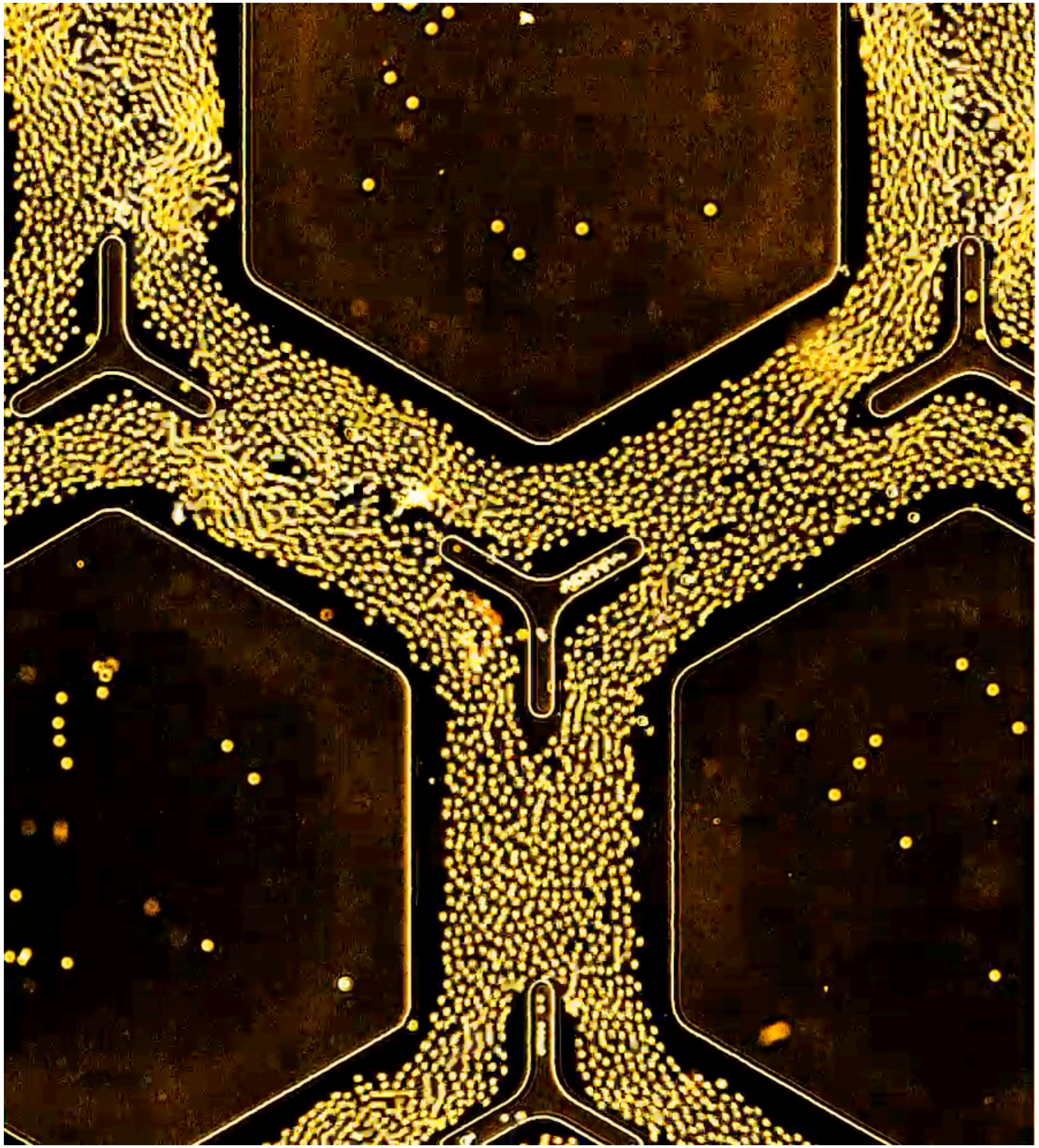
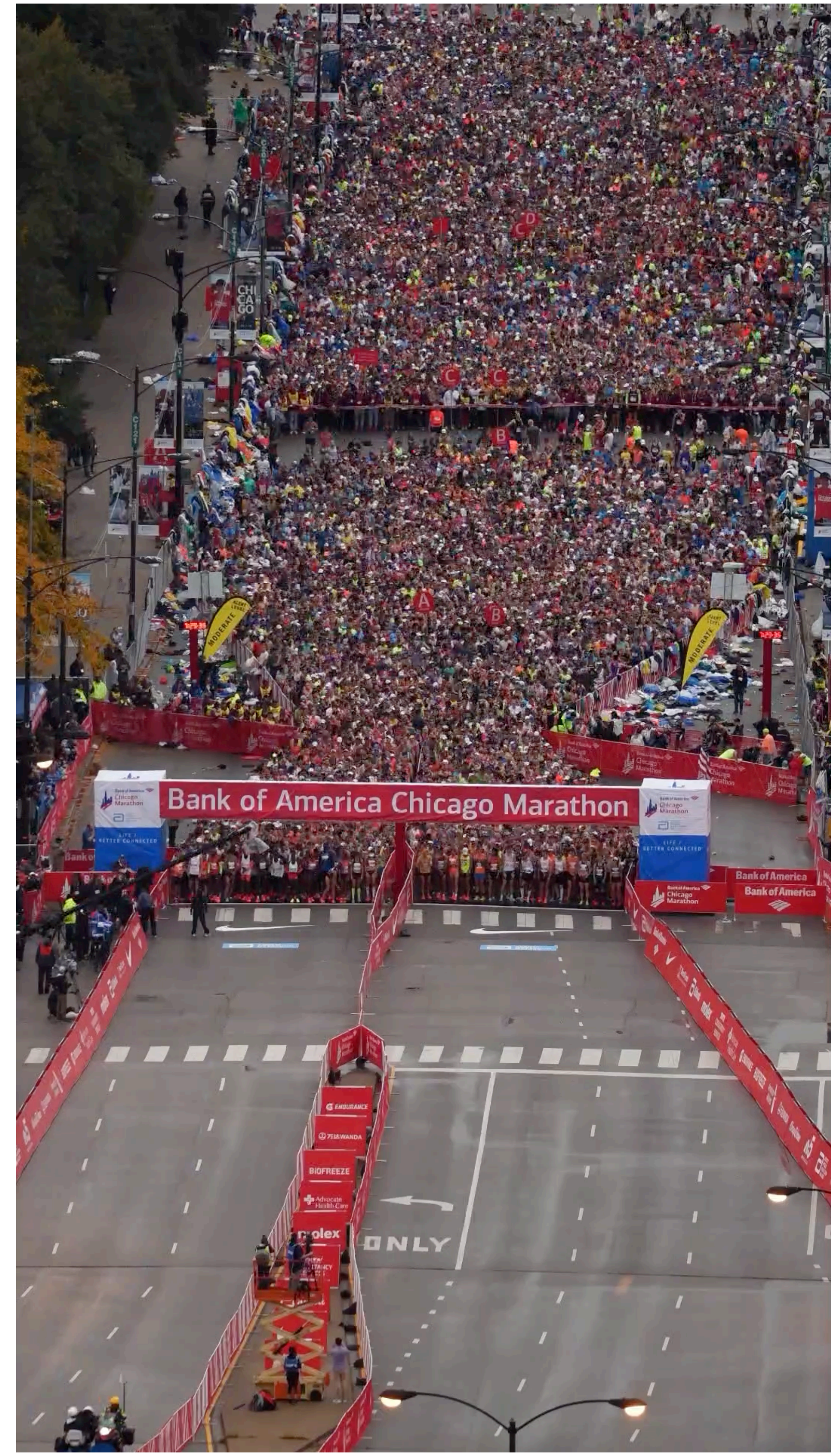
Flocks and crowds: active fluids

Denis BARTOLO
Laboratoire de Physique, ENS de Lyon

Flock hydraulics



Crowd hydrodynamics



How does active matter flow?

Active Matter

We are active solids

Marin Bartolo
Sardinia 2019

Fish school

Jake Butters and Denis Bartolo

Bird flock

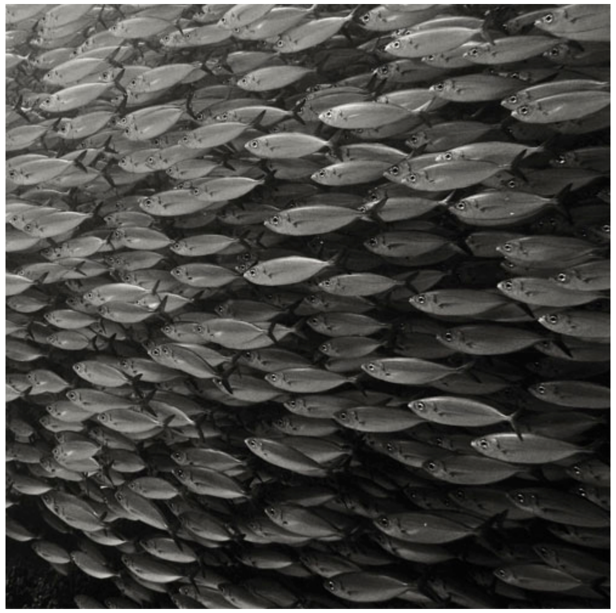
Starling flock, Roma (BBC)

Locust swarm

BBC

Active liquids

F. Nureldine, AFP



Steve Dunleavy

National geographic

National geographic

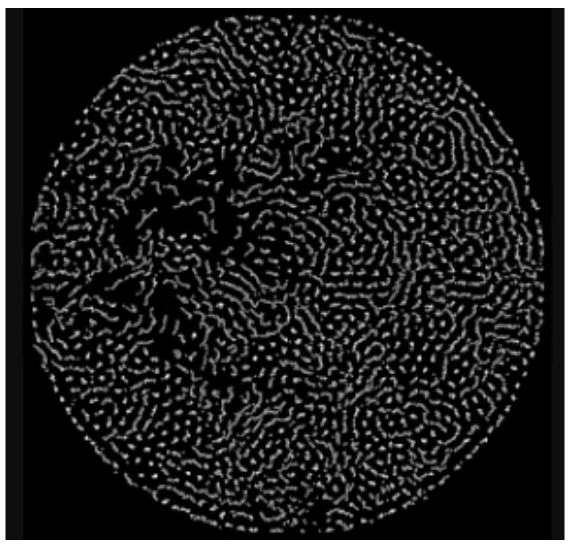
Flocks, schools and herds

as spontaneously flowing liquids

Synthetic active matter

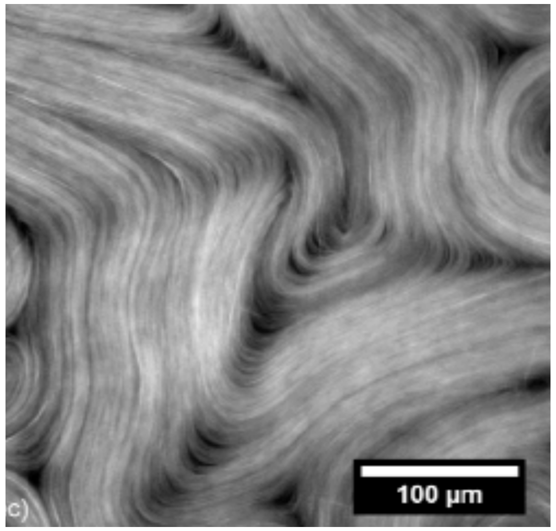
Synthetic active matter

Active emulsions



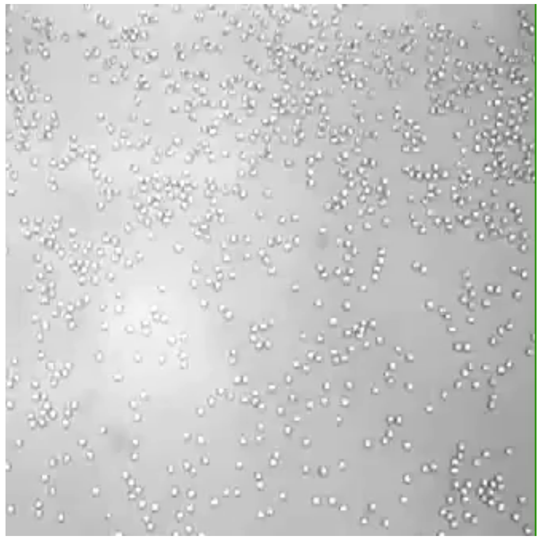
Thutupalli et al NJP (2011)

Active nematics



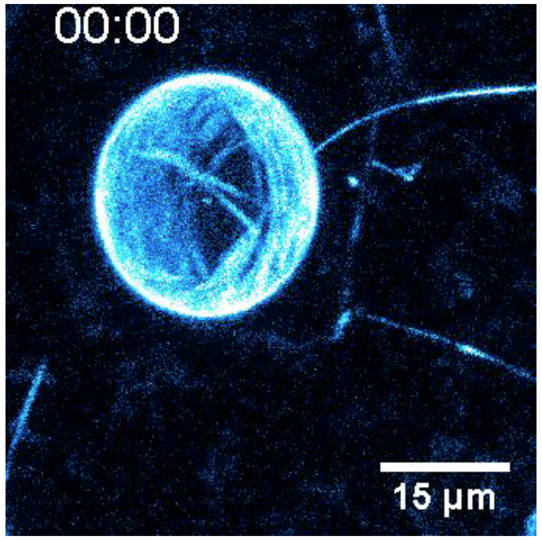
Sanchez et al Nature (2012)

Active colloids



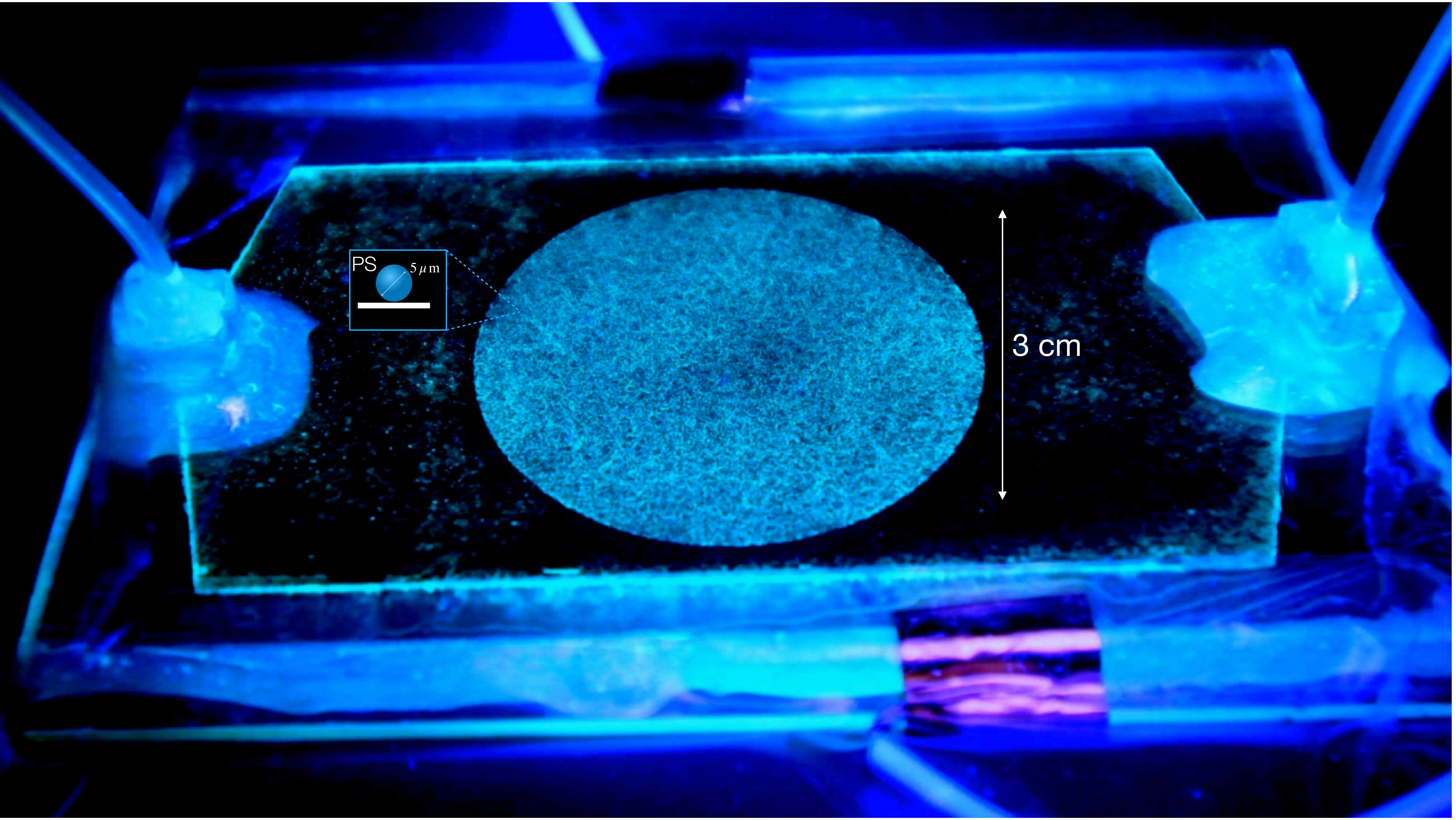
Palacci et al Science (2013)

Active membranes

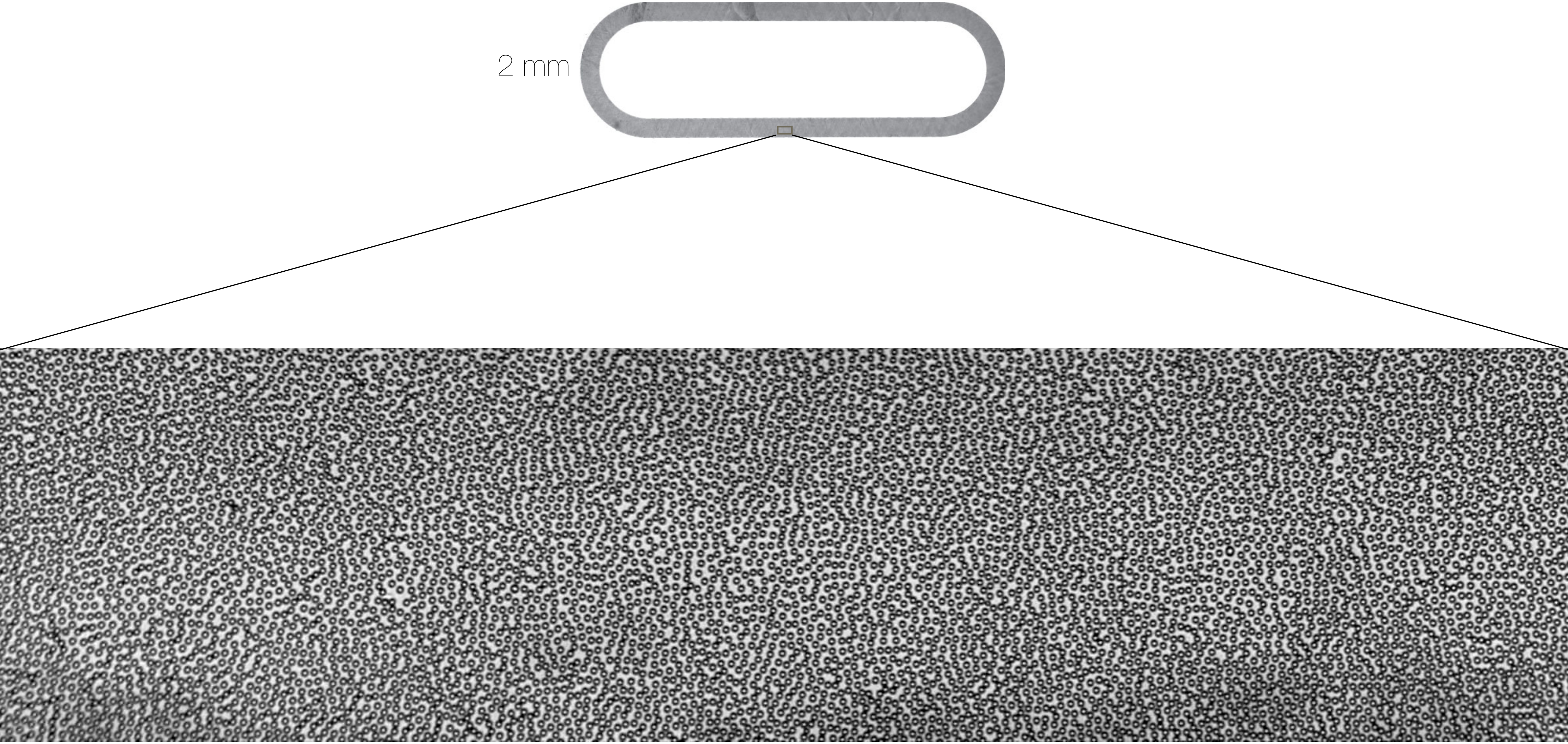


Keber et al Science (2014)

