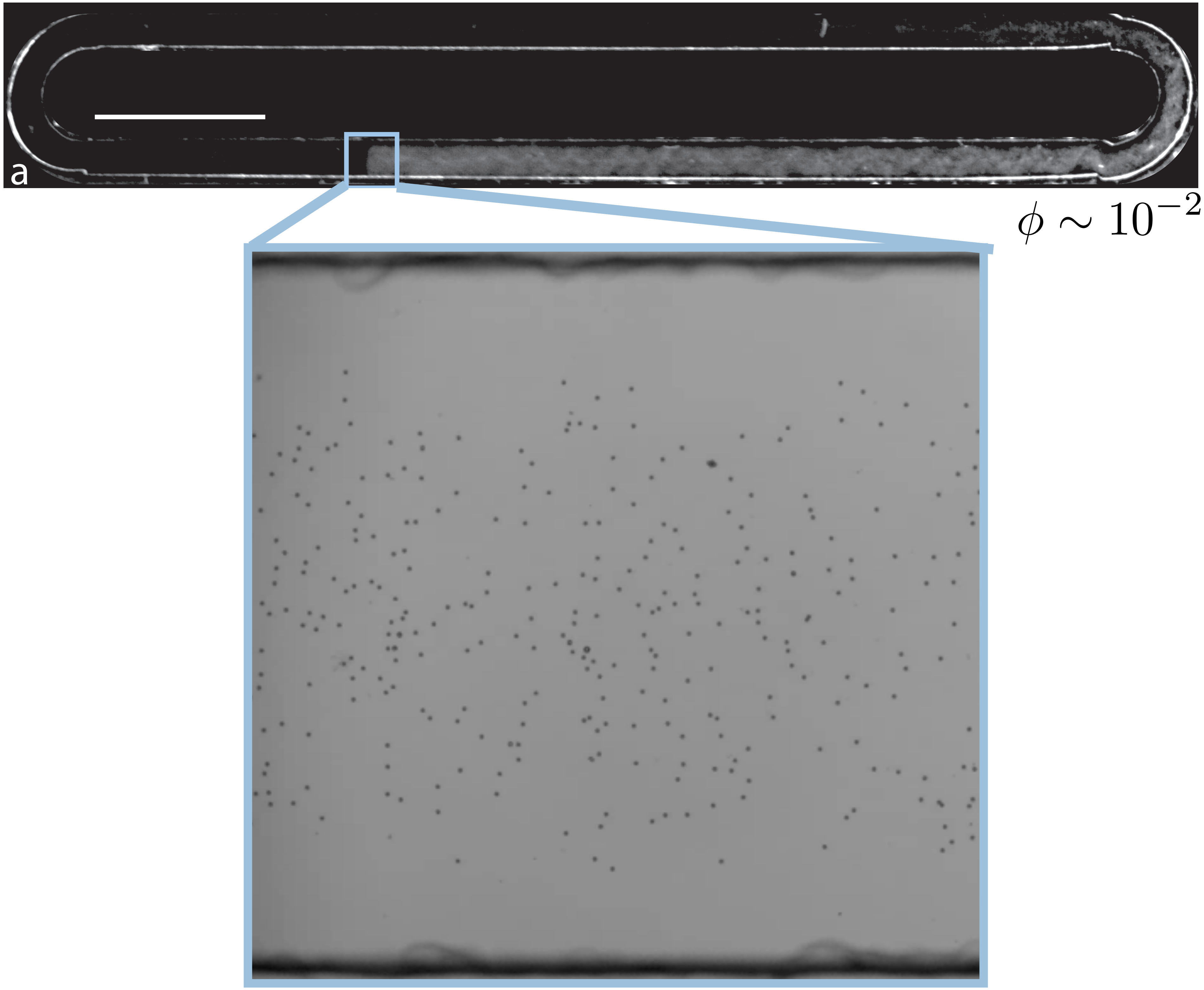
Bricard, Caussin, Desreumaux, Dauchot, and Bartolo, *Nature* (2013)

Flocking



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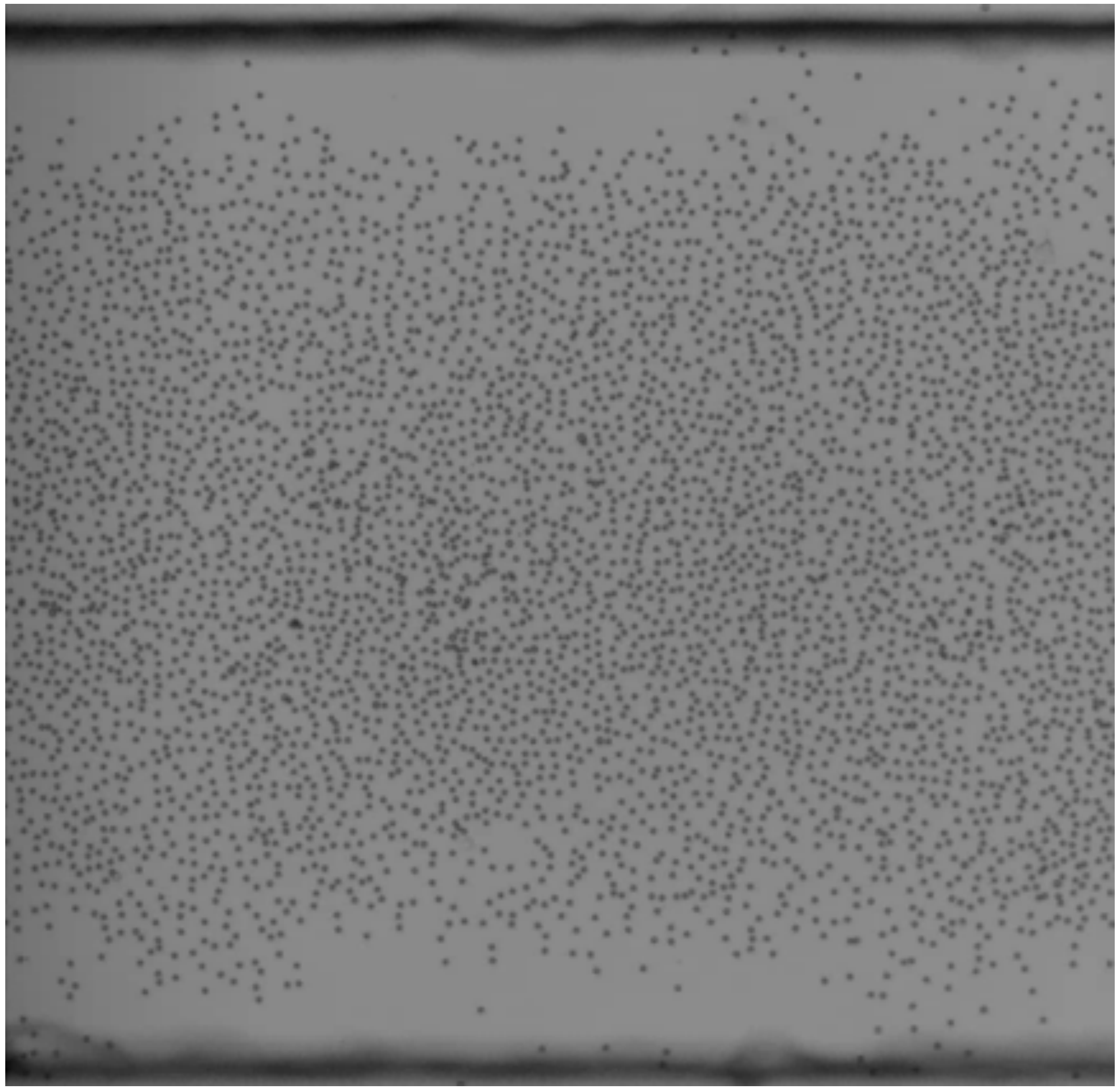
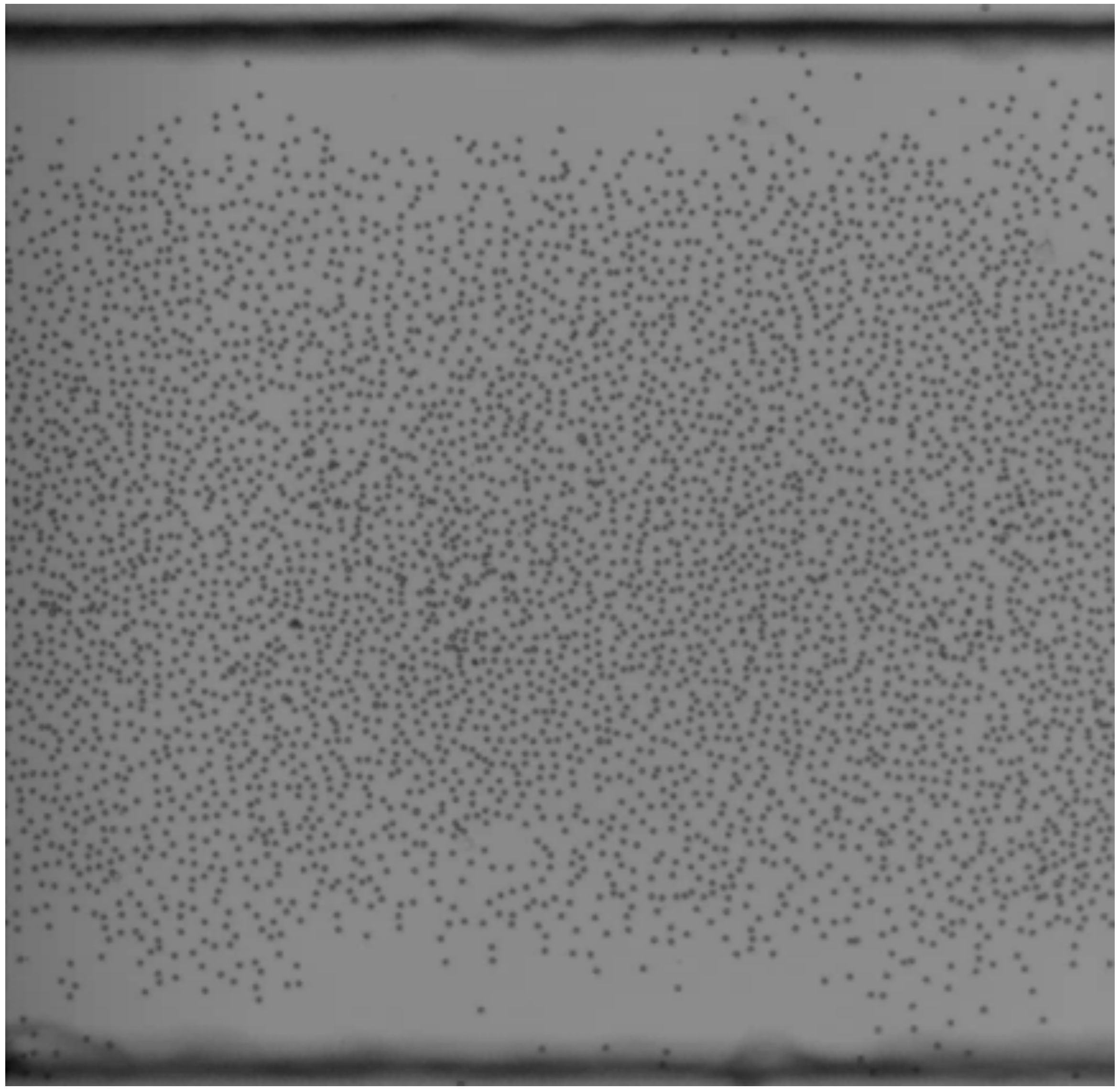
Bricard, Caussin, Desreumaux, Dauchot, and Bartolo, *Nature* (2013)

Polar-liquid phase



$\phi \sim 1.8 \times 10^{-1}$

Polar-liquid phase



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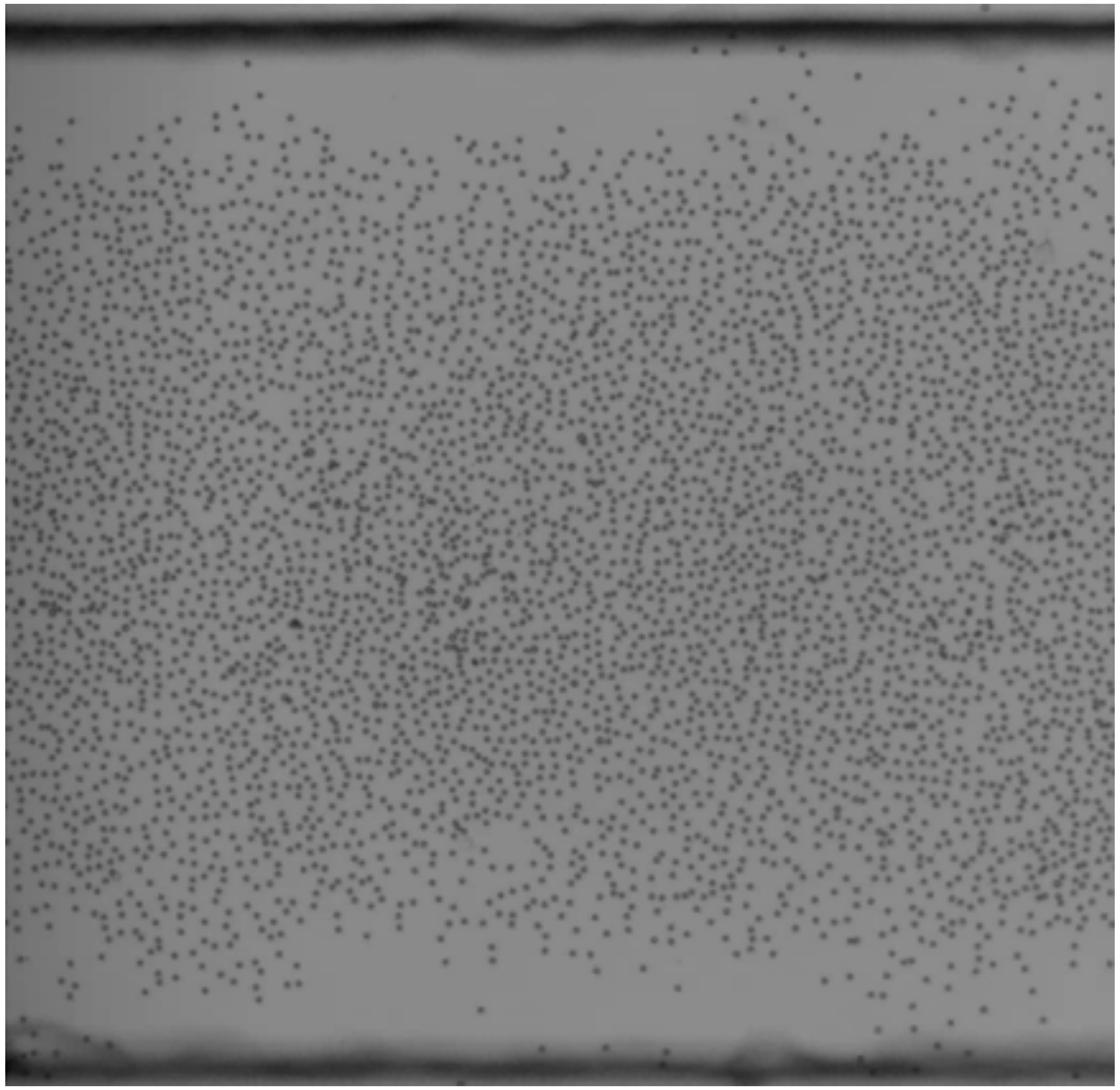
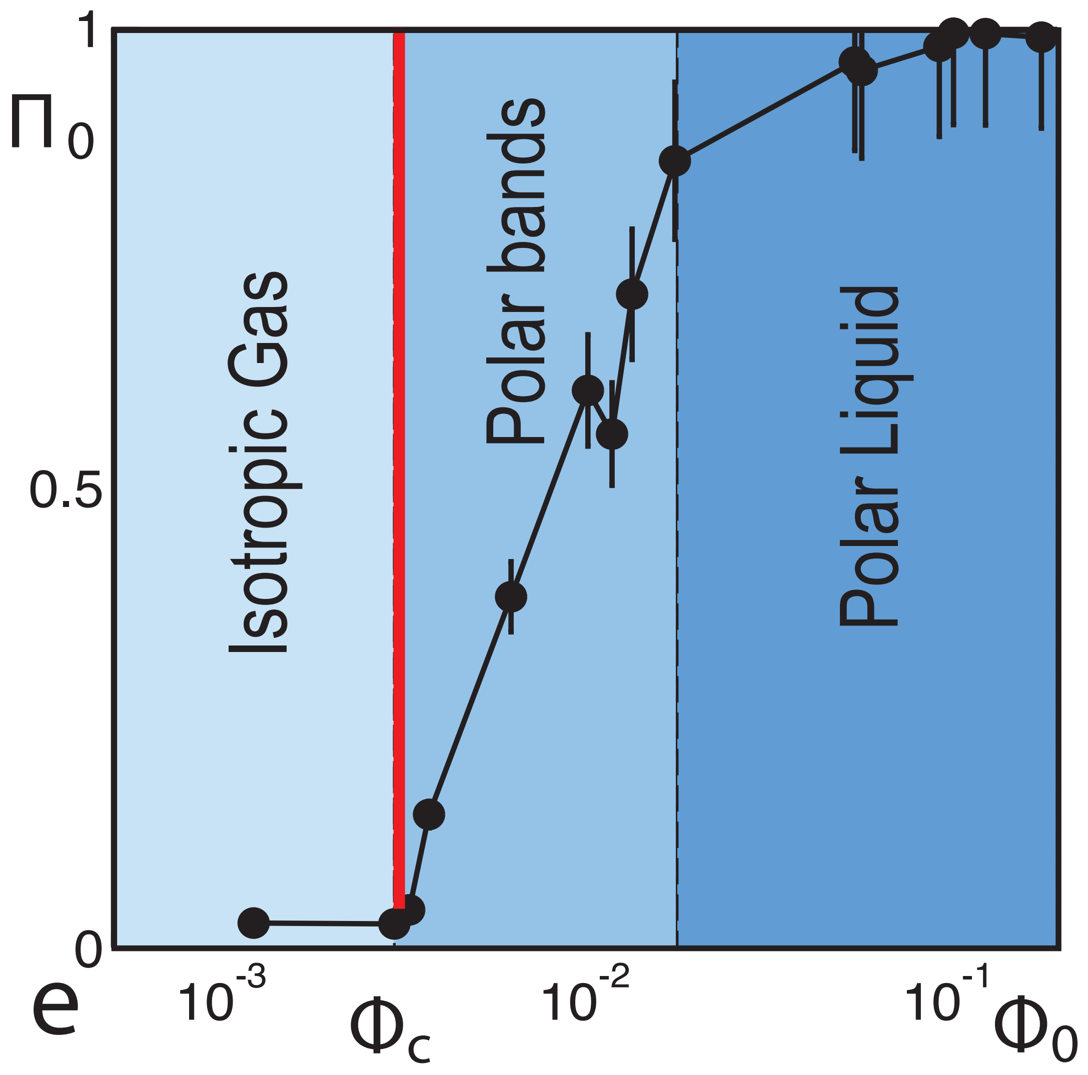