Synthetic flocks



Flocking fluids: laminar flows

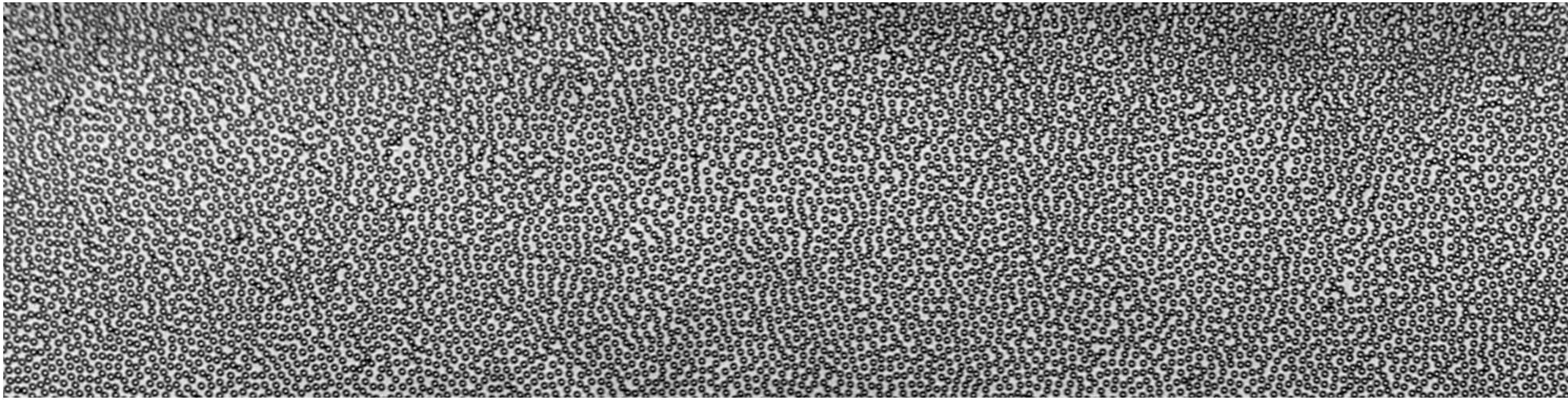


Colloïdal rollers

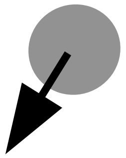
$\phi \sim 3 \times 10^{-1}$

Engineering flocking fluids

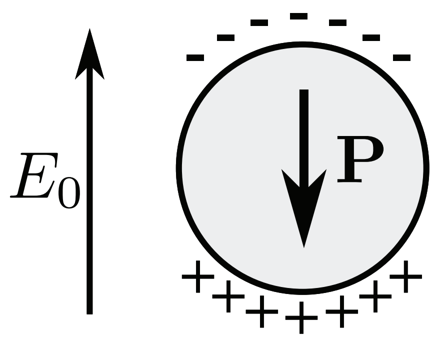
$\phi \sim 3 \times 10^{-1}$



Self-propelled units



Colloidal rollers



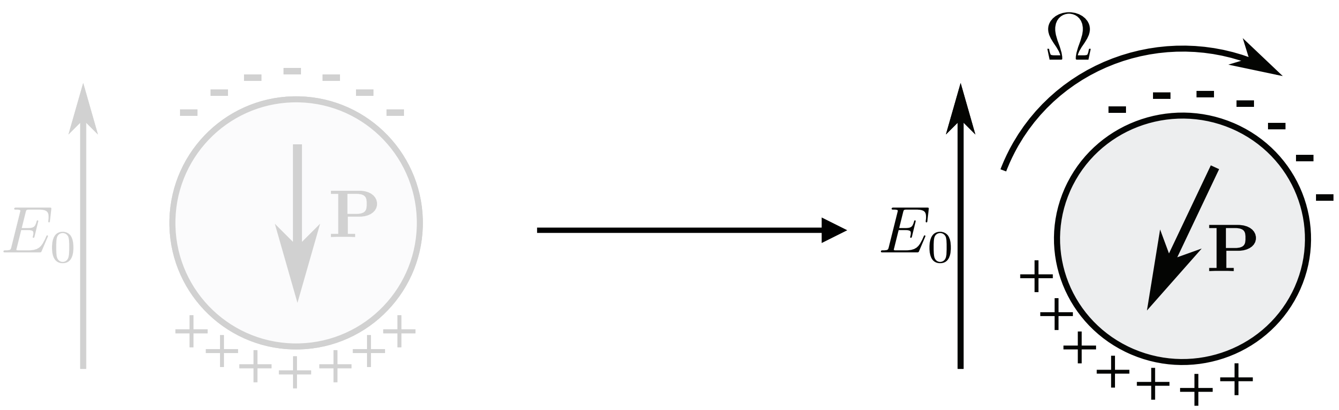
Insulating bead

Conducting fluid

DC **E** field

Colloidal rollers

Spontaneous rotation



Insulating bead

Conducting fluid

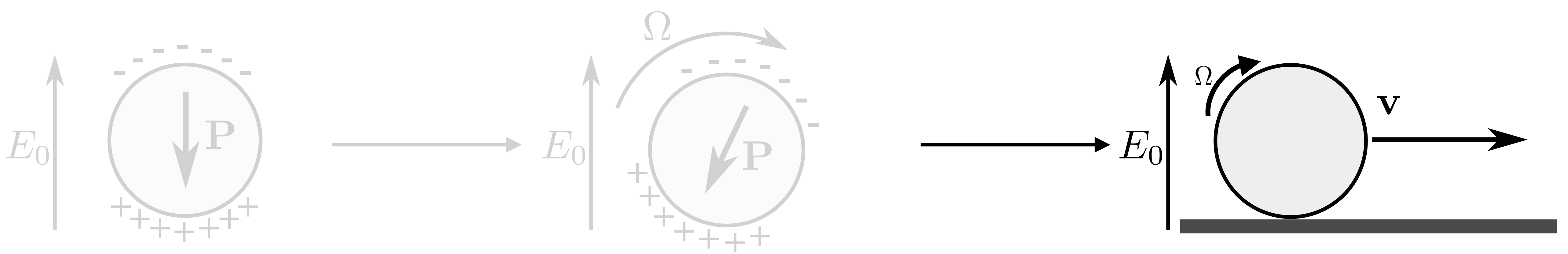
DC **E** field

Quincke
Electro-rotation

Colloidal rollers

Spontaneous rotation

Rolling Motion



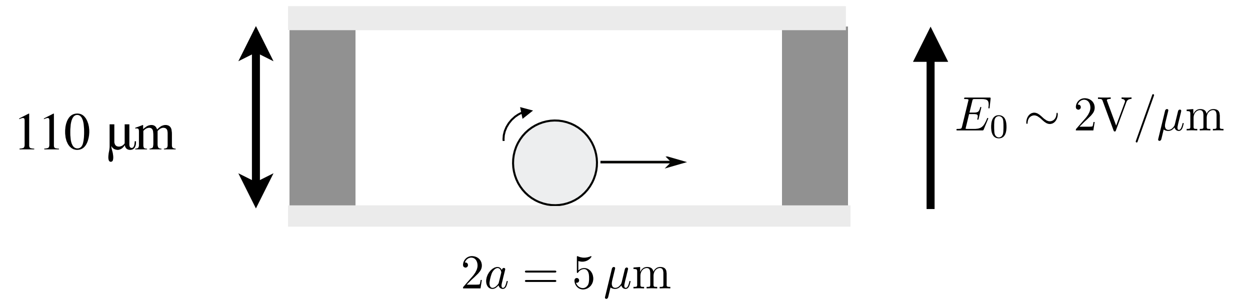
Insulating bead

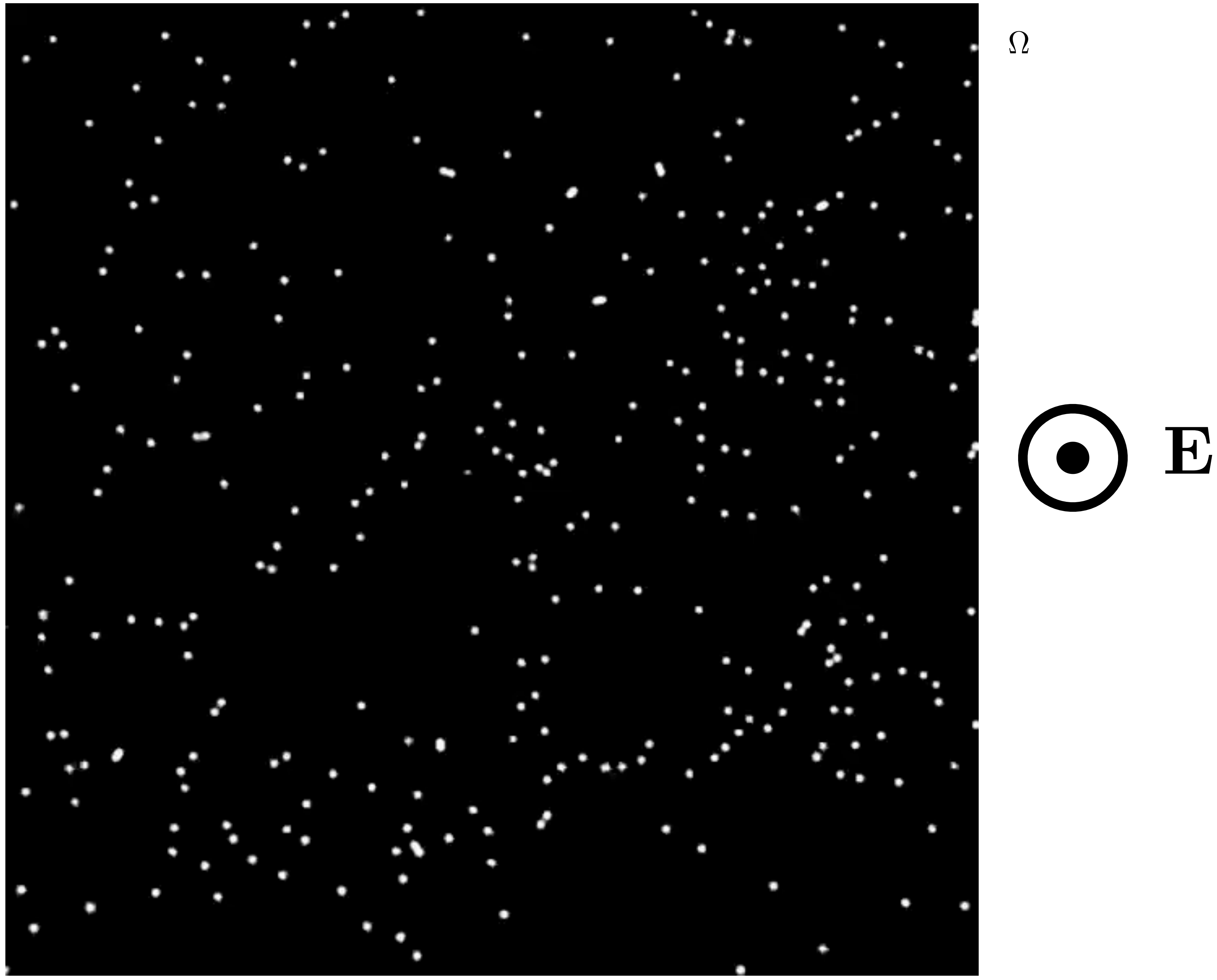
Conducting fluid

DC **E** field

Quincke
Electro-rotation

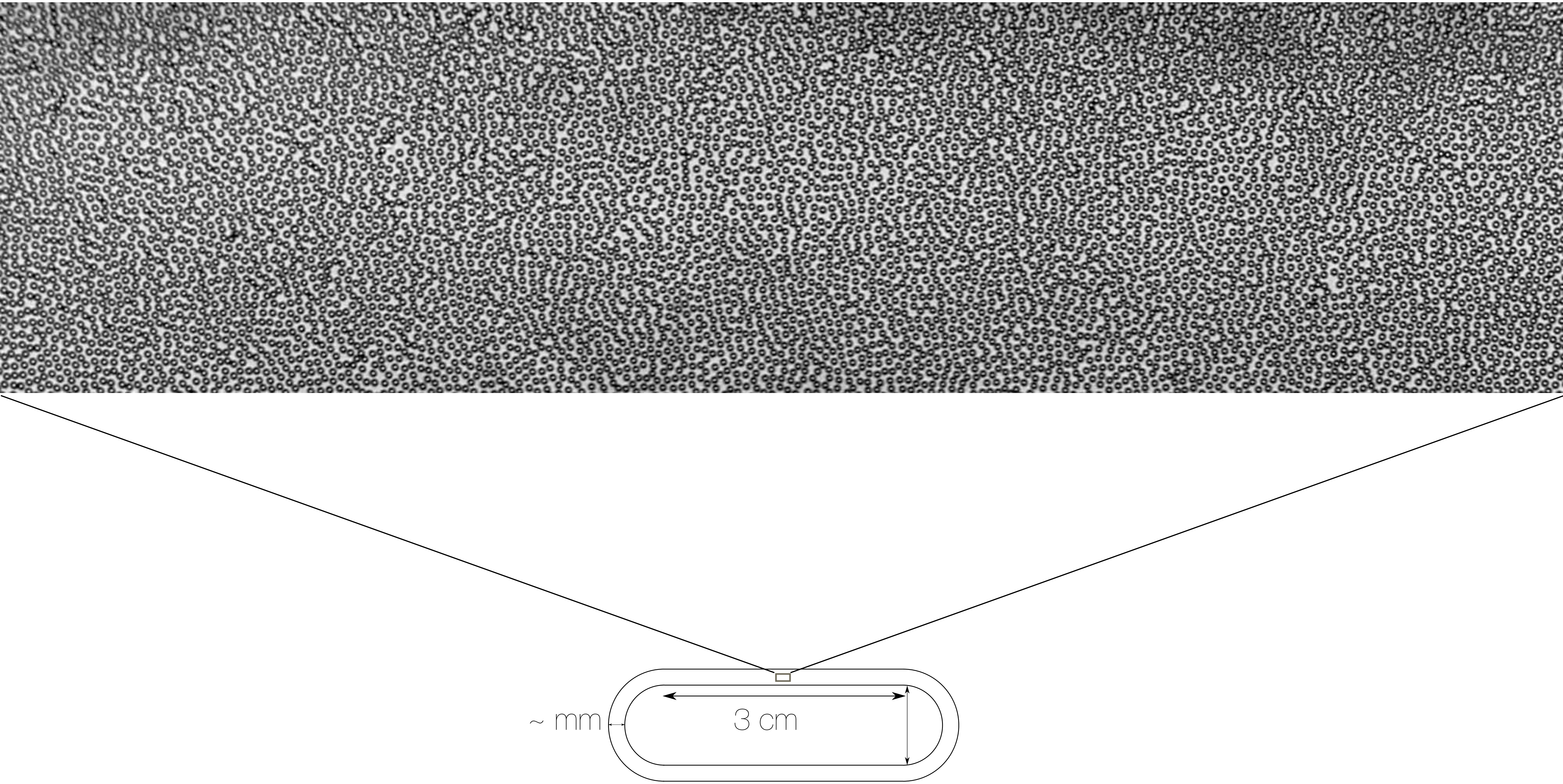