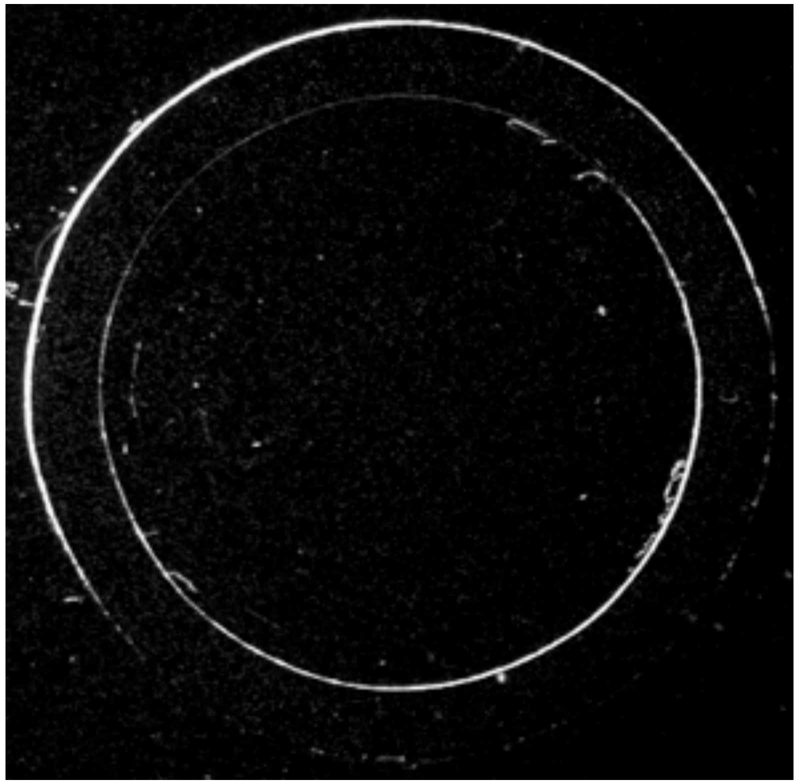
$\phi \sim 1.8 \times 10^{-1}$

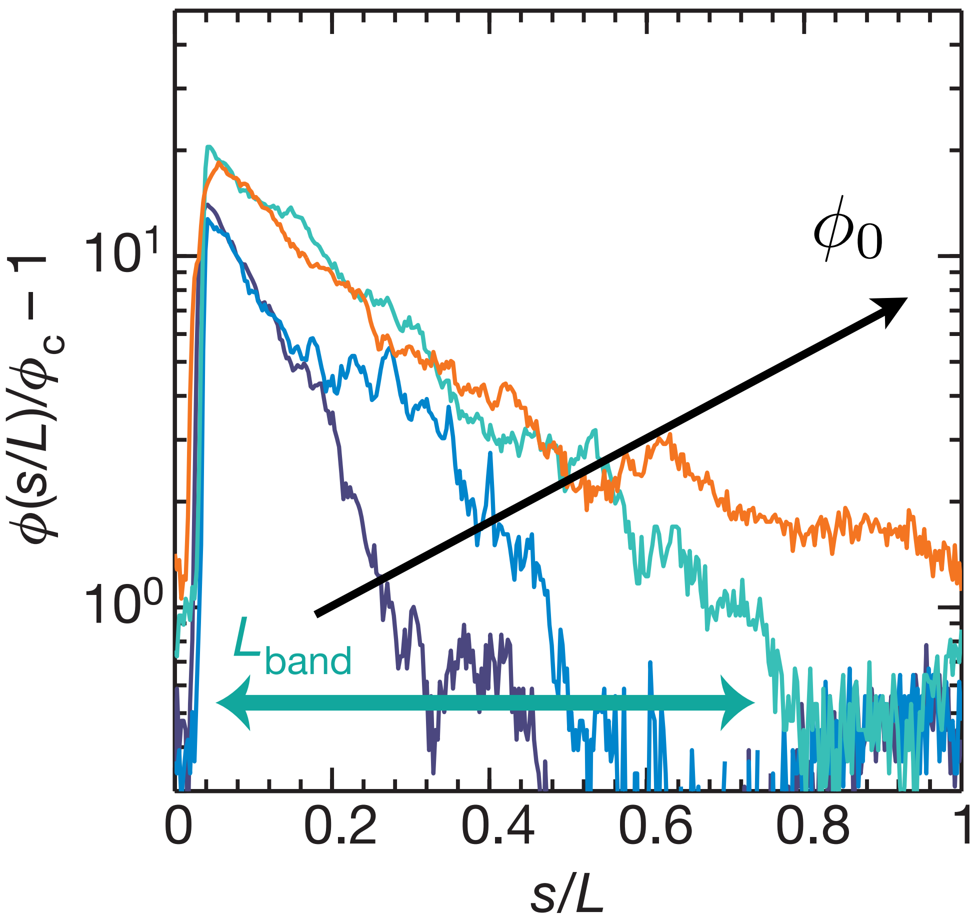
Phase behavior



Does NOT depend on the field amplitude

Colloidal swarms: Polar bands



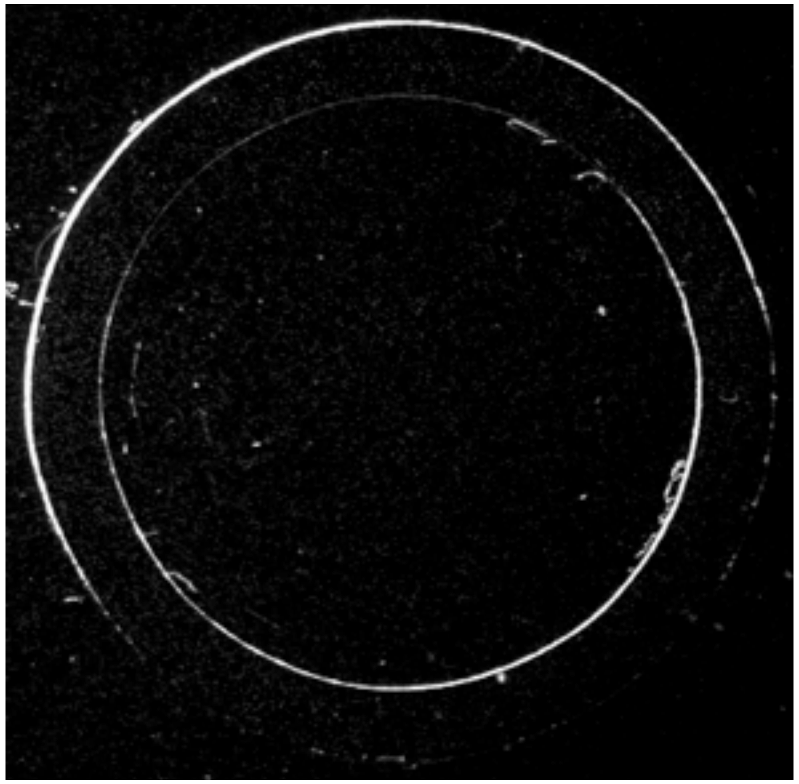


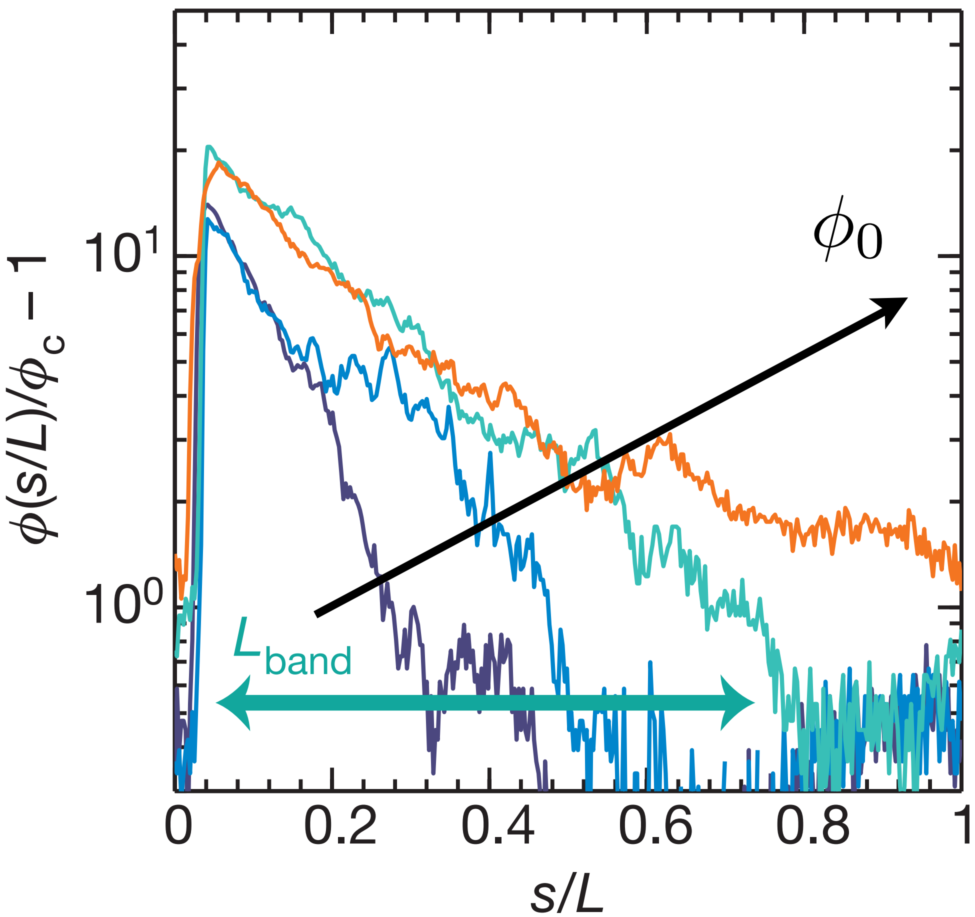
Exponential tail

$\phi_\infty \sim \phi_c$

$L_{\mathrm{band}} \nearrow \ \phi_0 \nearrow$

Colloidal swarms: Polar bands



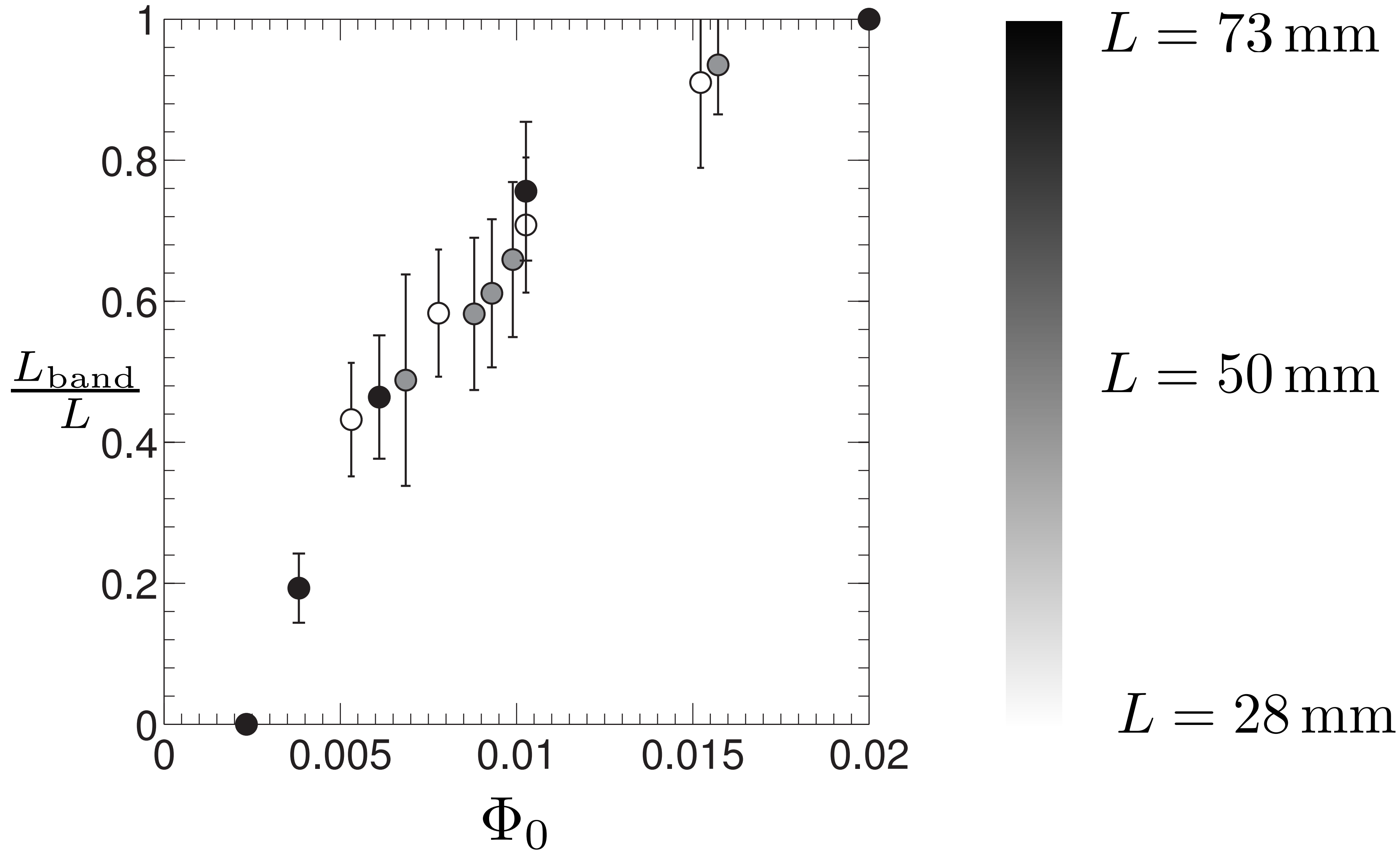


Exponential tail

$\phi_\infty \sim \phi_c$

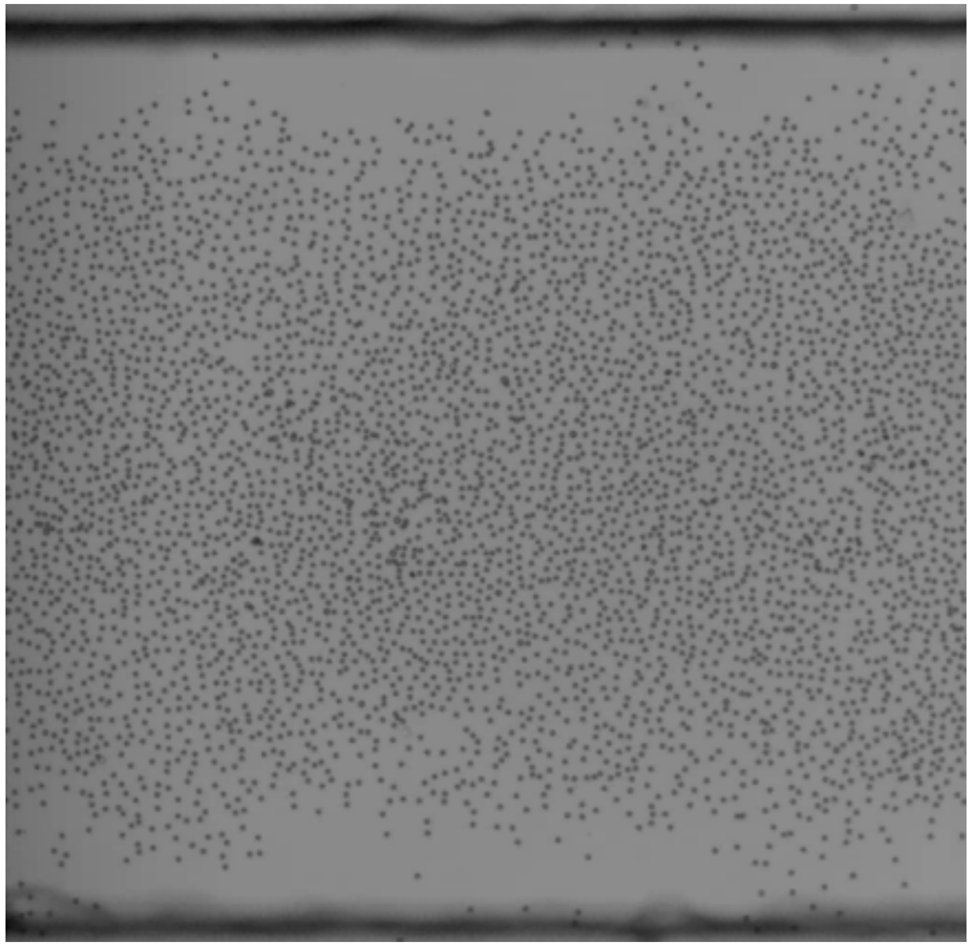
$L_{\mathrm{band}} \nearrow \; \phi_0 \nearrow$