Quincke rollers





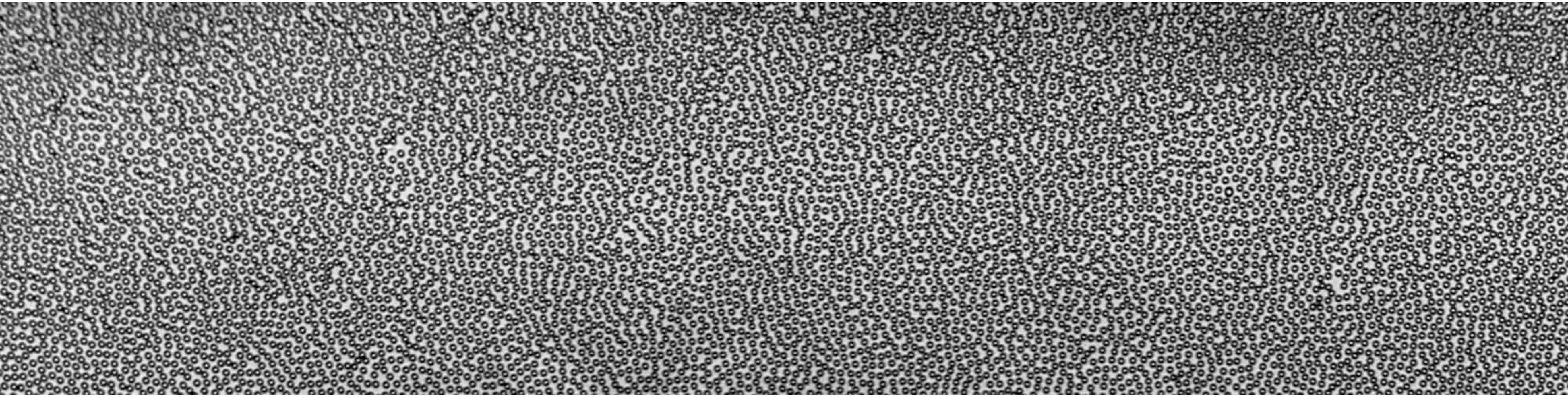
$\phi \sim 10^{-4}$

Flocking transition



$\phi \sim 3 \times 10^{-1}$

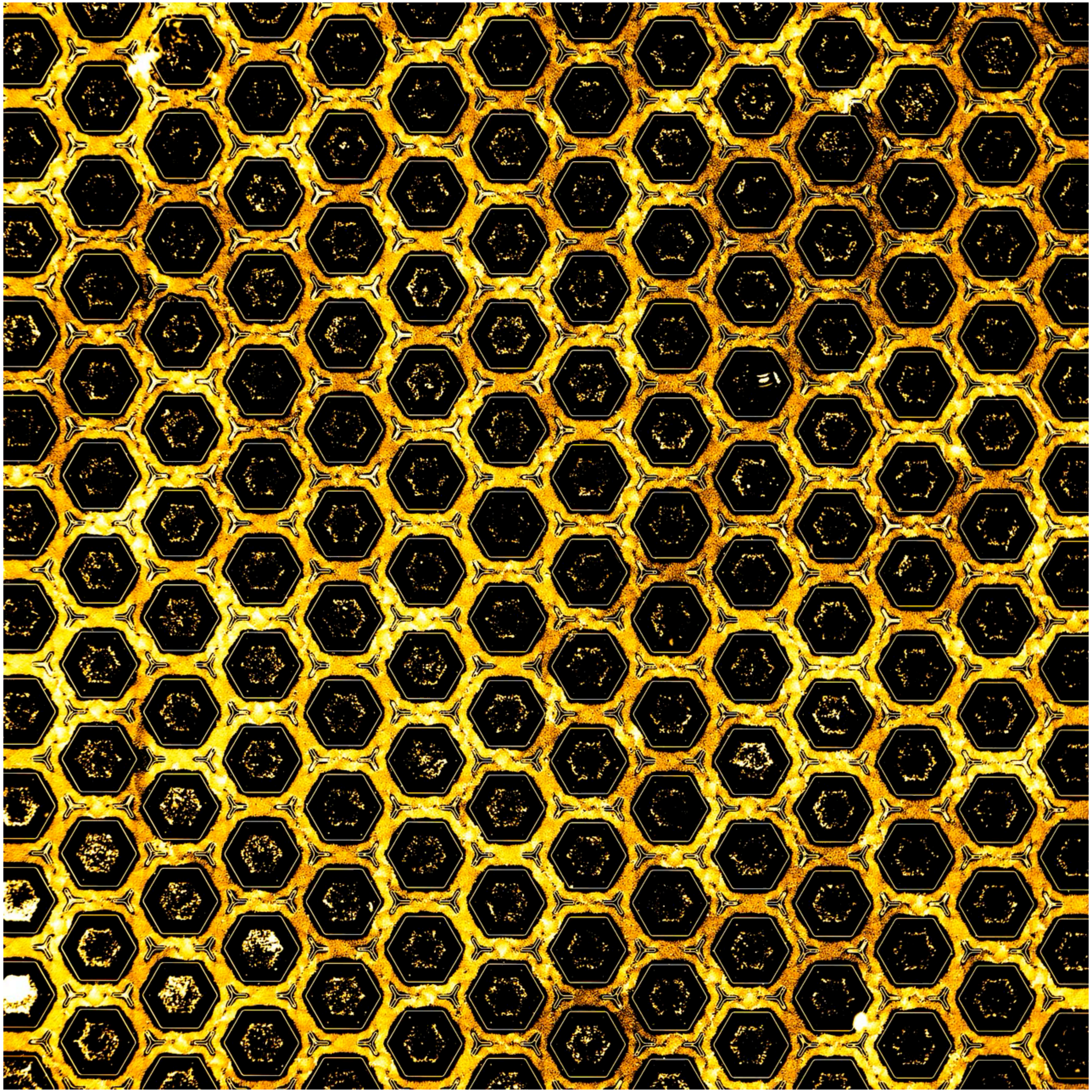
Flocking fluids



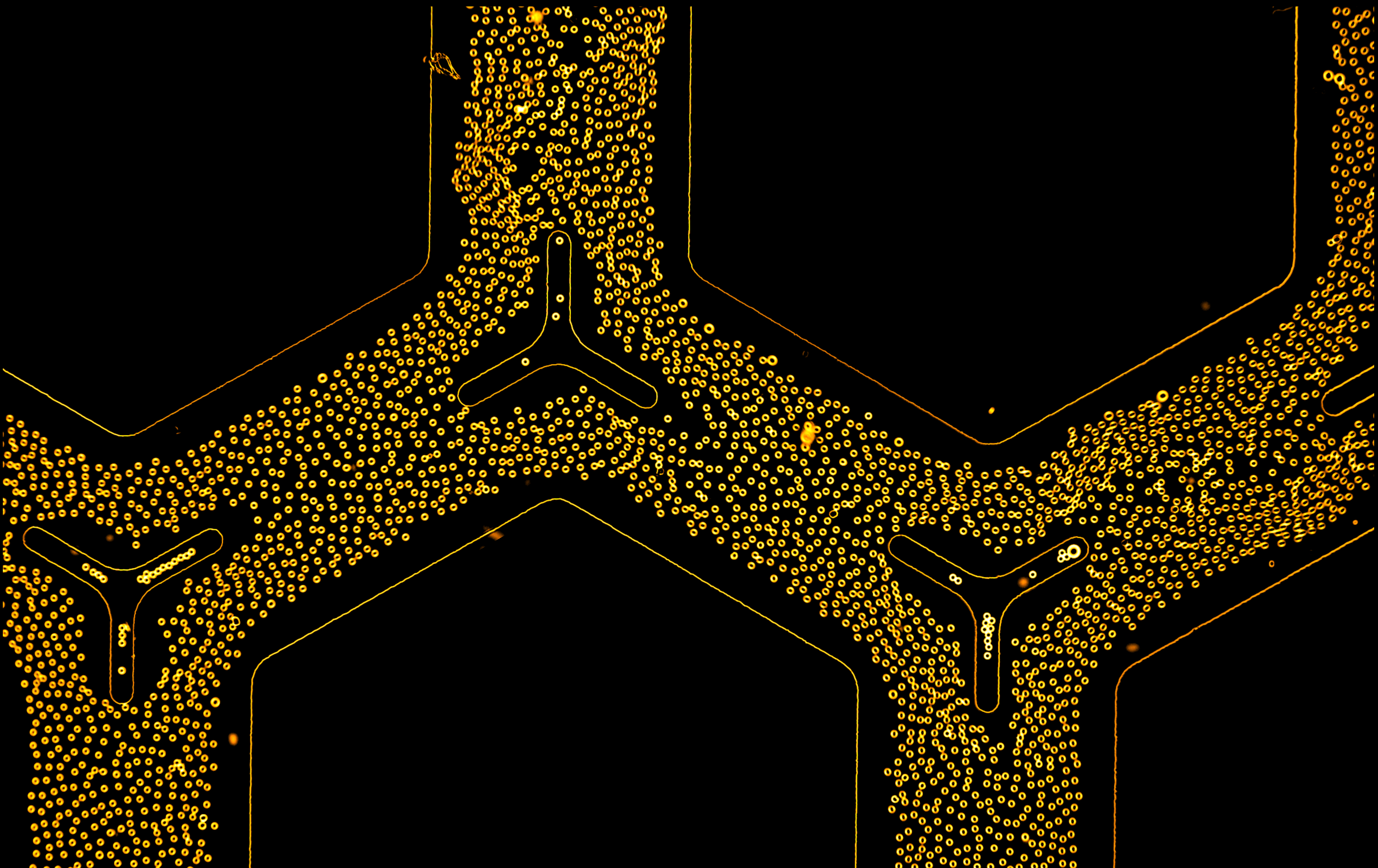
Spontaneous laminar flows
in channels and pipes

$\phi \sim 3 \times 10^{-1}$

Active flows in pipe networks?

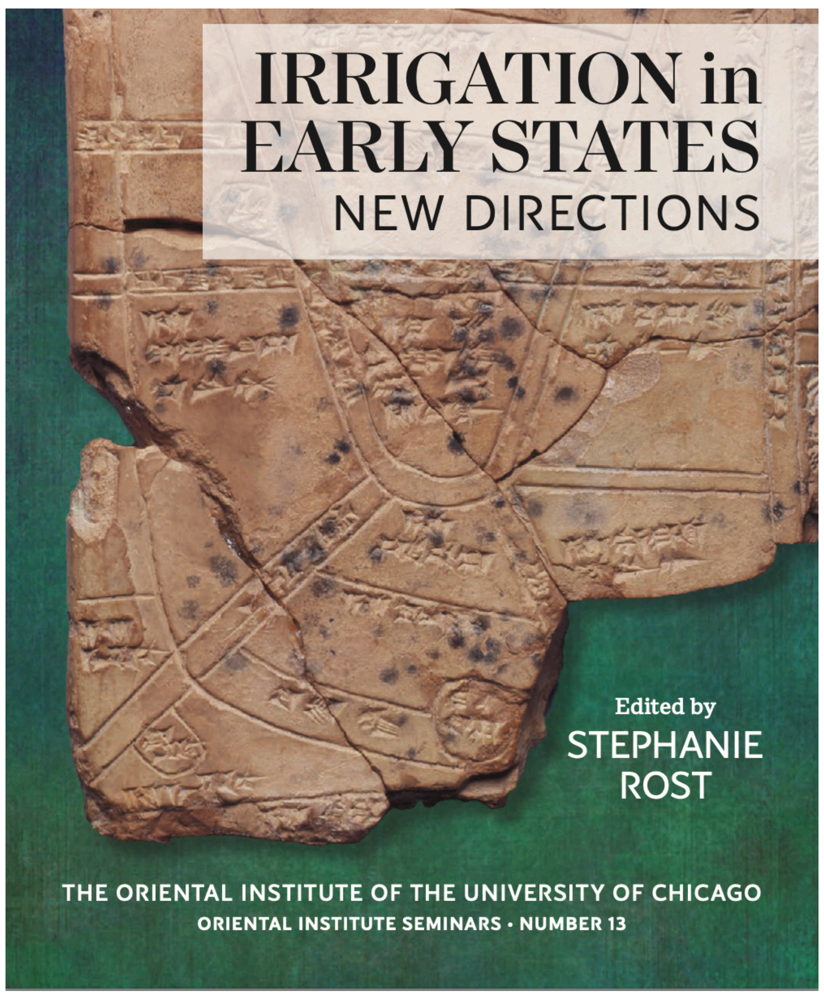


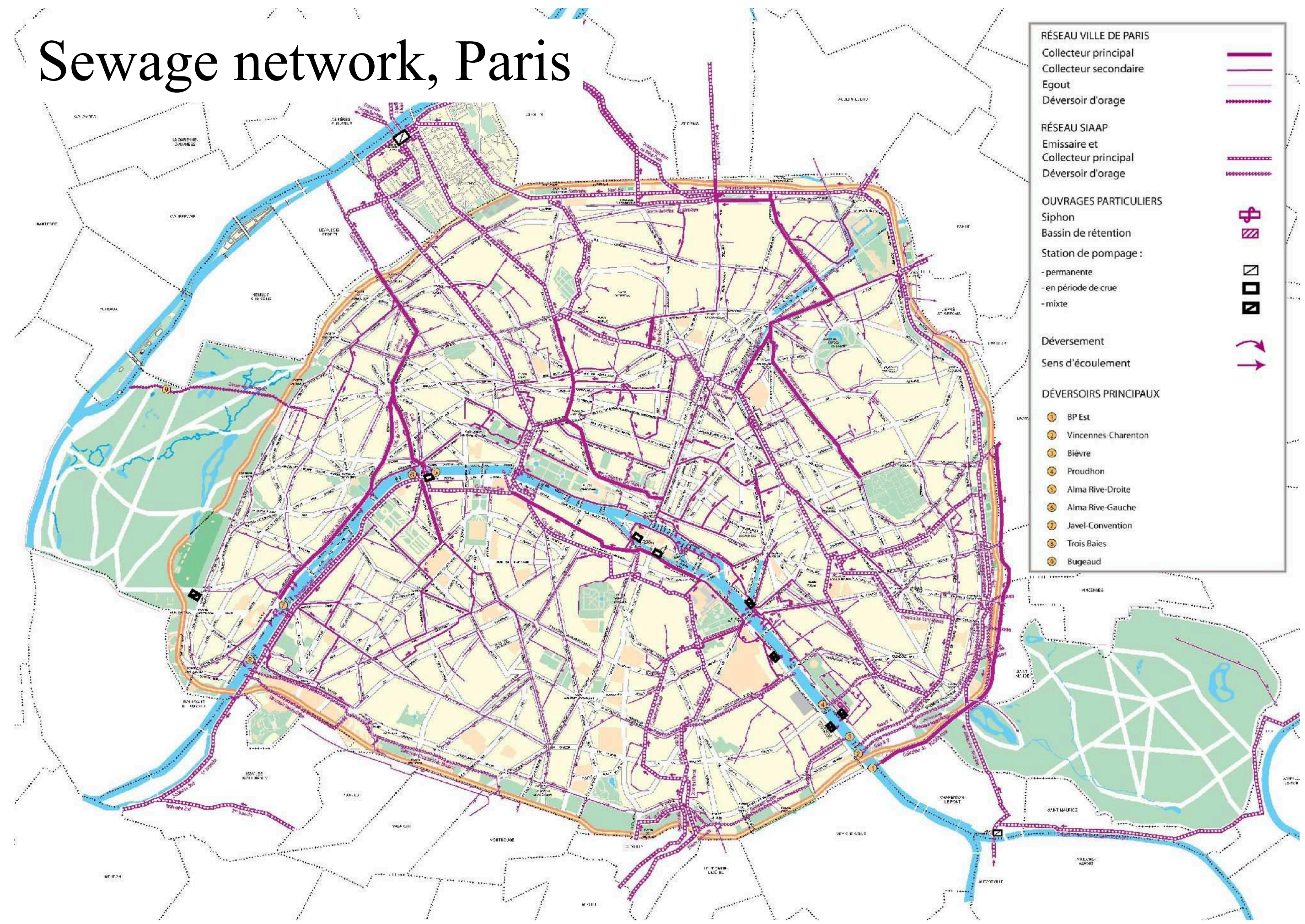
Active Hydraulics?



Hydraulics

Conveyance of liquids through pipes and channels

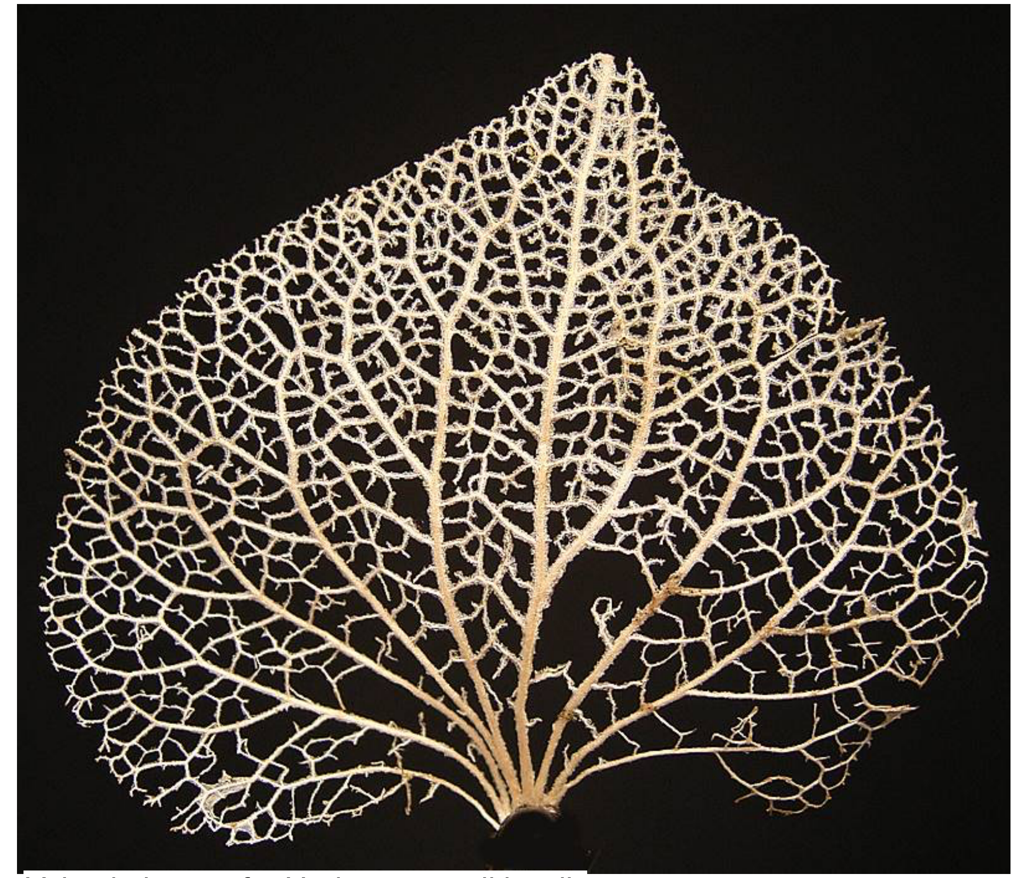




-6000 2022 Time [y]

Hydraulics

Linear problem

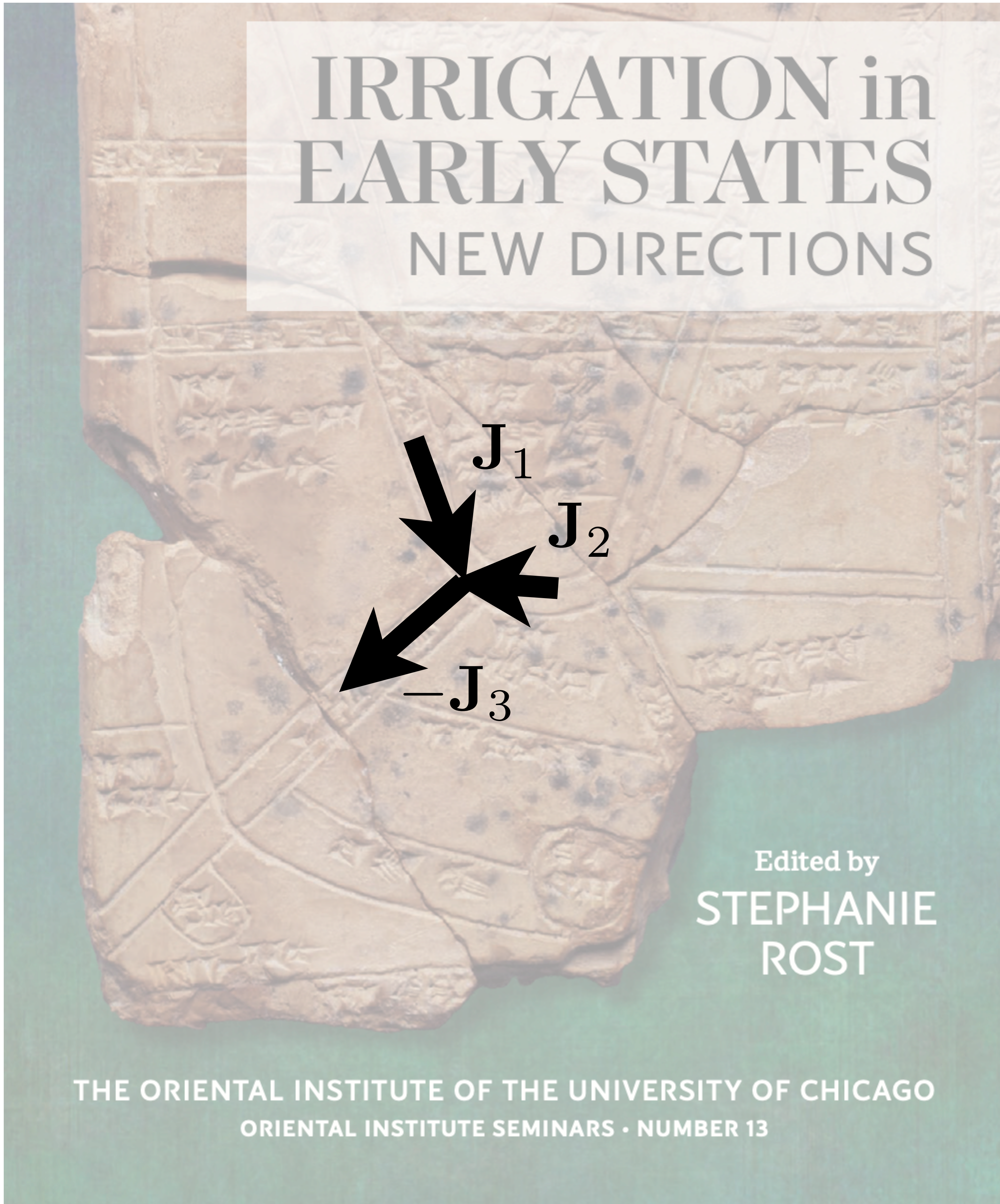


Vein skeleton of a Hydrangea ,wikipedia

London’s hydraulic Network 1960, Power water networks

Mass conservation

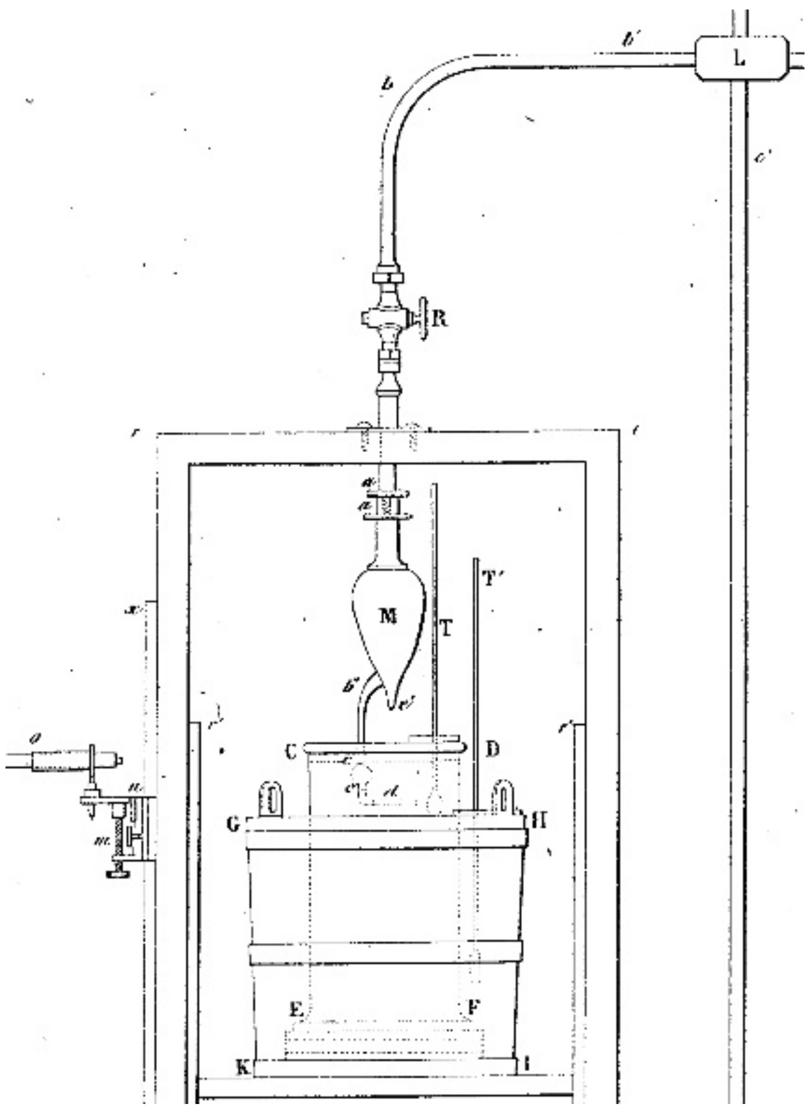
$$\sum_{\text{node } i} \mathbf{J}_i = 0$$