No intrinsic length scale



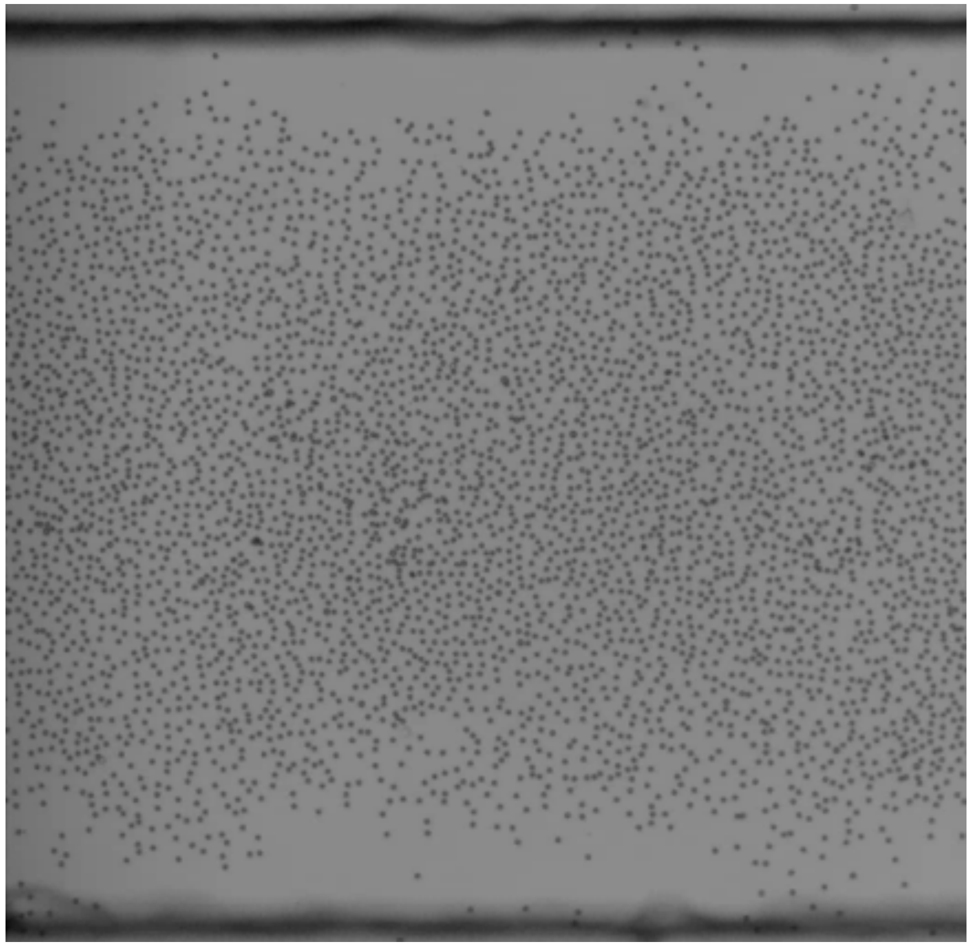
« Phase coexistence »

Polar liquid



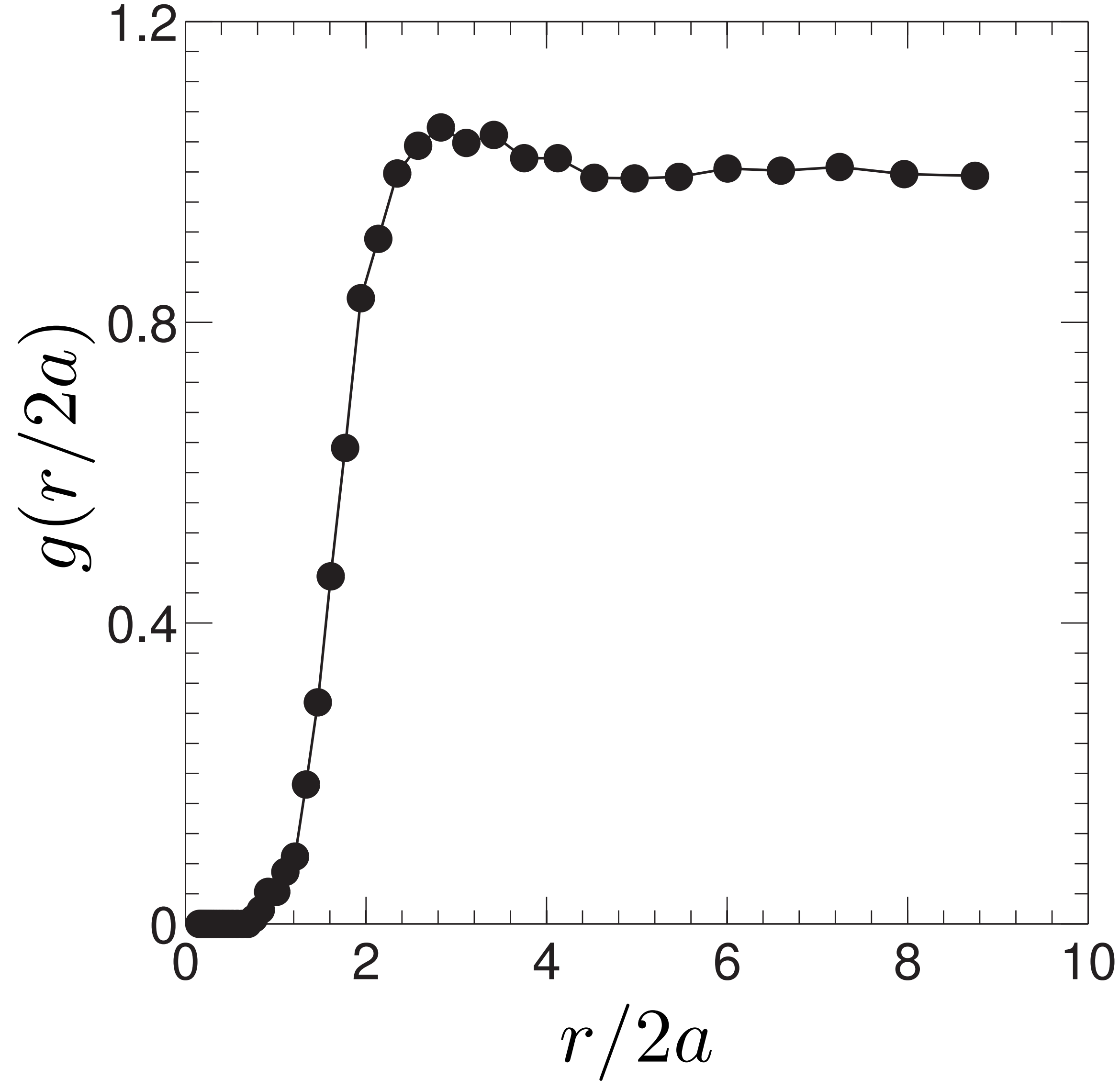
Spontaneously flowing liquid

Polar liquid



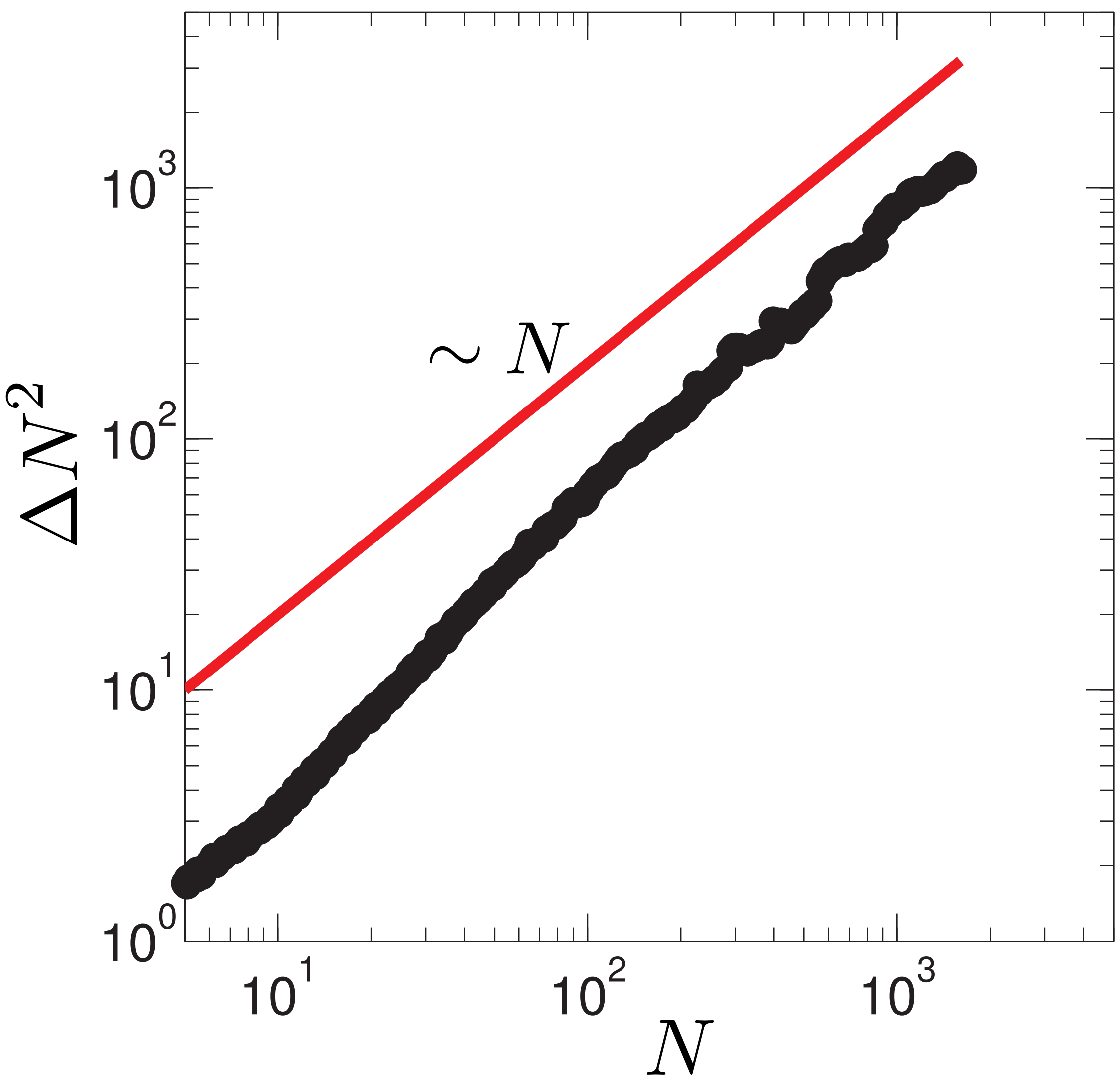
Spontaneously flowing liquid

Polar liquid: Structure



Weakly correlated "liquid"

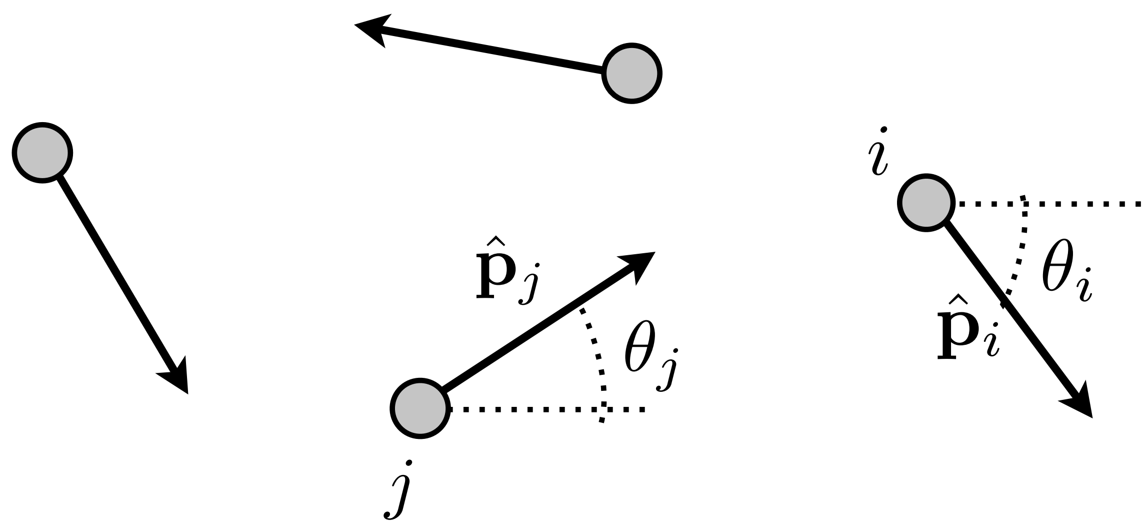
Polar liquid: Density fluctuations



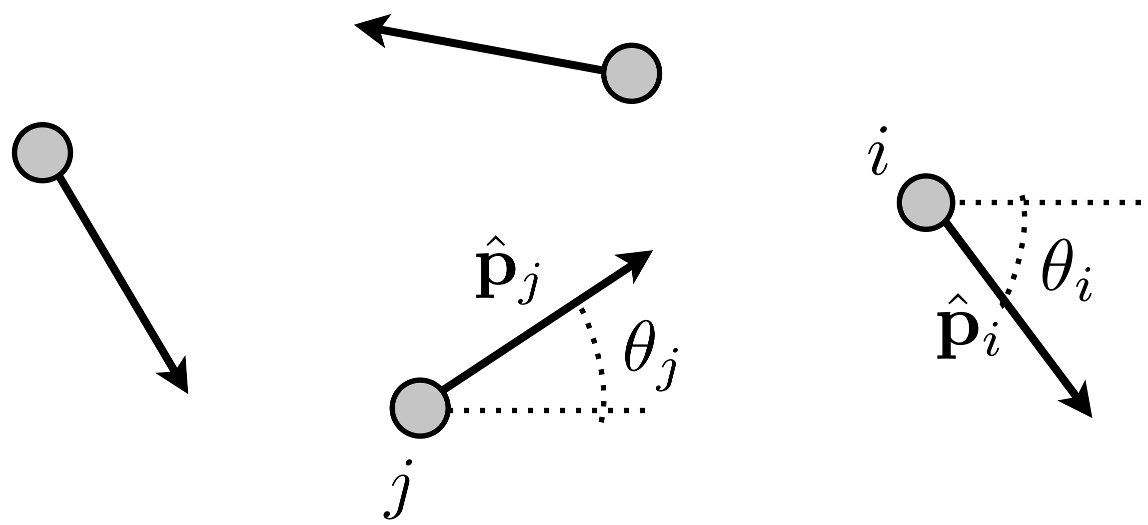
No Giant-Number Fluctuations !

Equations of motion

Stokes equation
\+ Maxwell equation
\+ outstanding student



Equations of motion



$$\dot{\mathbf{r}}_j = v_0 \hat{\mathbf{p}}_j$$ constant speed

$$\dot{\theta}_j = -\frac{\partial}{\partial \theta_j} \sum_{i \neq j} \mathcal{H}_{\mathrm{eff}}(\mathbf{r}_j - \mathbf{r}_i, \hat{\mathbf{p}}_i, \hat{\mathbf{p}}_j) \; + \xi_j(t)$$ effective potential interaction

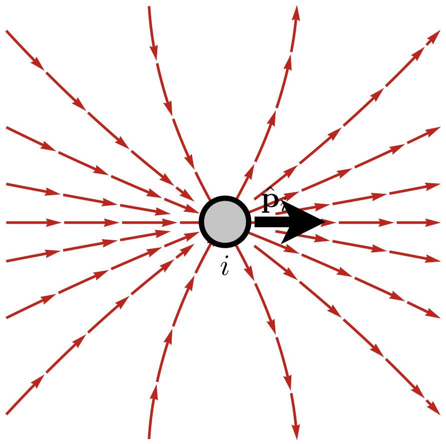
Hydrodynamics does matter

$$\dot{\mathbf{r}}_j = v_0 \hat{\mathbf{p}}_j$$

$$\dot{\theta}_j = -\frac{\partial}{\partial \theta_j} \sum_{i \neq j} \mathcal{H}_{\text{eff}}(\mathbf{r}_j - \mathbf{r}_i, \hat{\mathbf{p}}_i, \hat{\mathbf{p}}_j) \; + \xi_j(t)$$

Alignement interactions

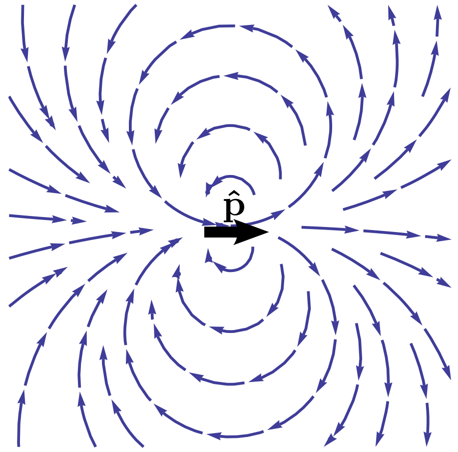
$$\mathcal{H}_{\text{eff}}(\mathbf{r}, \hat{\mathbf{p}}_i, \hat{\mathbf{p}}_j) = -A(r)\, \hat{\mathbf{p}}_i \cdot \hat{\mathbf{p}}_j \; - B(r)\hat{\mathbf{r}} \cdot \hat{\mathbf{p}}_j \; - C(r)\hat{\mathbf{p}}_i \cdot (2\hat{\mathbf{r}}\hat{\mathbf{r}} - \mathbf{I}) \cdot \hat{\mathbf{p}}_j$$