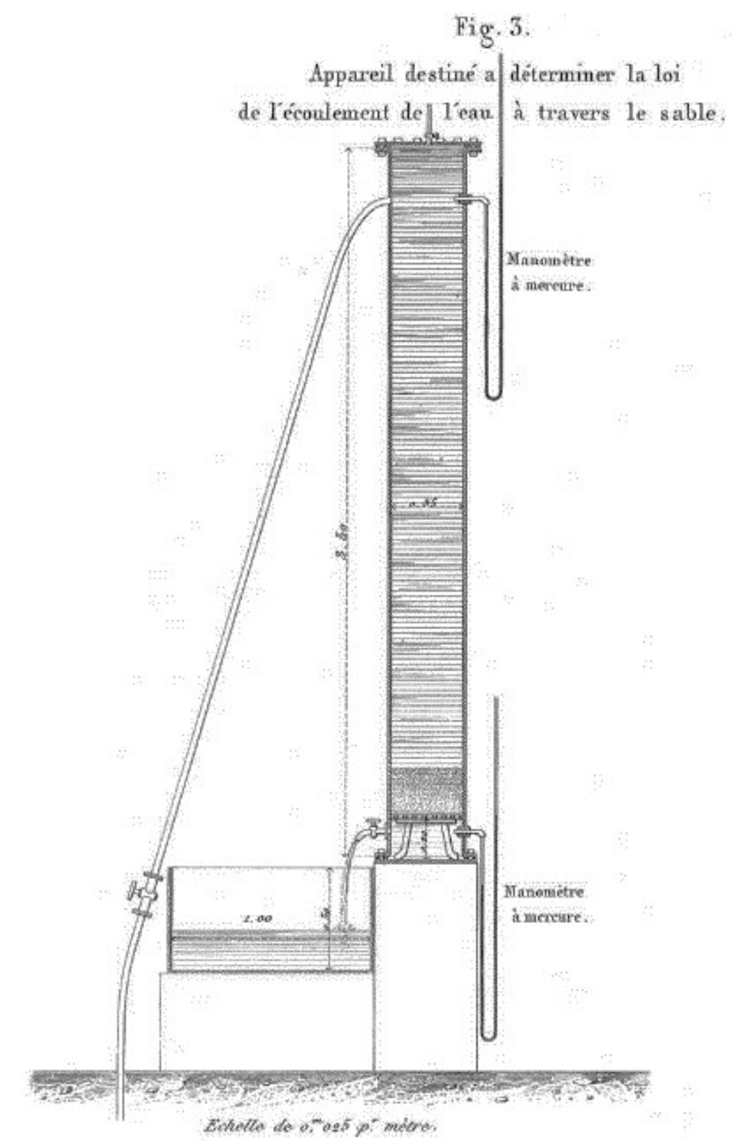


Constitutive relation

Poiseuille (1840)

Darcy (1856)

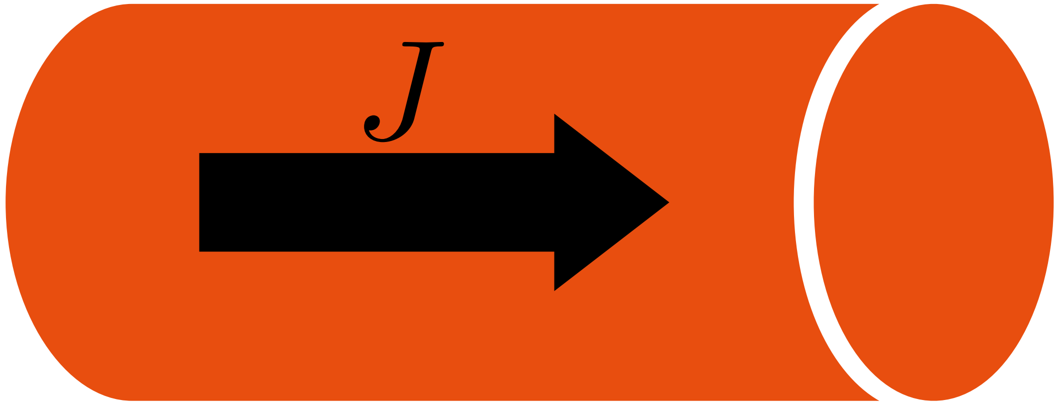




Recherches expérimentales sur le mouvement des liquides, dans les tubes de très petits diamètres, 1840

Fontaines publiques de la ville de Dijon, 1856

Darcy's law



$$J = -K\Delta P$$

Flux

Pressure drop

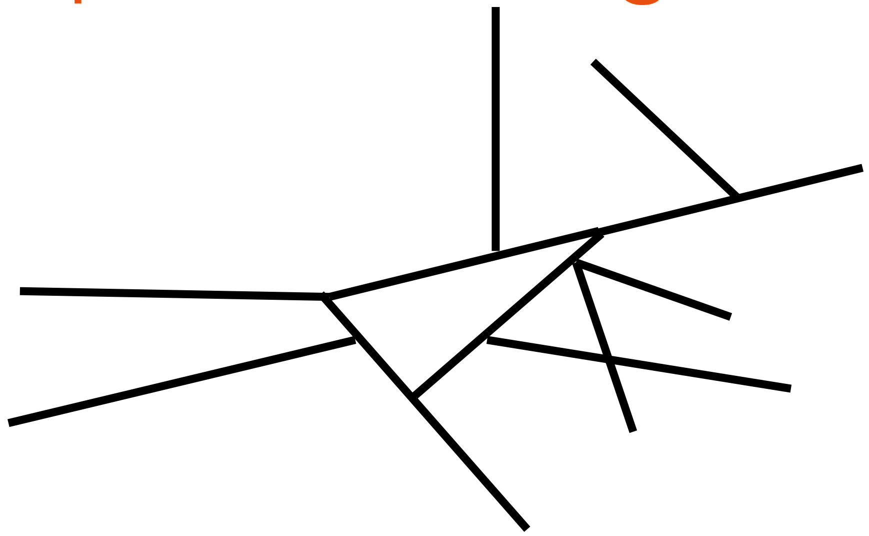
Hydraulics Newtonian fluids

Linear relations

$$J = -K\Delta P$$

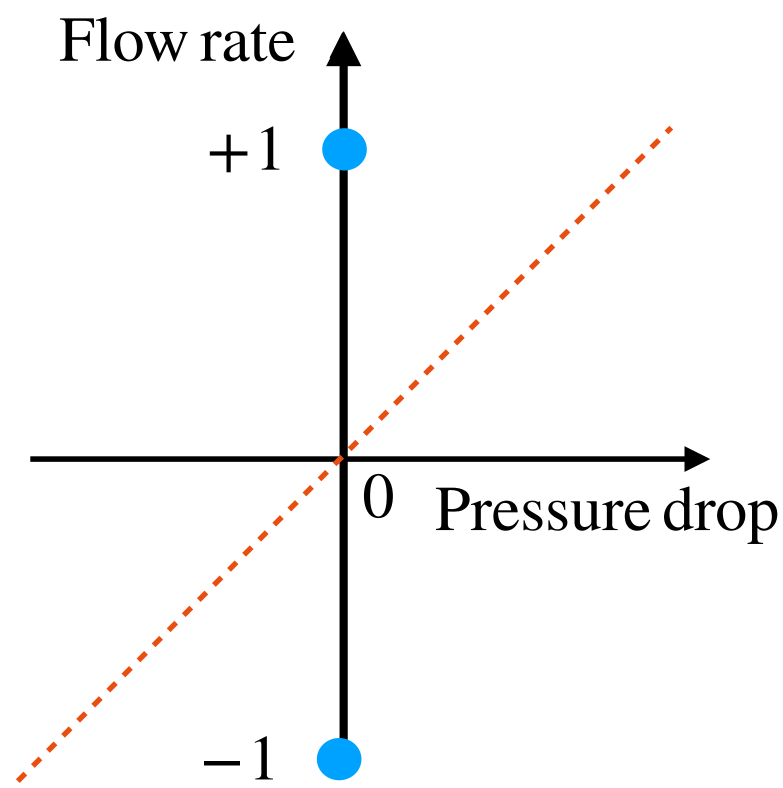
$$\sum_{\mathrm{node}\, i} \mathbf{J}_i = 0$$

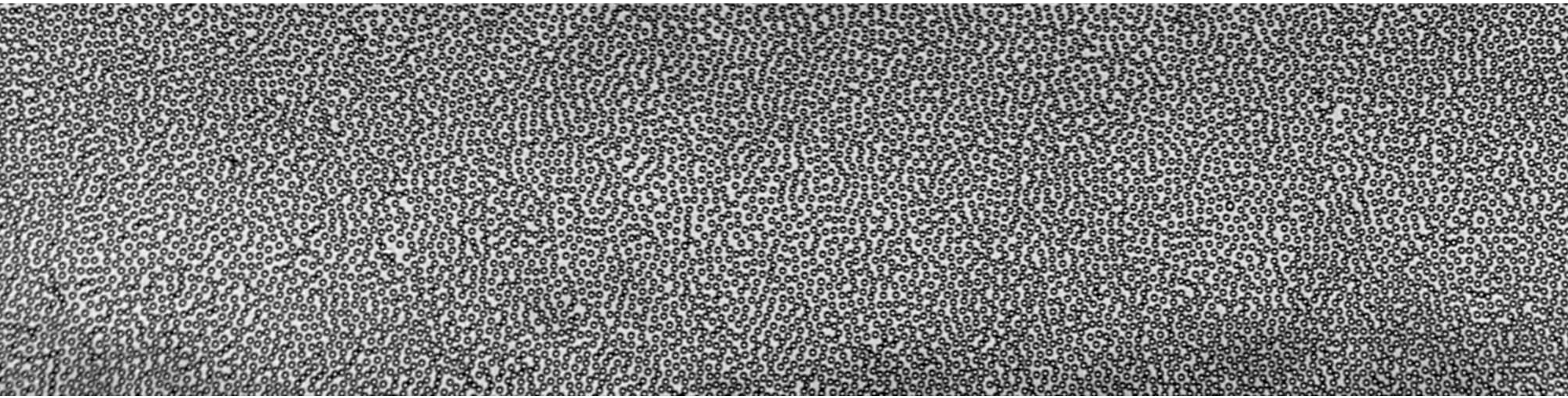
Pipe network geometry



✓

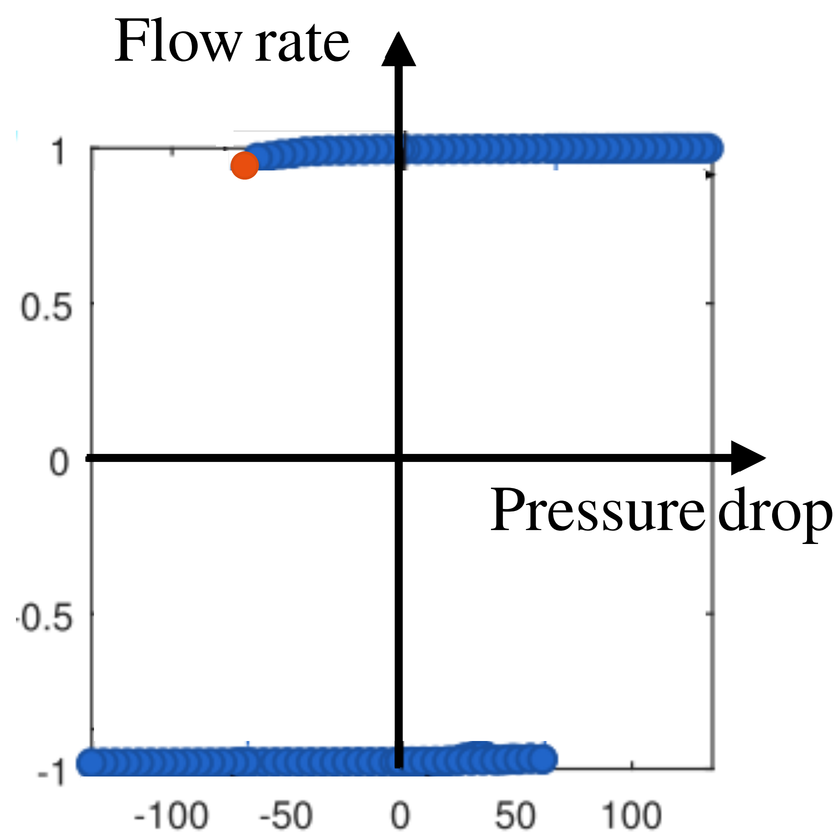
Confined Active Flows: Nonlinear



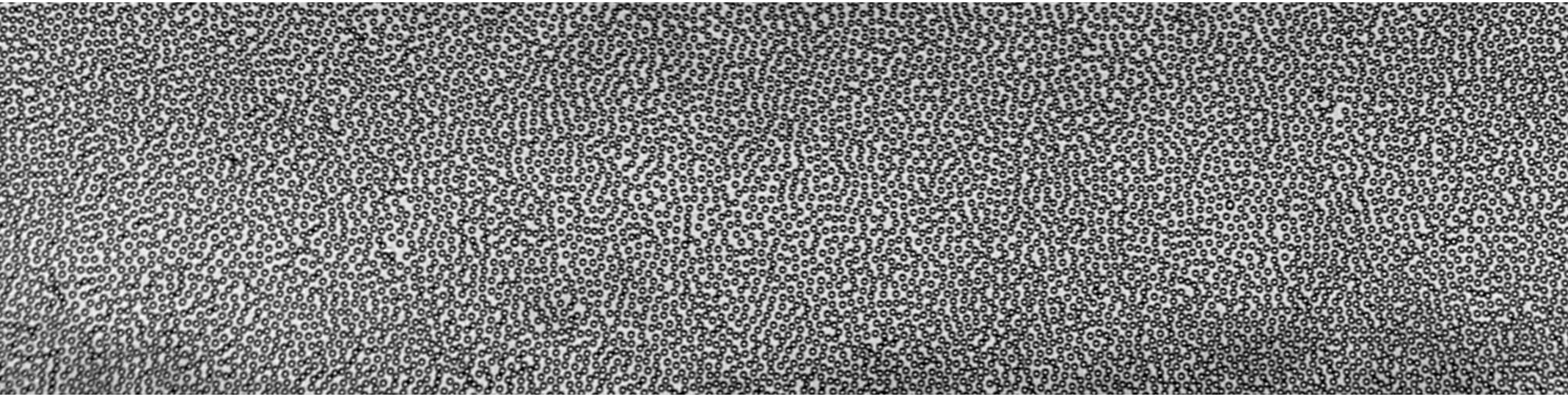


Colloïdal rollers

Active fluids: Bistable flows



$$J = \pm J_0$$



Colloïdal rollers

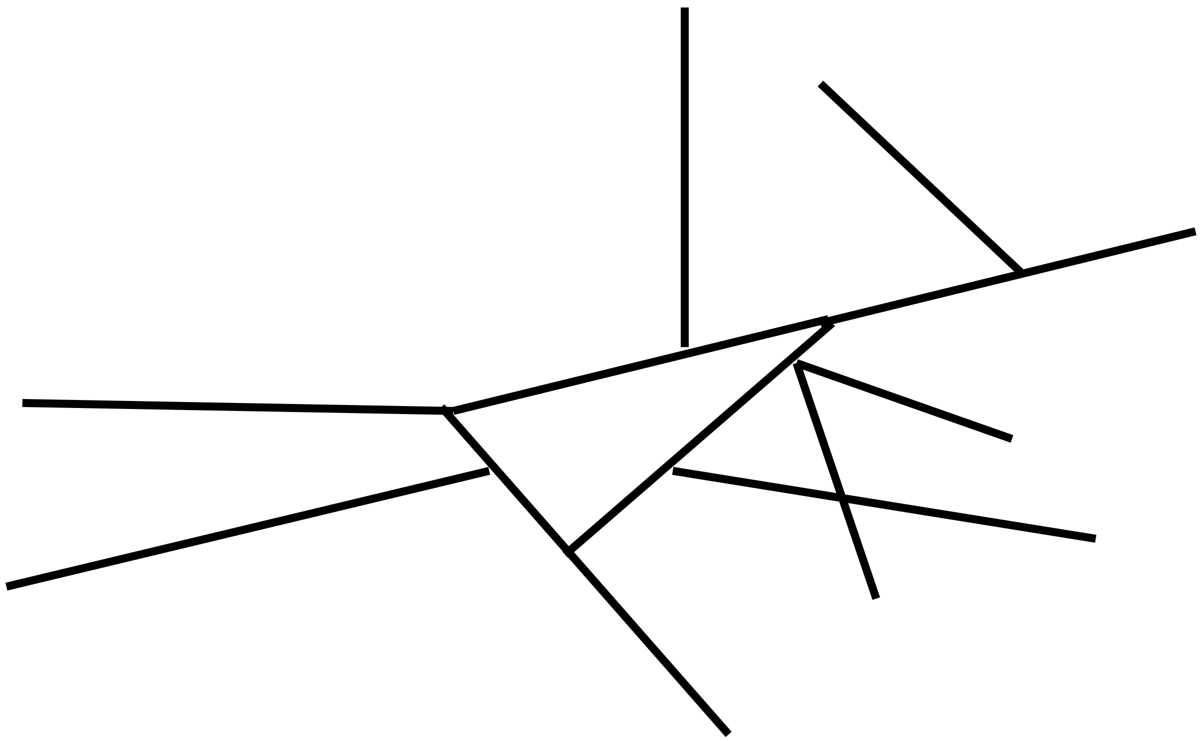
Active Hydraulics

Two constraints

$$J_i = \pm J_0$$

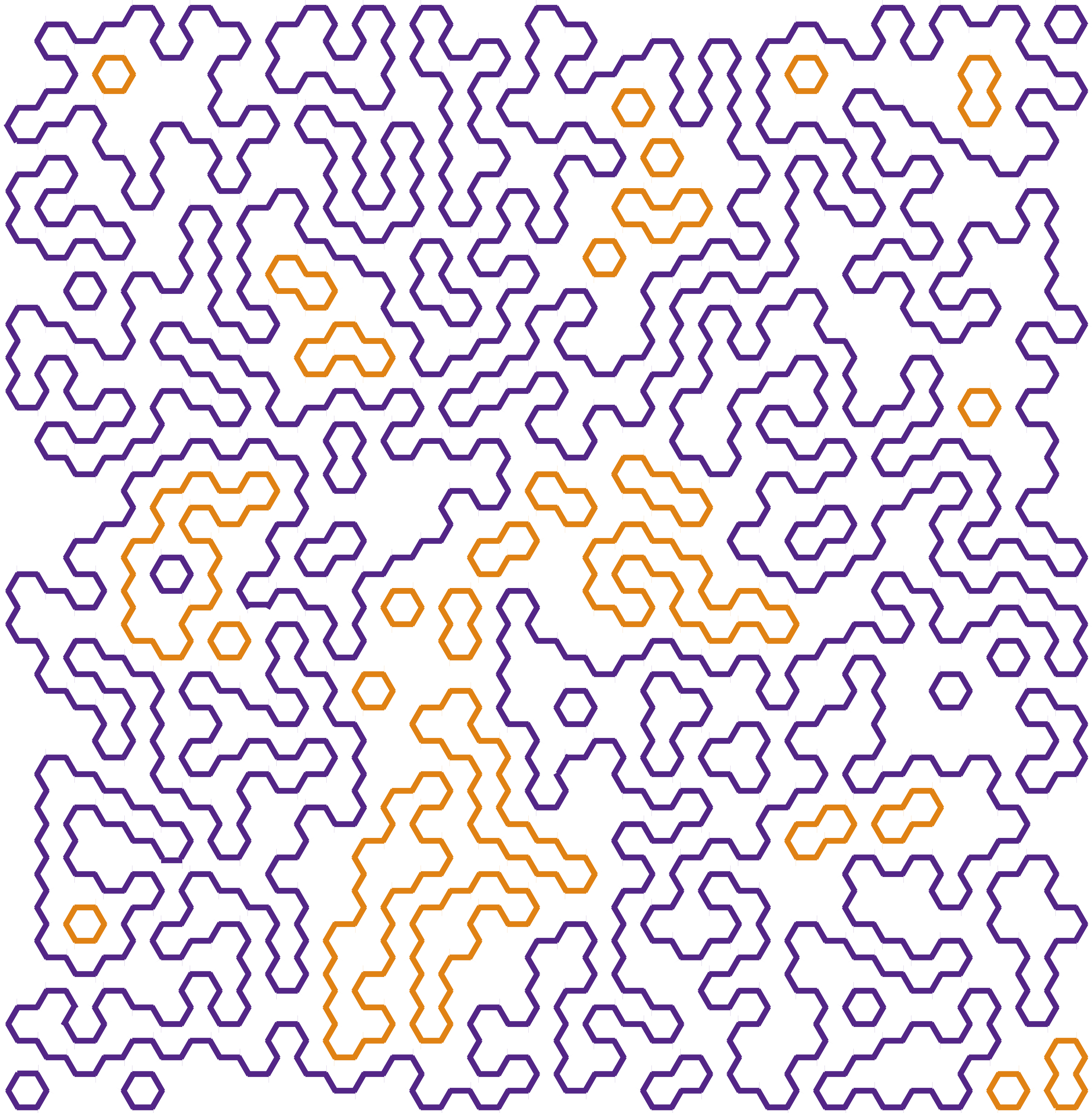
$$\sum_{\text{node } i} \mathbf{J}_i = 0$$

Pipe-network geometry



Vertex problem

Emergent flow patterns?



Simplest Geometry

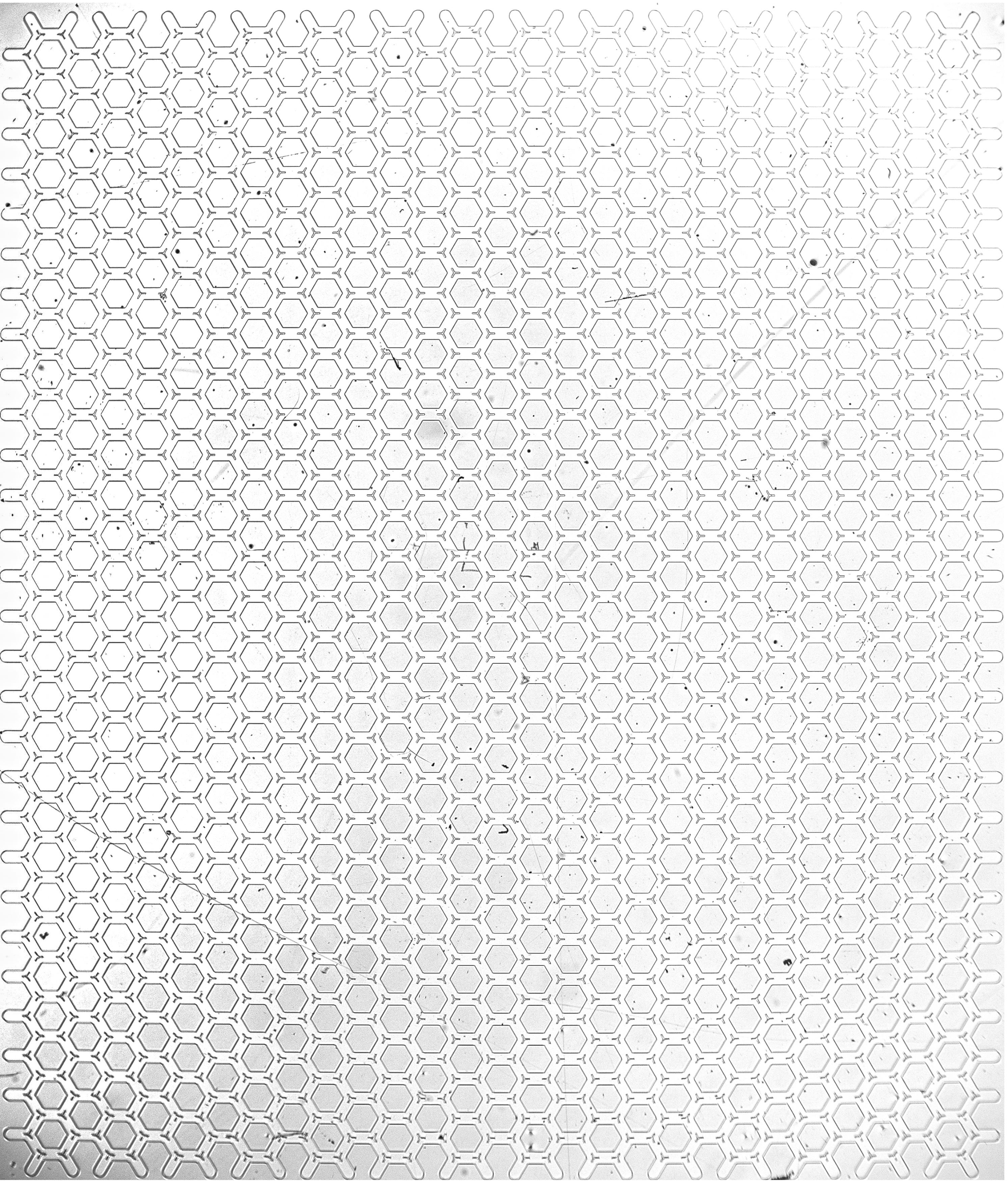
Bivalent Units

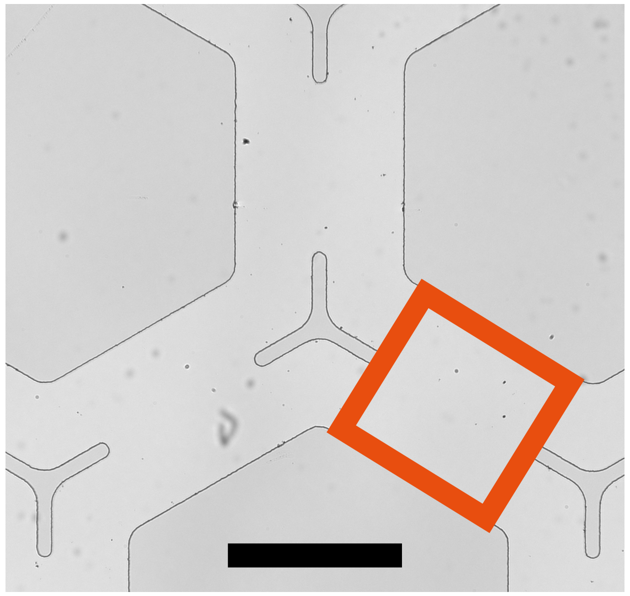
Pipe

Trivalent Units

Network

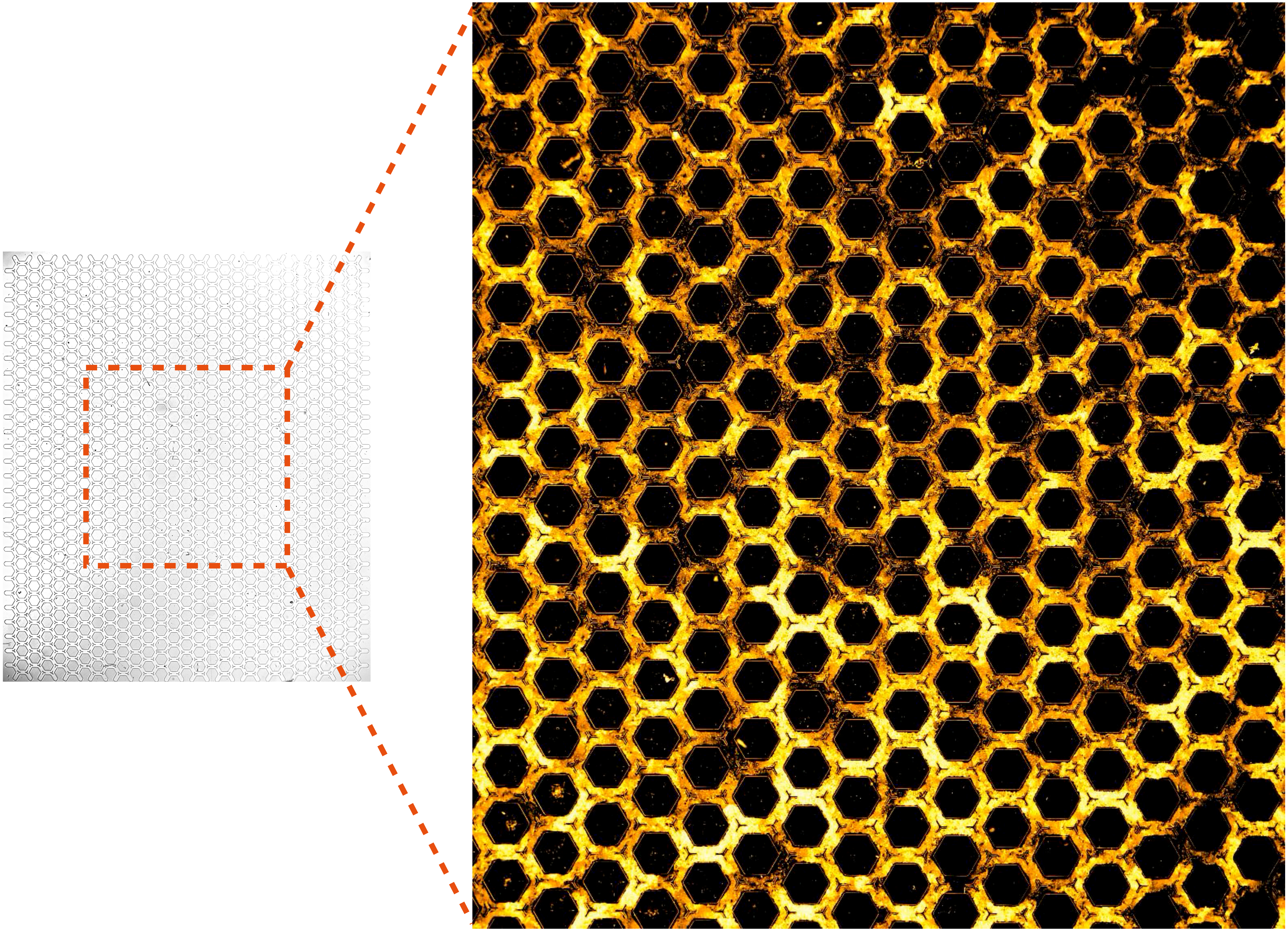
Honeycomb Lattice



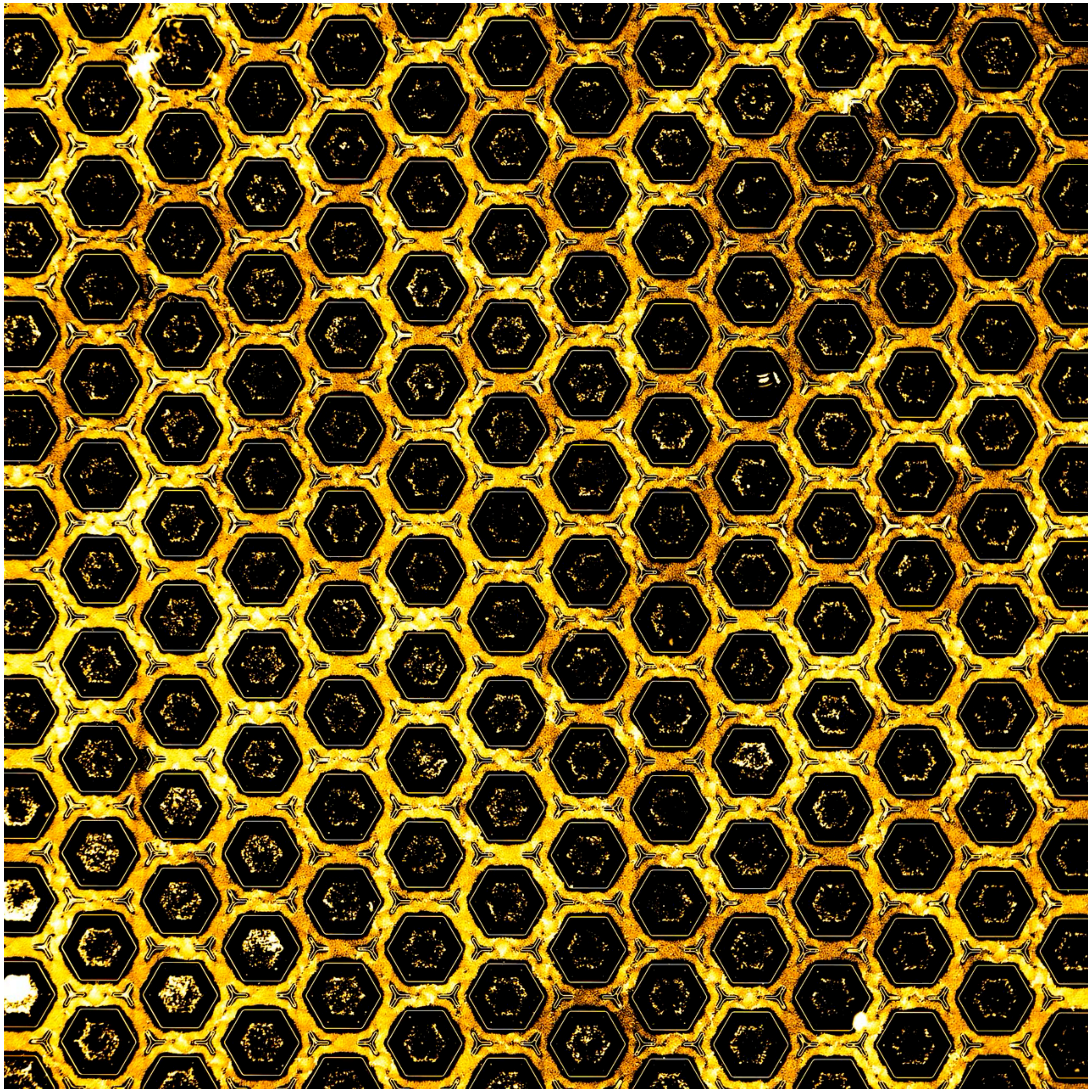


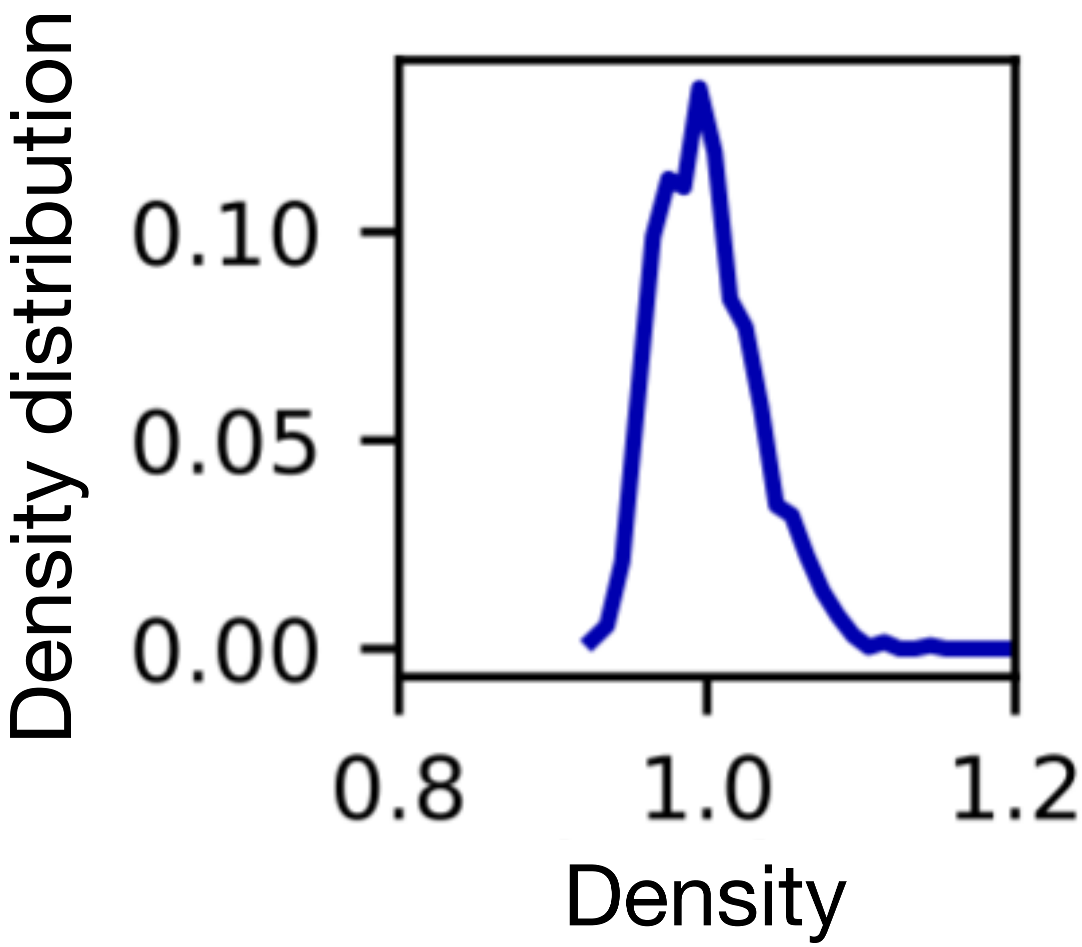
Aspect ratio: 0.7—1.7

Colloidal Roller Fluid

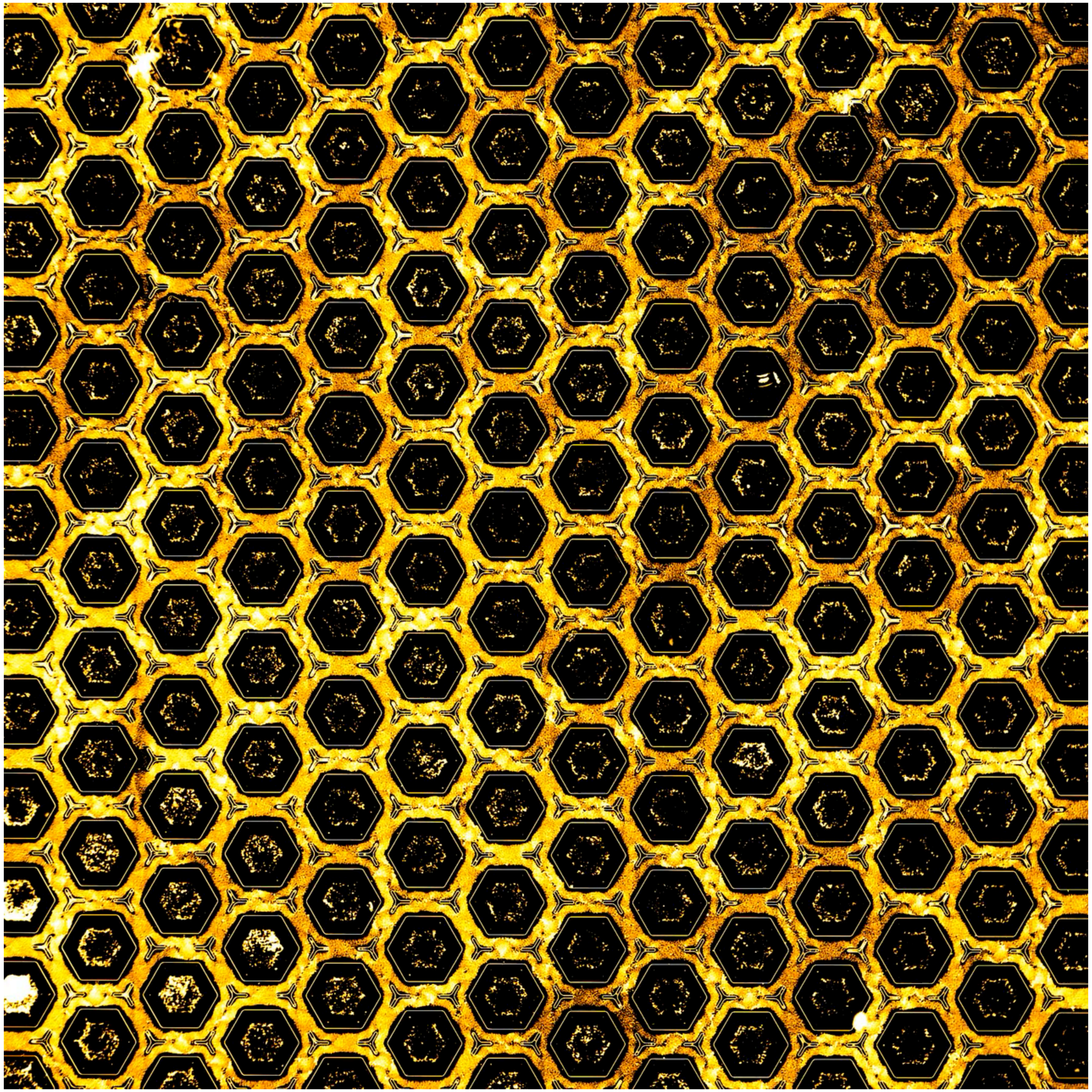


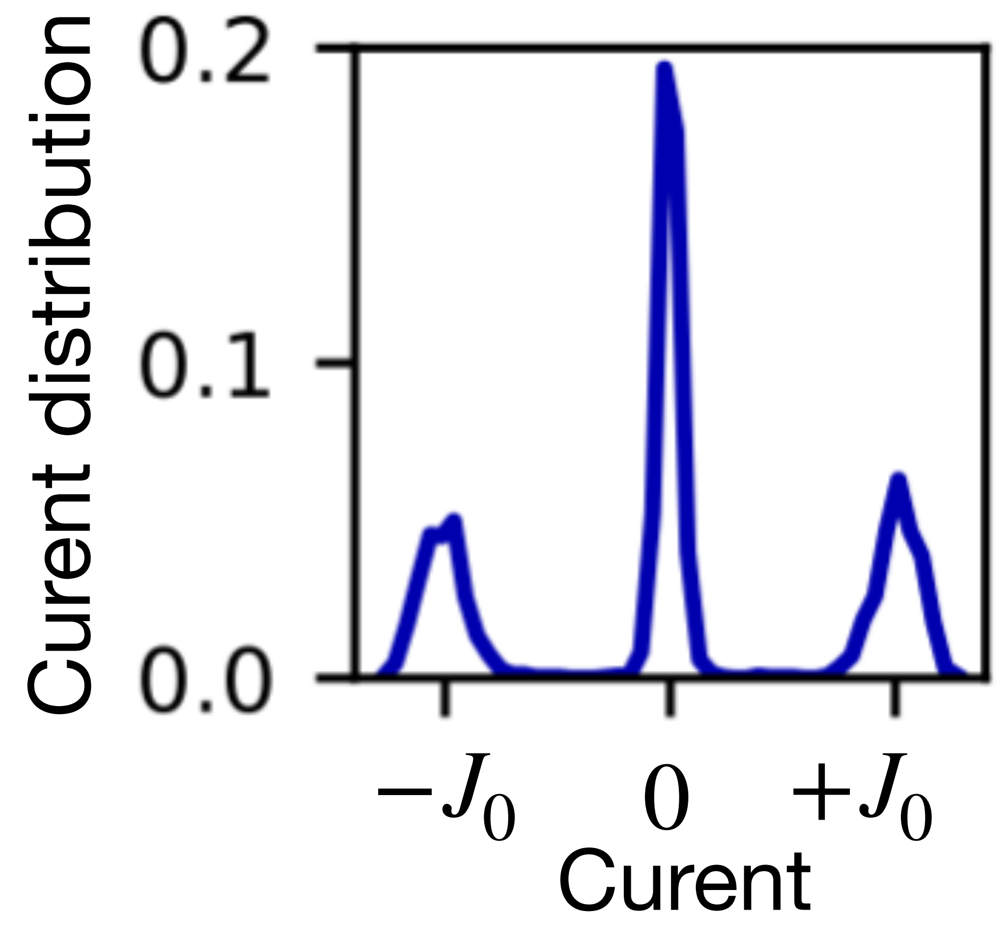