Hydrodynamics does matter

Suppression of the giant number fluctuations

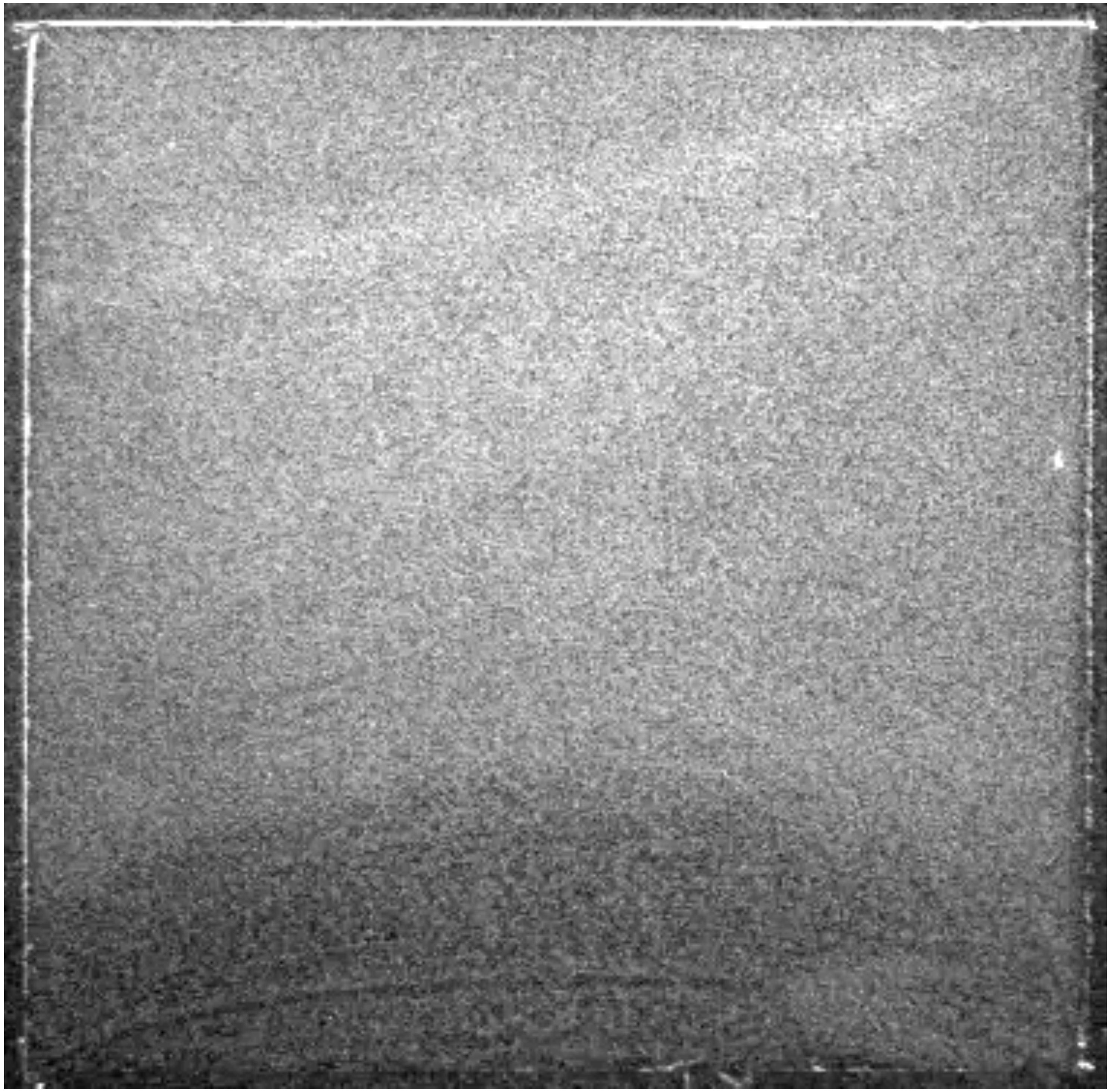
$$\mathcal{H}_{\rm eff}(\mathbf{r},\hat{\mathbf{p}}_i,\hat{\mathbf{p}}_j) = -A(r)\,\hat{\mathbf{p}}_i\cdot\hat{\mathbf{p}}_j - B(r)\hat{\mathbf{r}}\cdot\hat{\mathbf{p}}_j - C(r)\hat{\mathbf{p}}_i\cdot(2\hat{\mathbf{r}}\hat{\mathbf{r}}-\mathbf{I})\cdot\hat{\mathbf{p}}_j$$



Damping of the splay modes

Brotto, Caussin, Lauga, and Bartolo, *Phys Rev Lett* (2013)

Destroying the polar liquid phase



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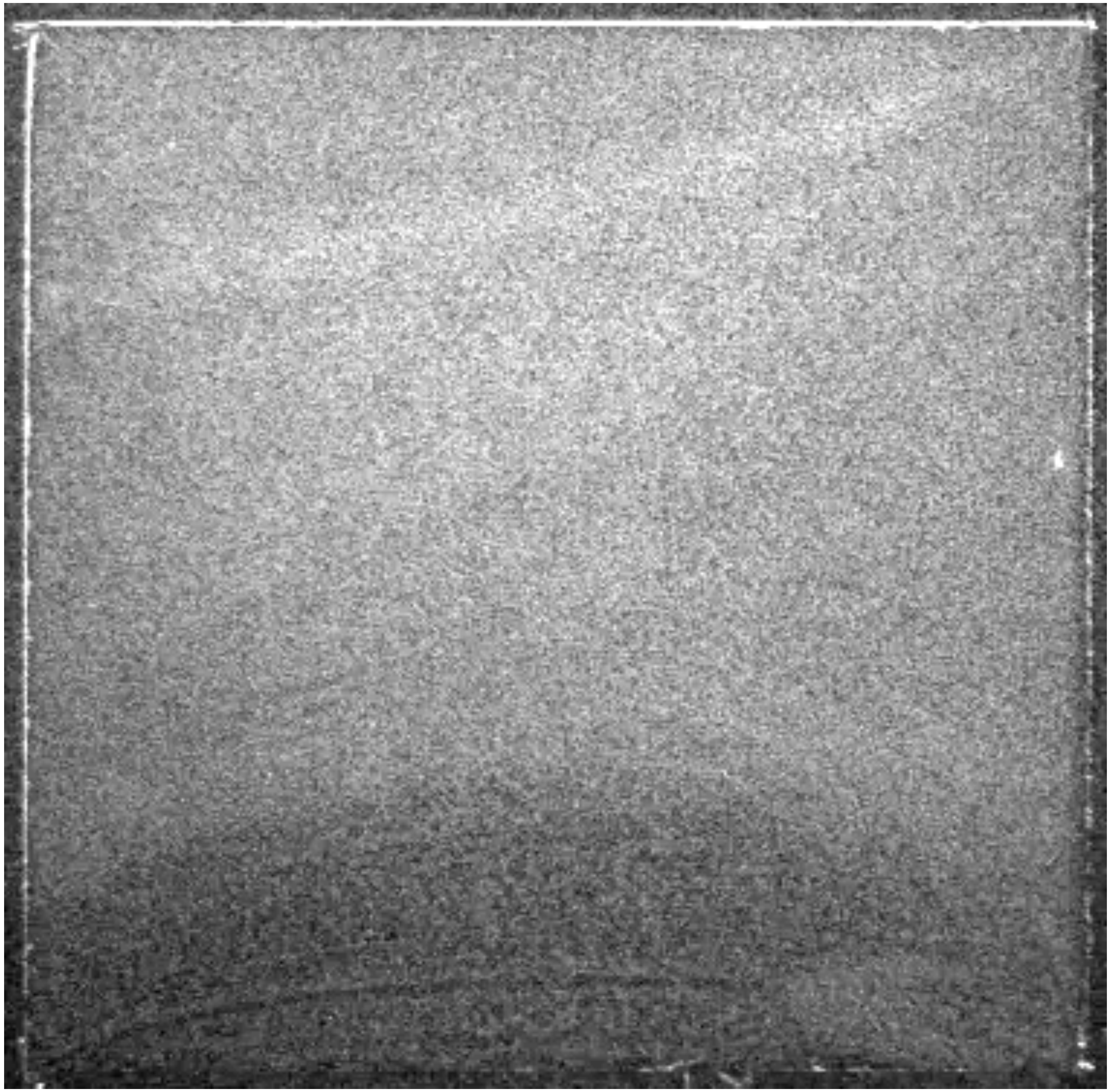
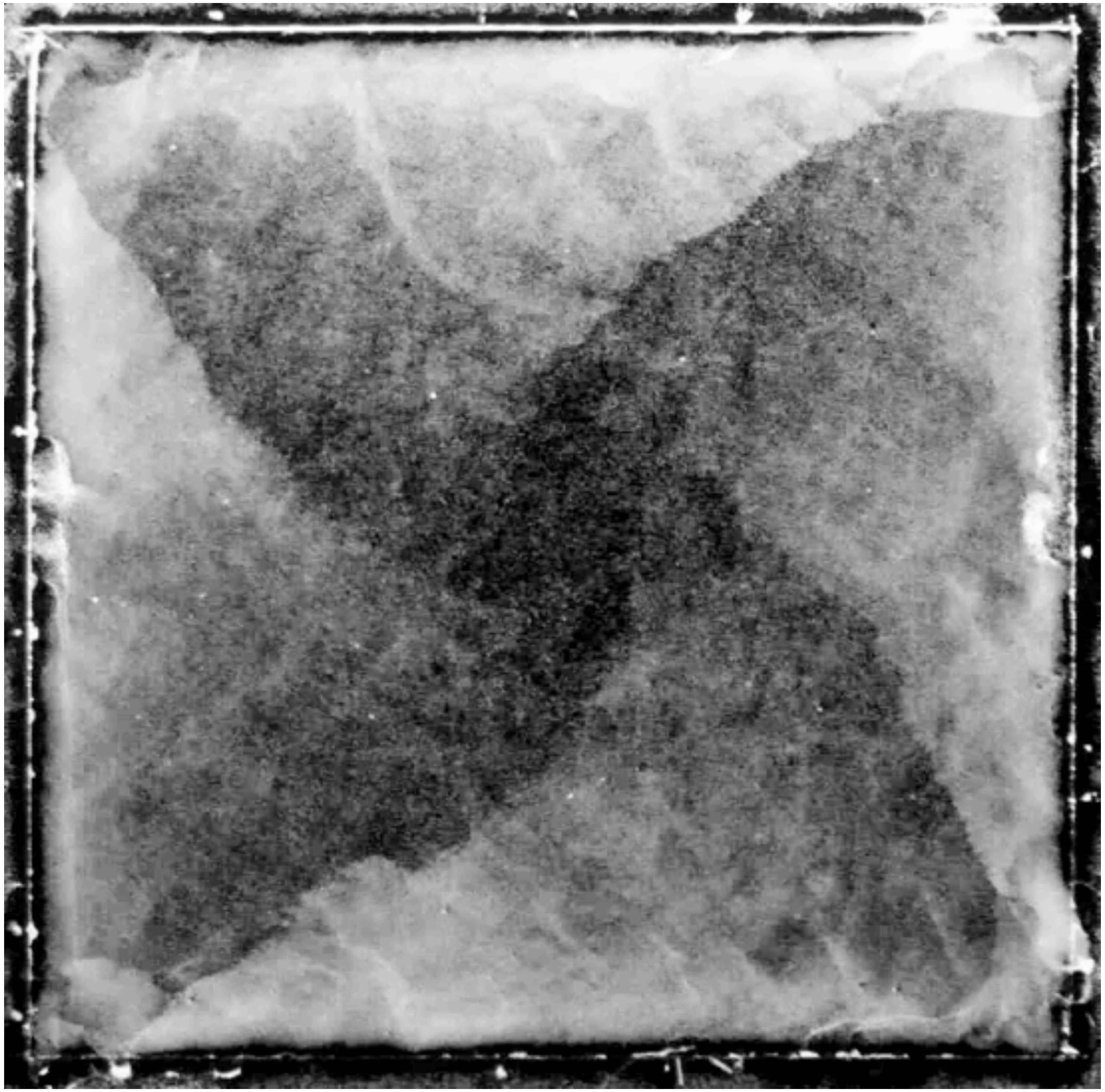
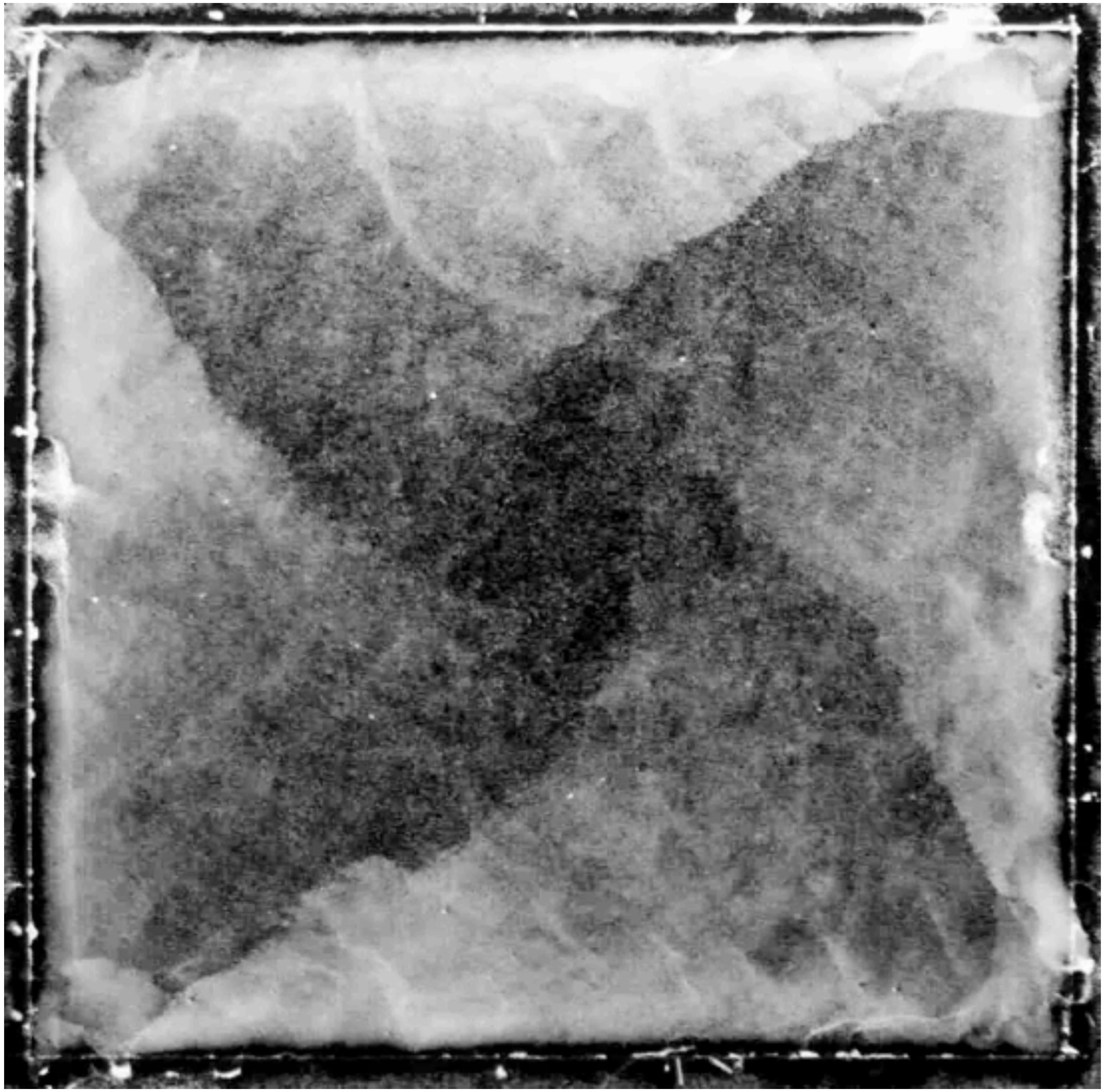