Steady state: Uniform packing fraction





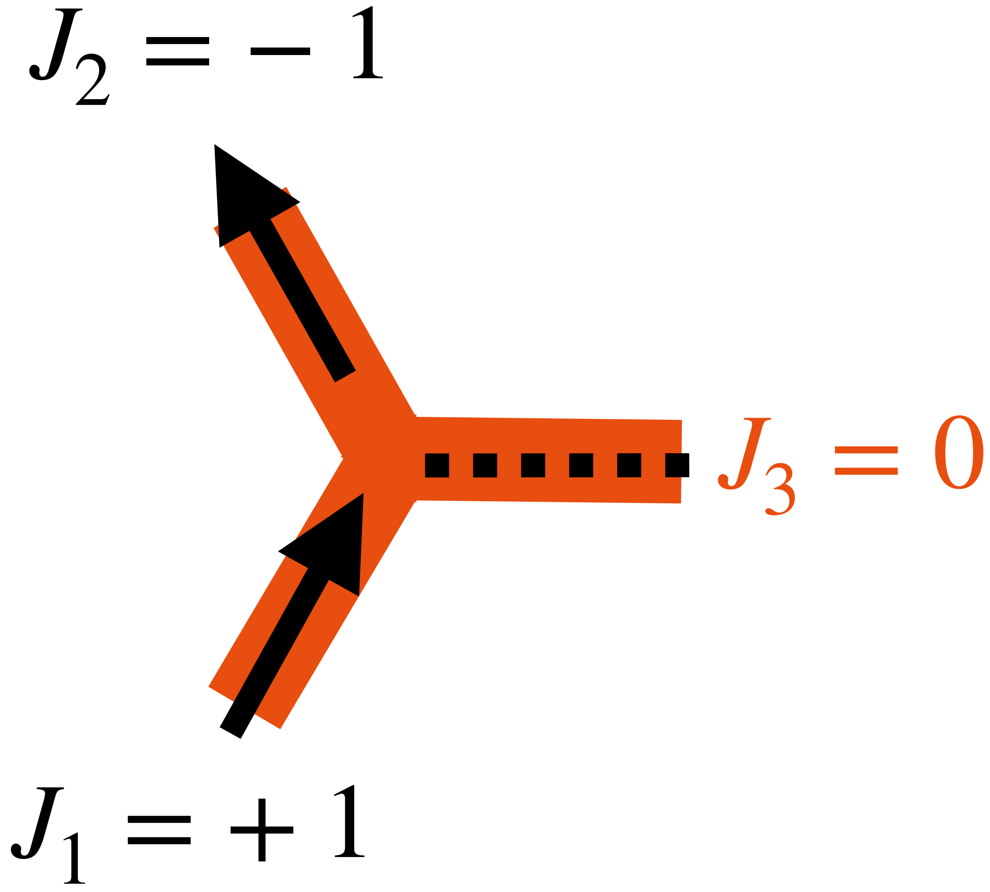
Steady state: Current statistics





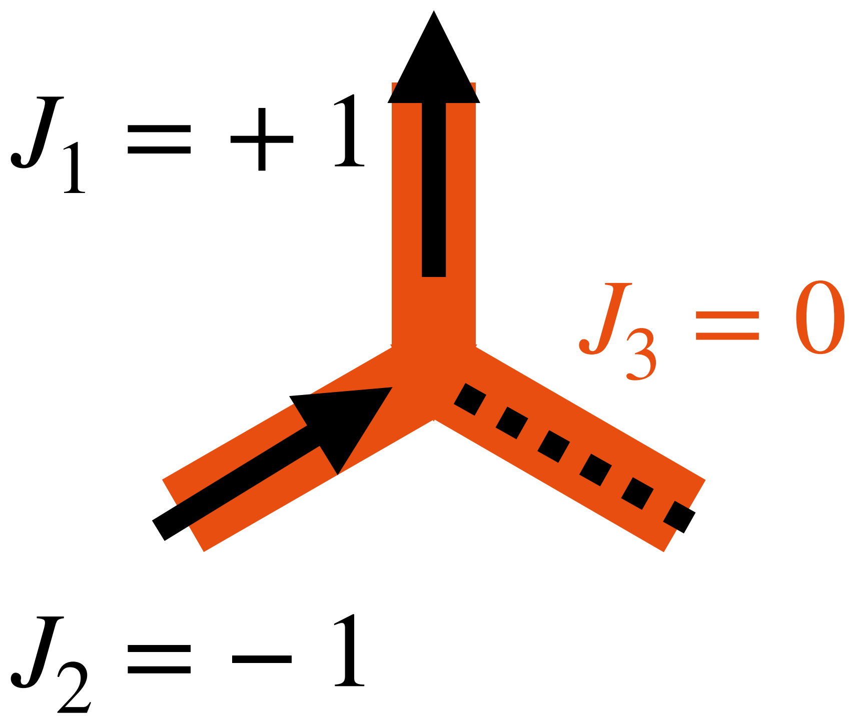
$$J_i \neq \pm J_0$$

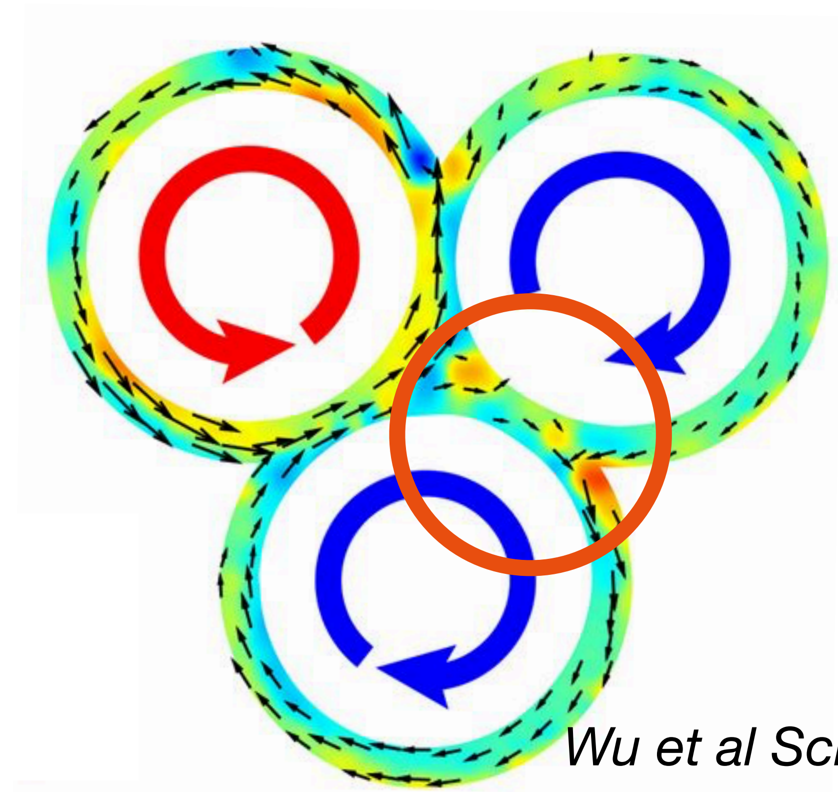
Geomerical Frustration



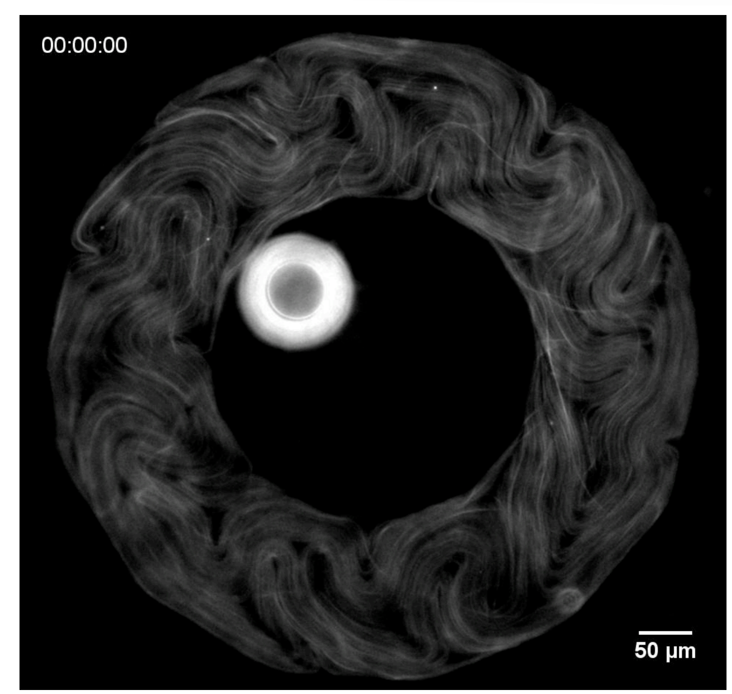
Activity forbids uniform laminar flows

Geomerical Frustration



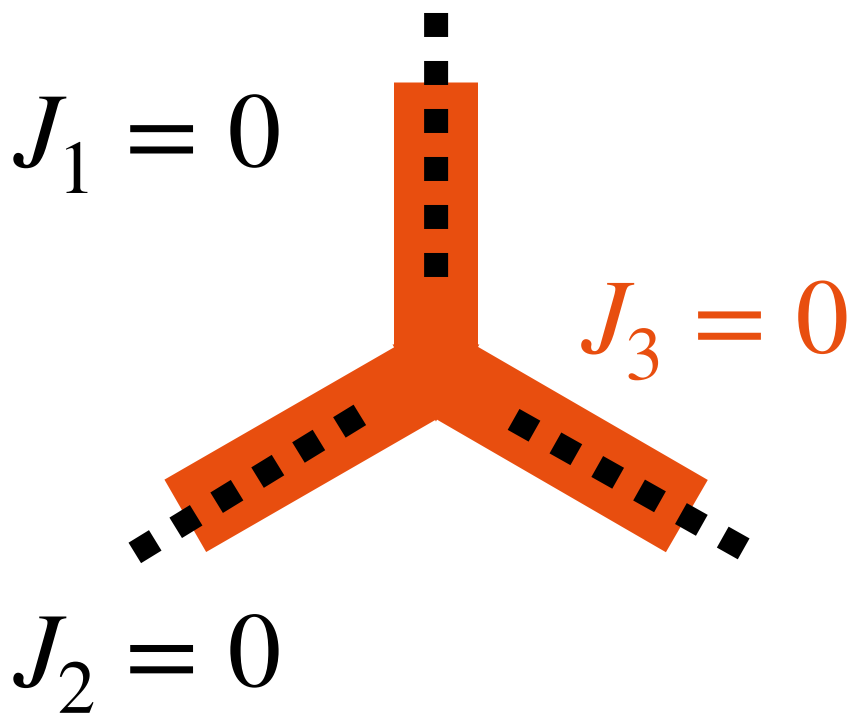


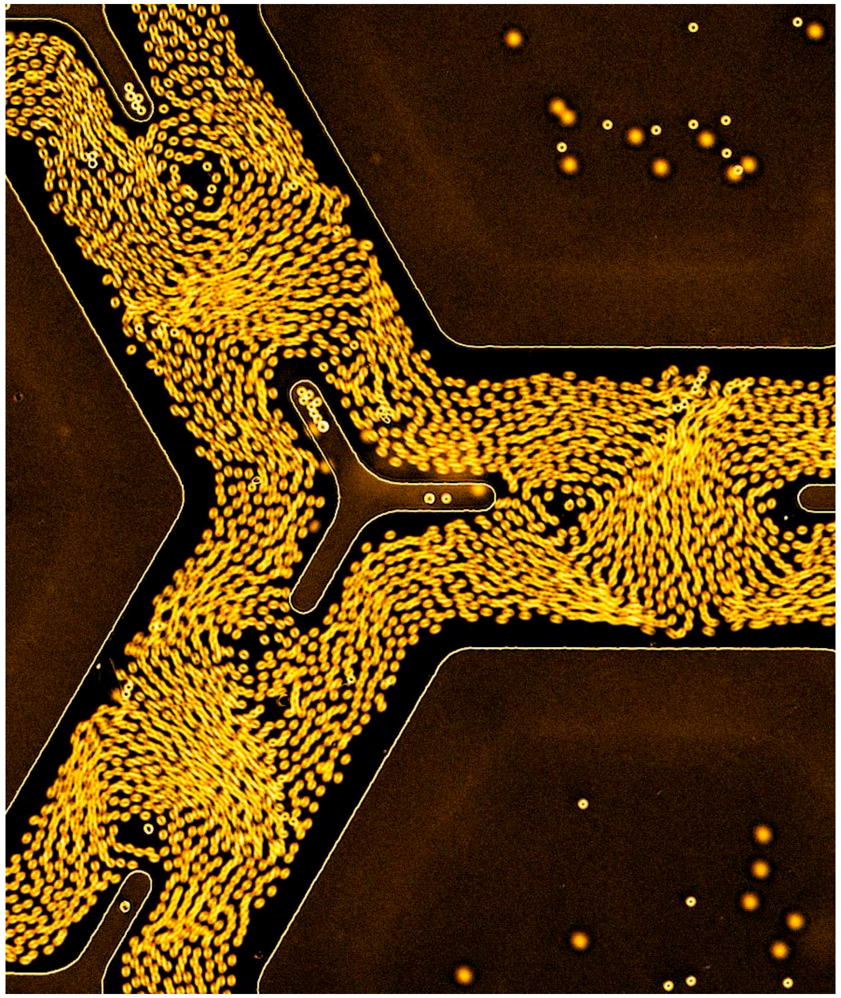
Wu et al Science 2017



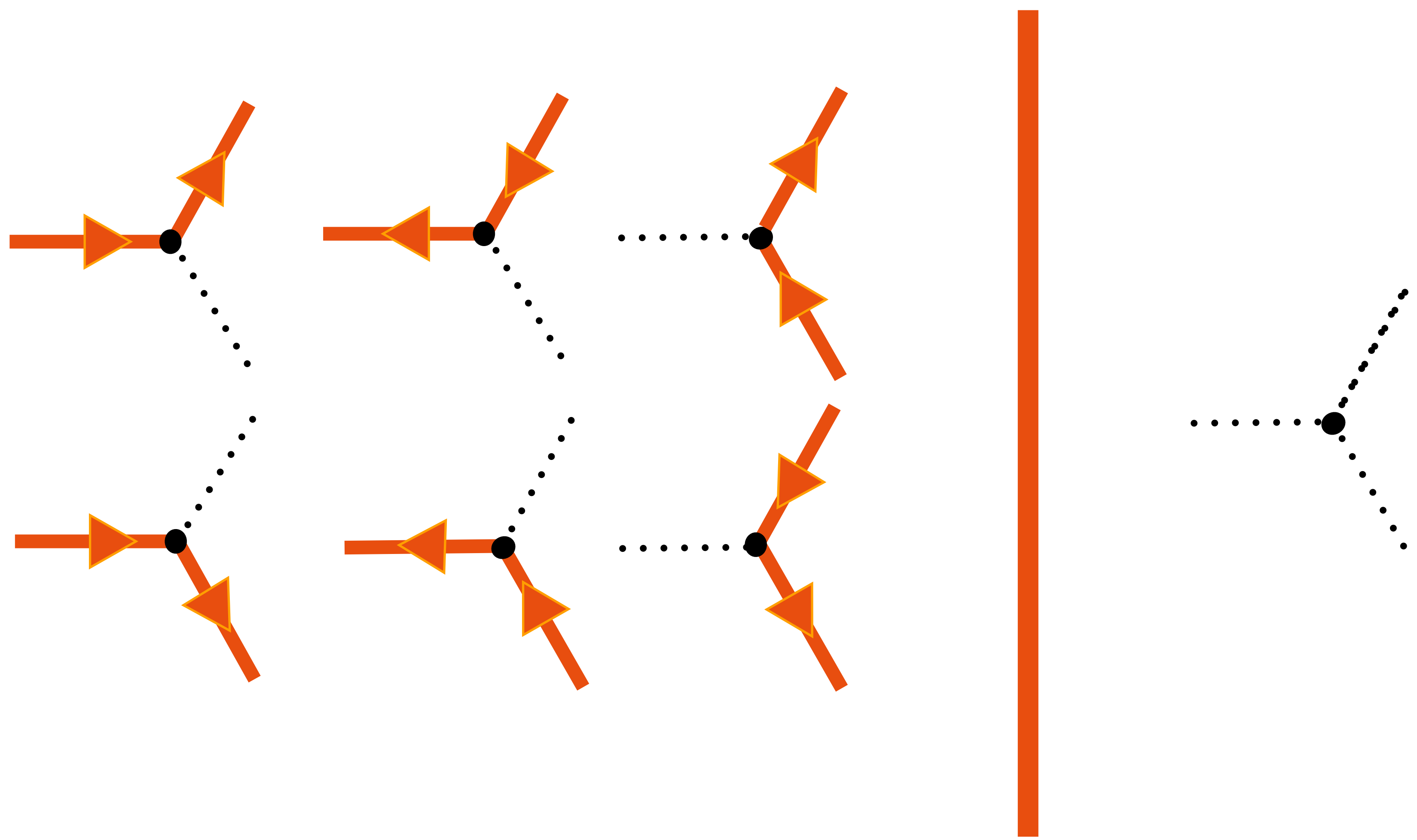
Opathalage et al PNAS 2019

Geomerical Frustration

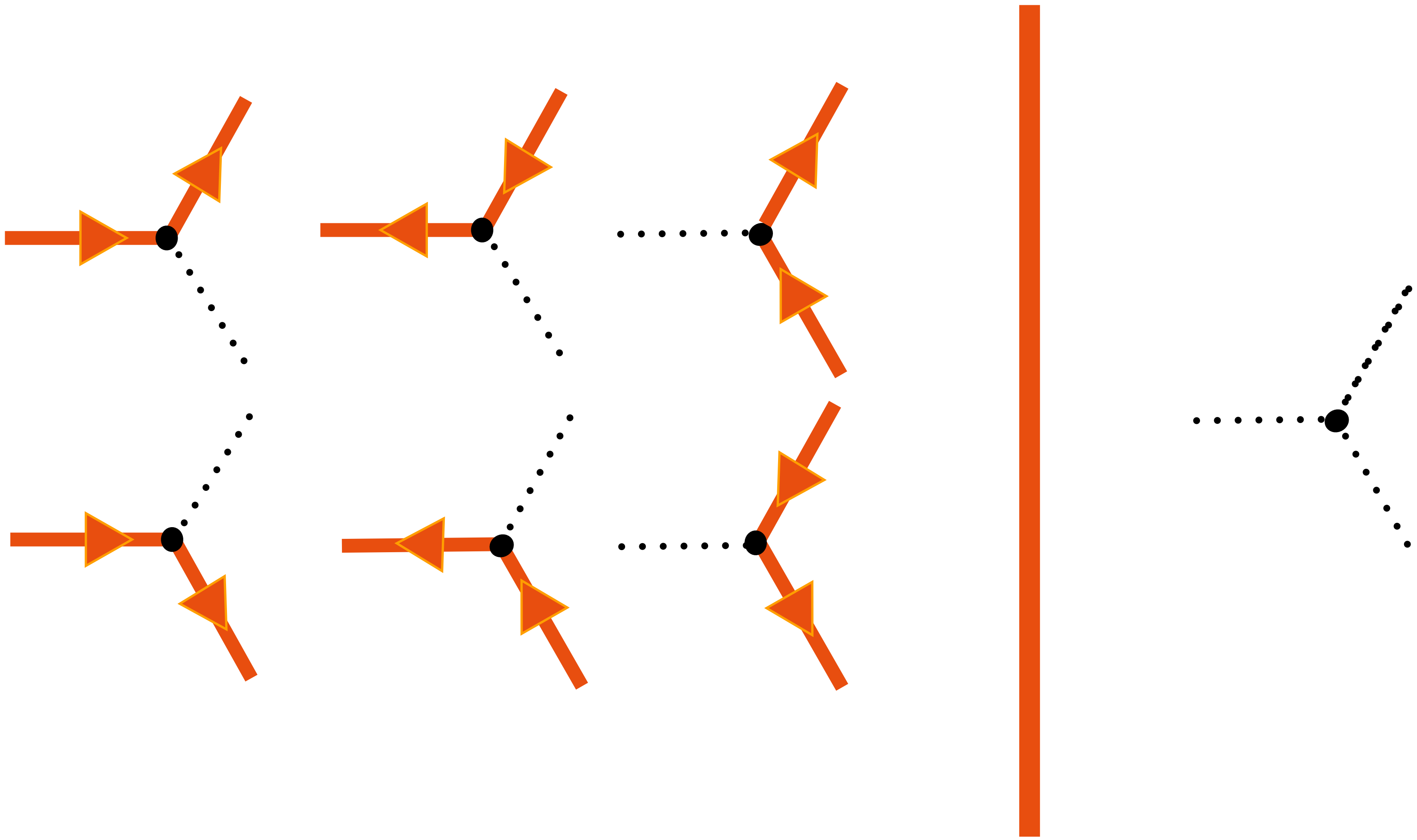




Seven vertex configurations

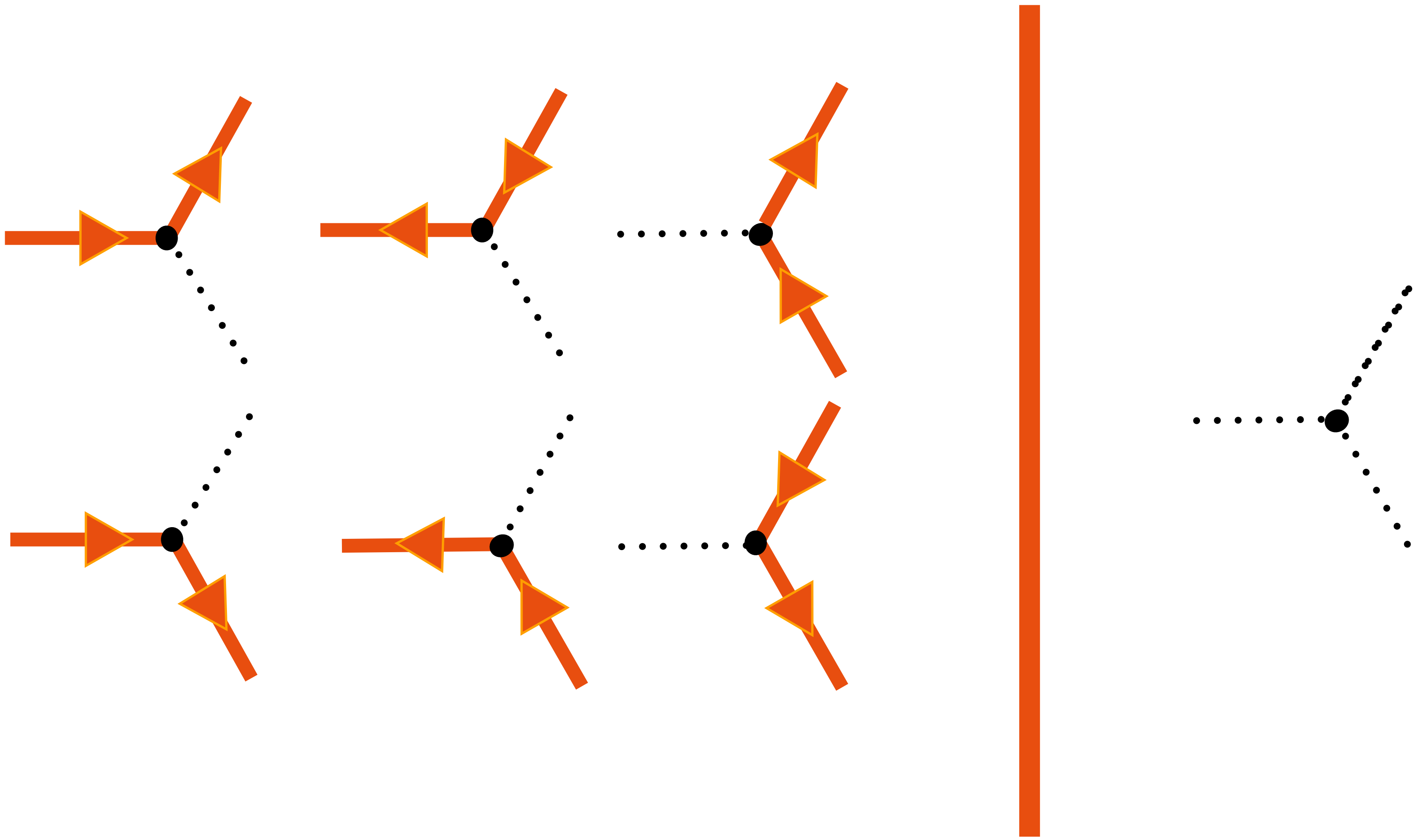


Active Fluidic Network Theory



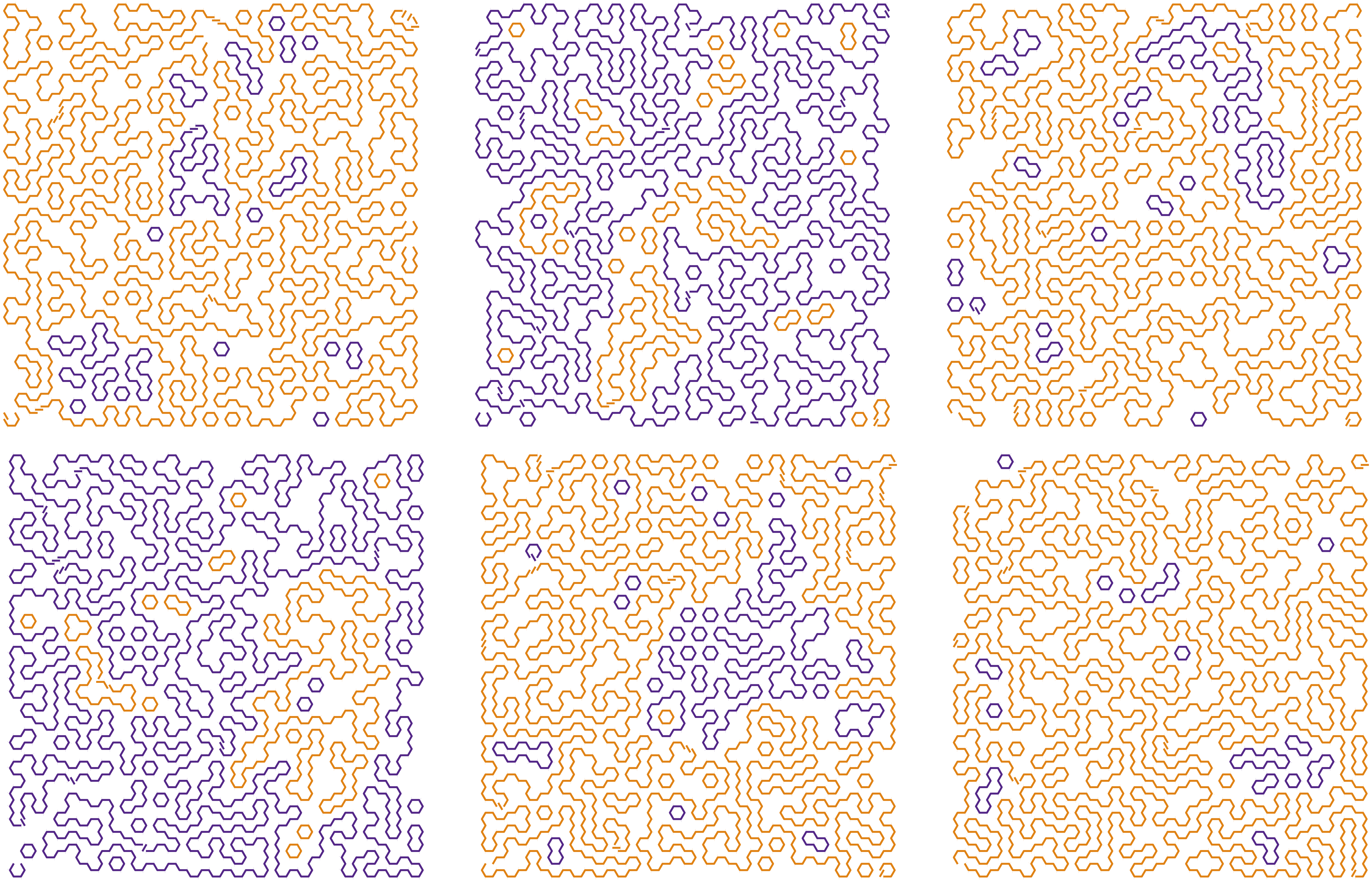
F. Woodhouse and J. Dunkel

Seven vertex configurations



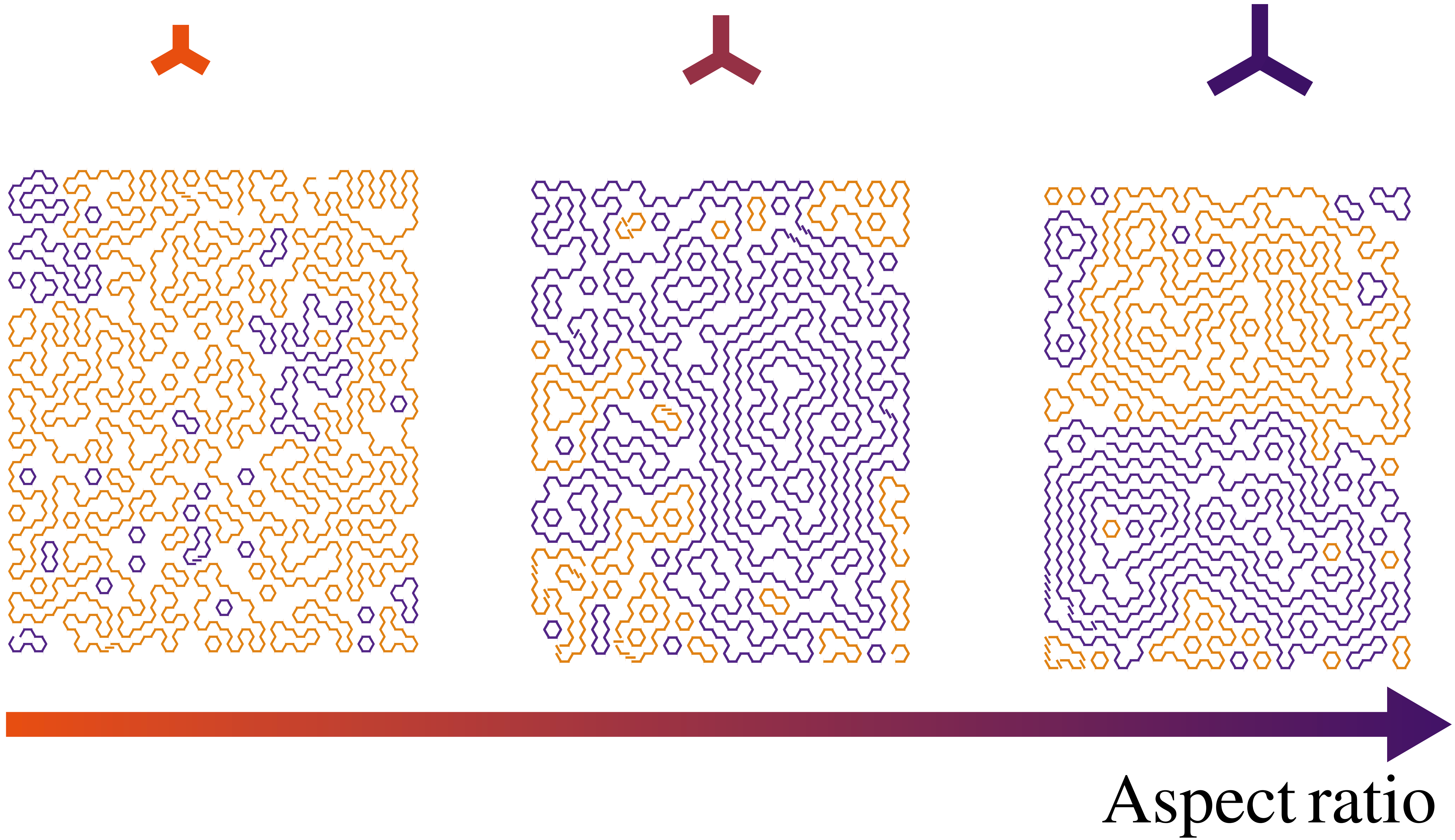
Generators of self-avoiding random walks