Destroying the polar liquid phase

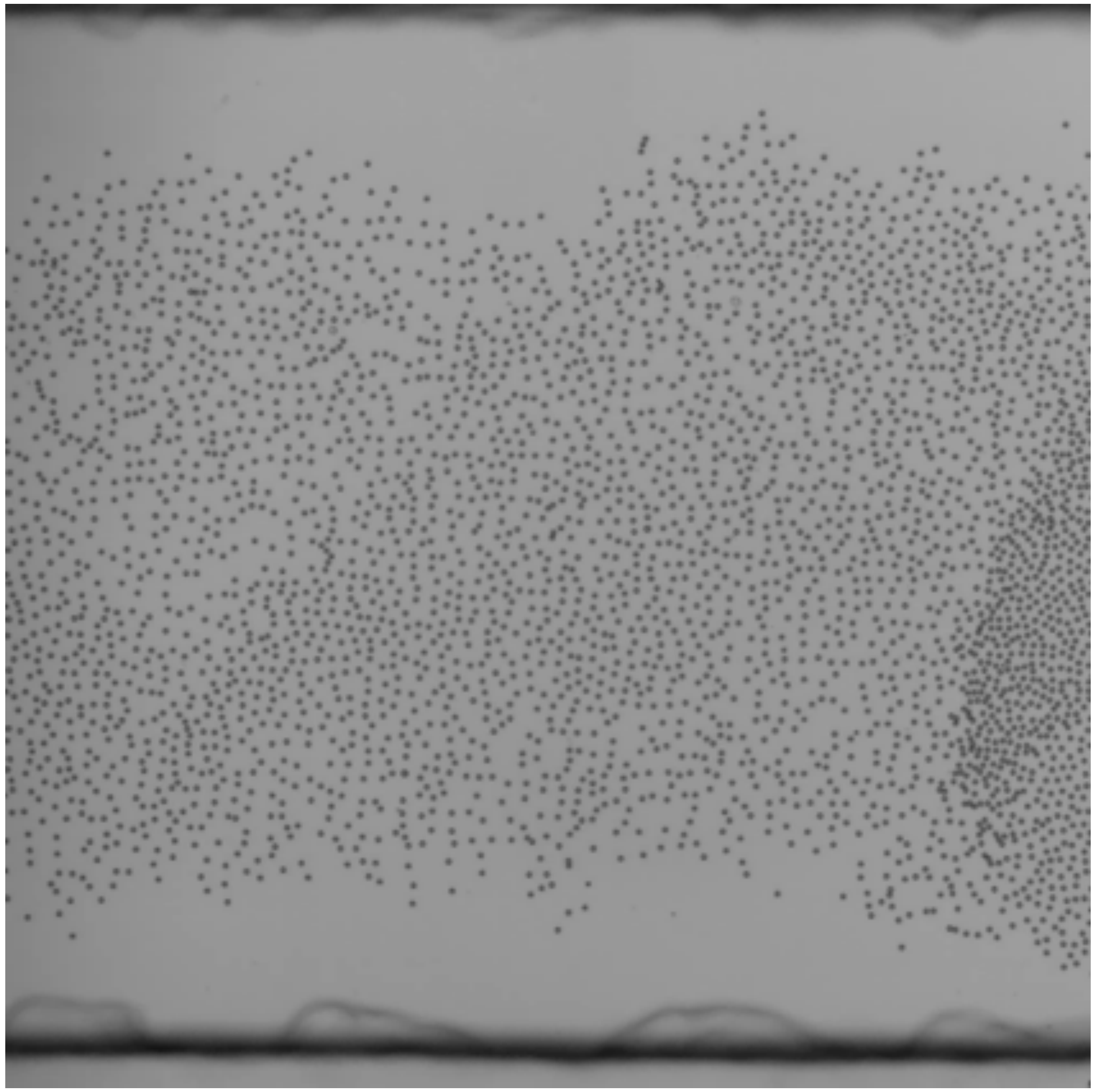


Destroying the polar liquid phase



with

Antoine Bricard	(Experiements)
Jean-Baptiste Caussin	(Theory)
Nicolas Desreumaux	(Experiements)
&	
Olivier Dauchot	(EC2M,ESPCI)



with

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