Streamlines: Self-avoiding loops



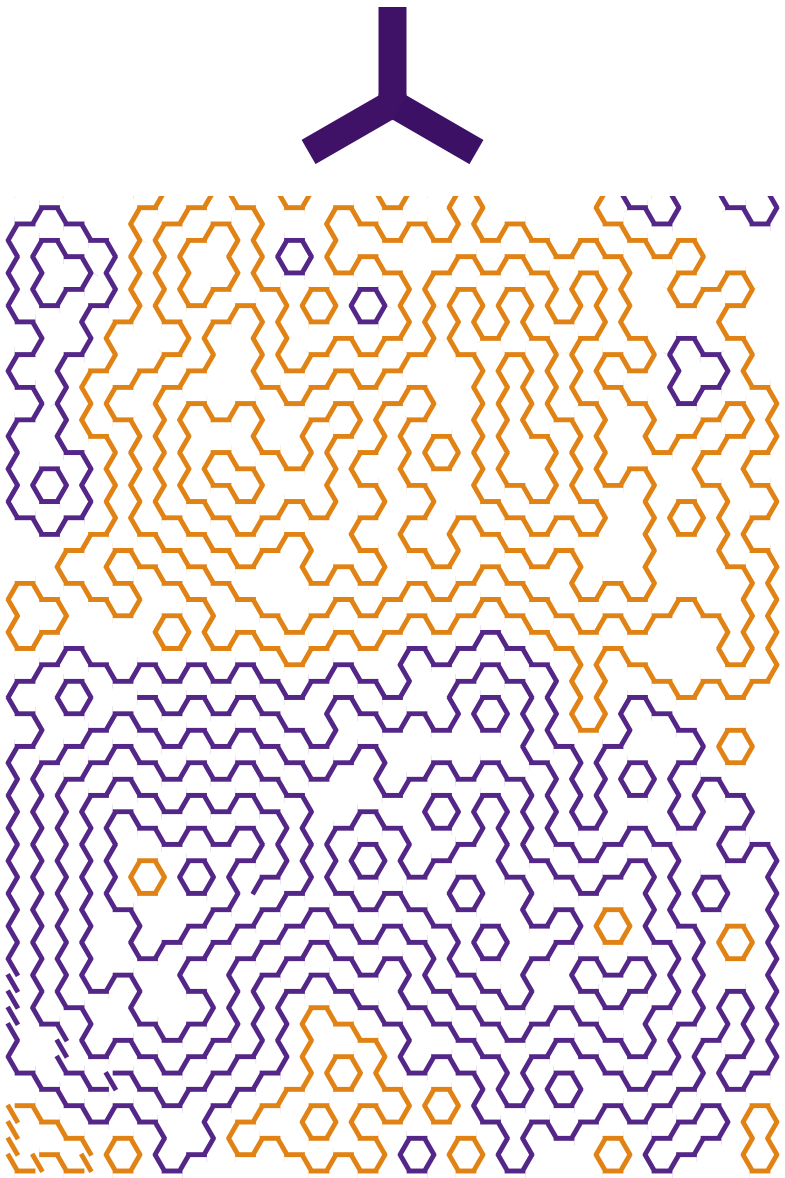
Steady state degeneracy

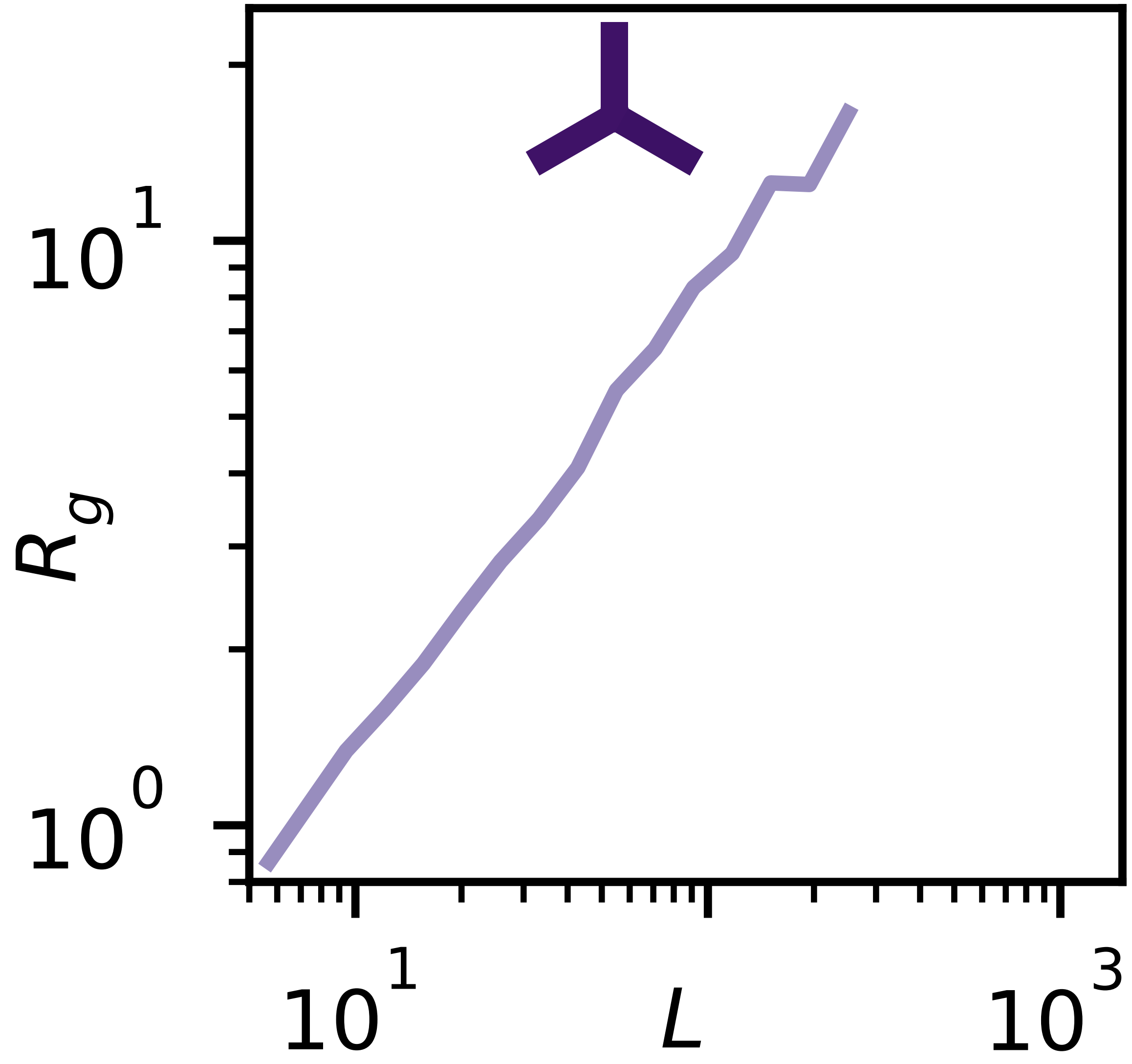
Impact of the channel geometry



Structural change

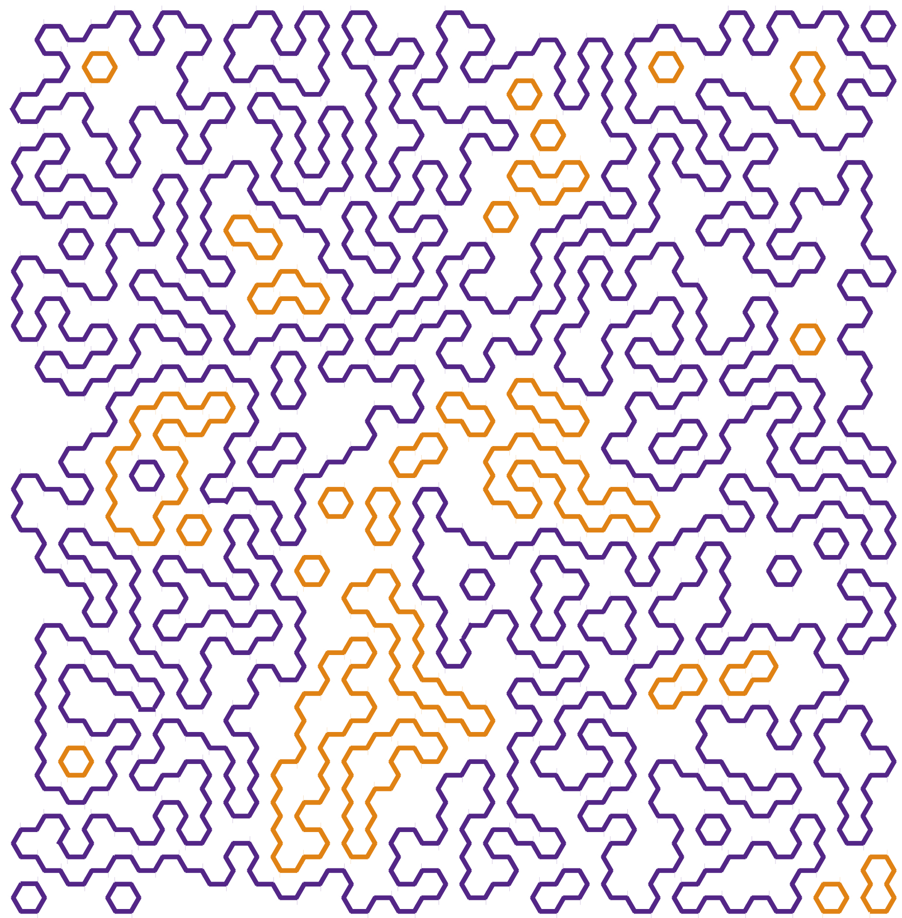
Gyration radius

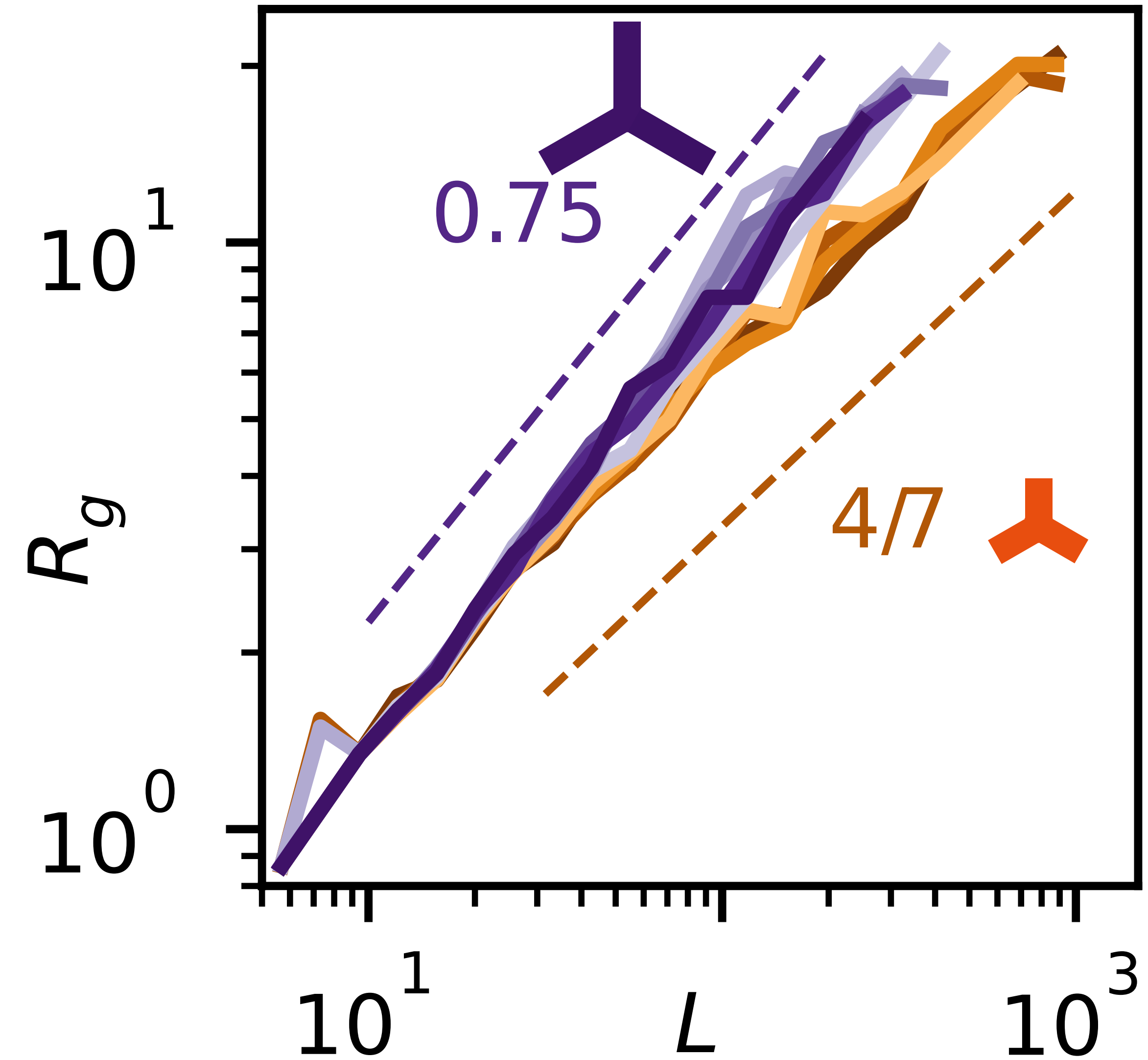




$$R_\mathrm{g} \sim L^{\nu}$$

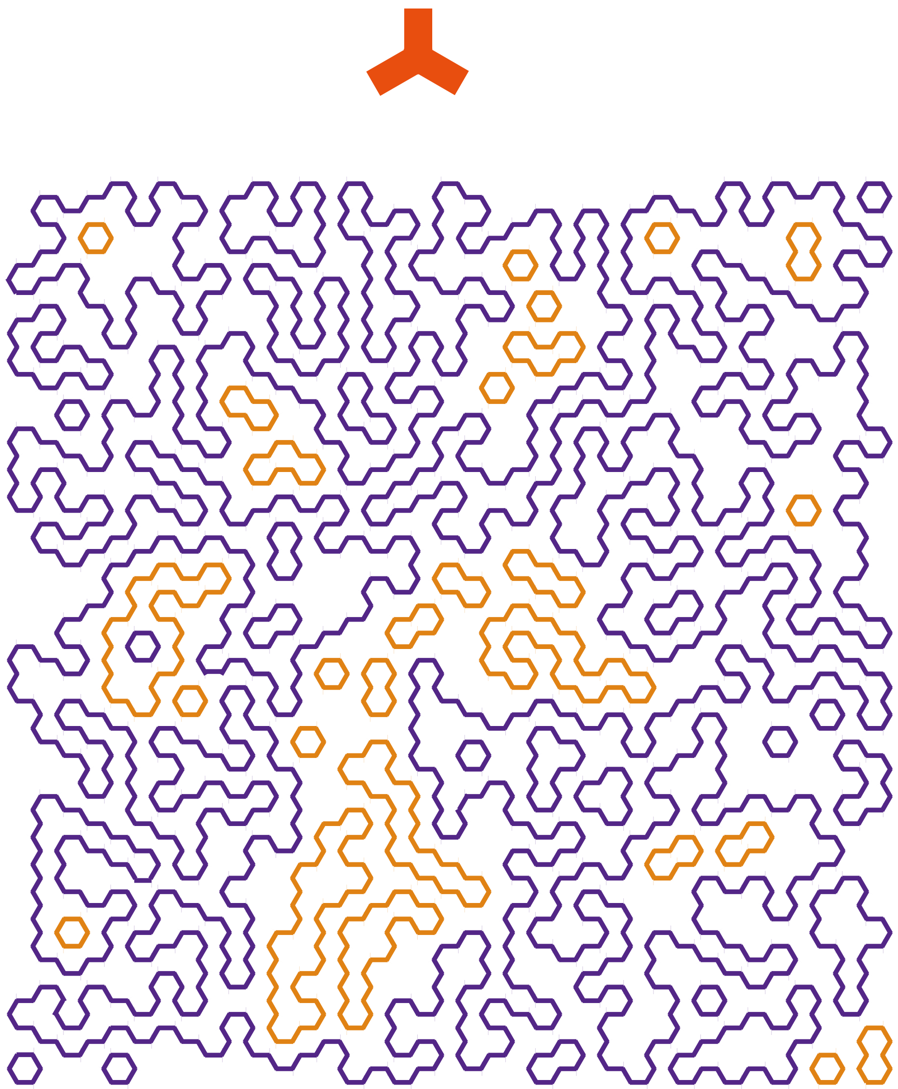
Gyration radius

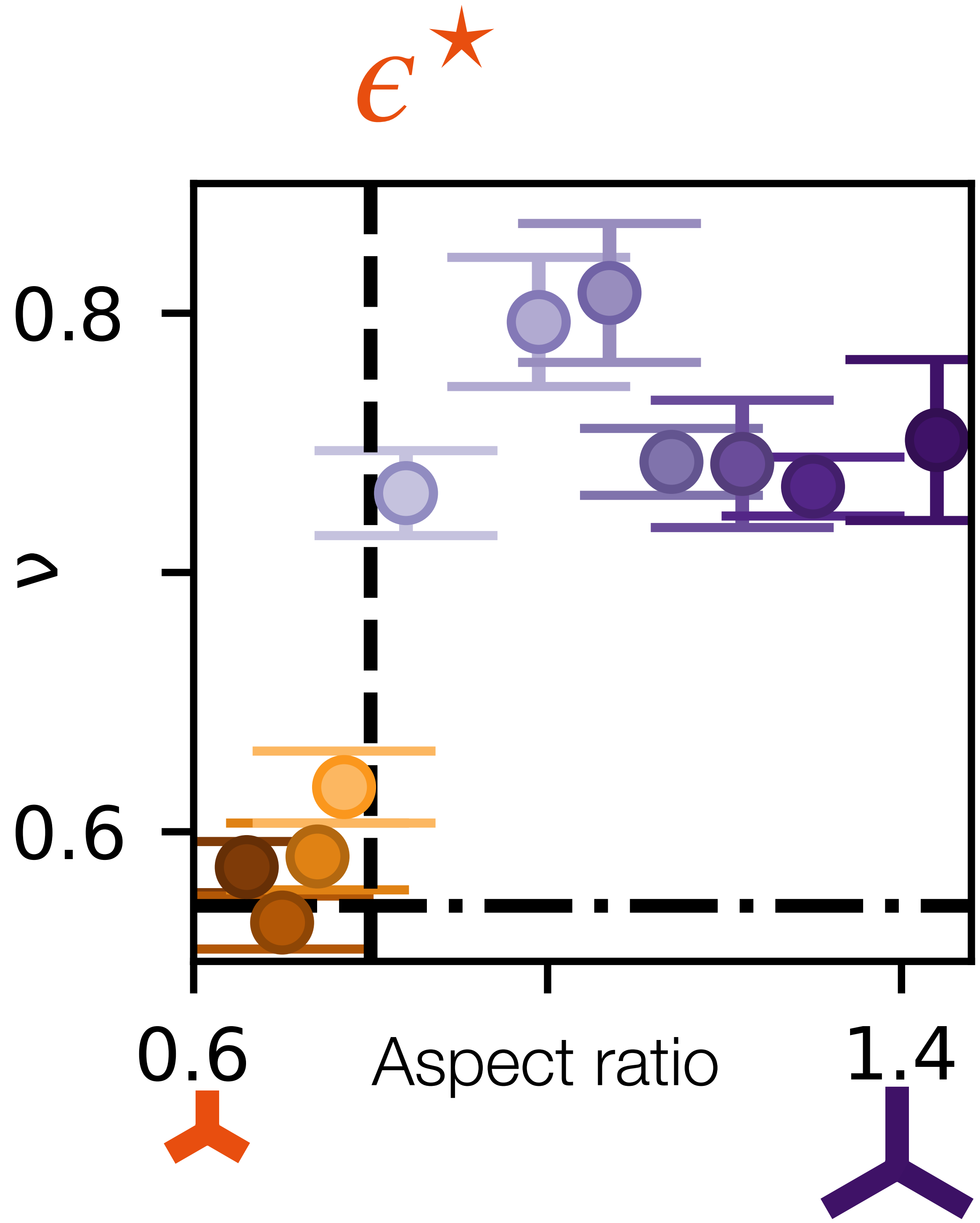




$$R_g \sim L^{\nu}$$

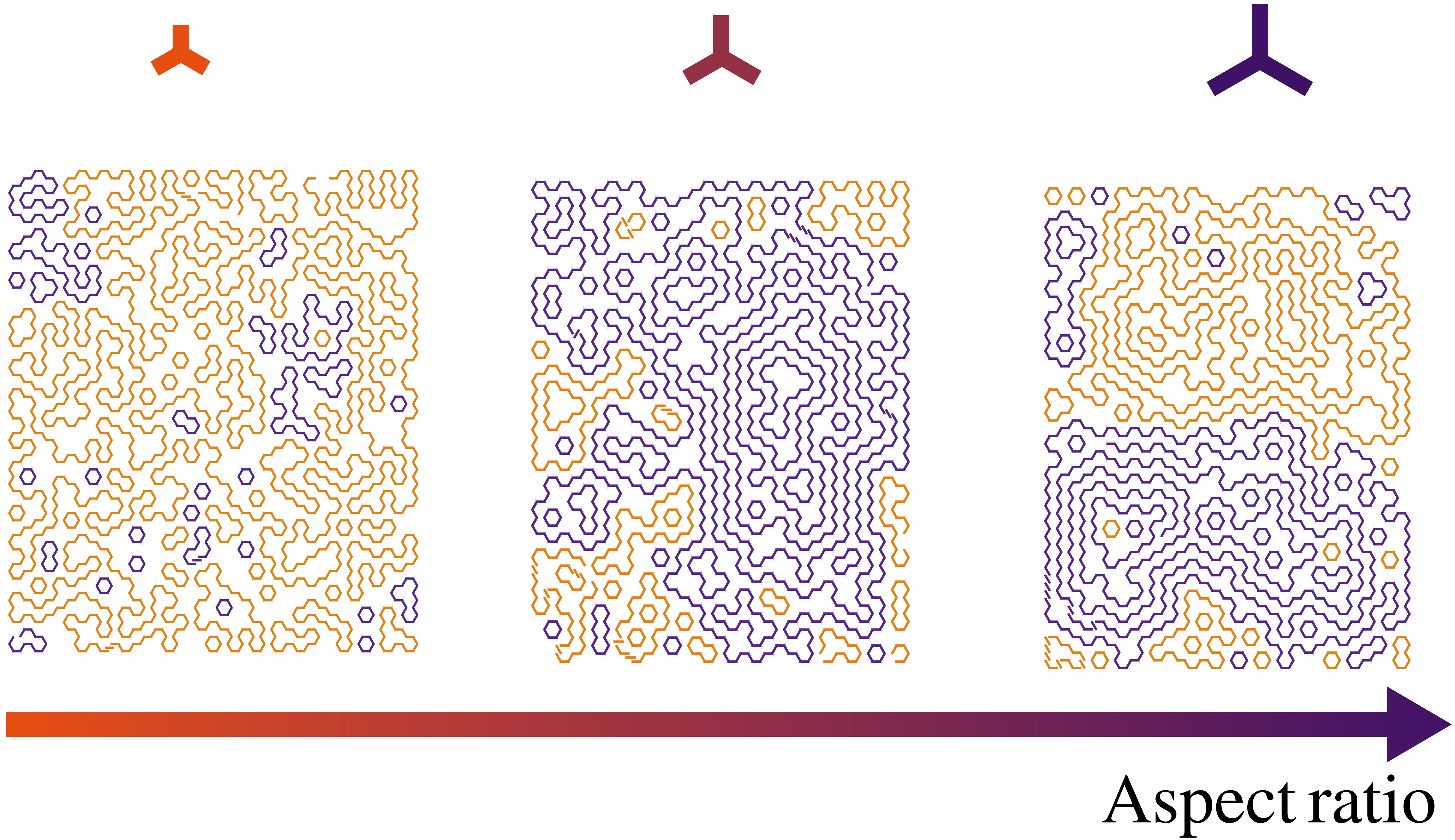
Gyration radius



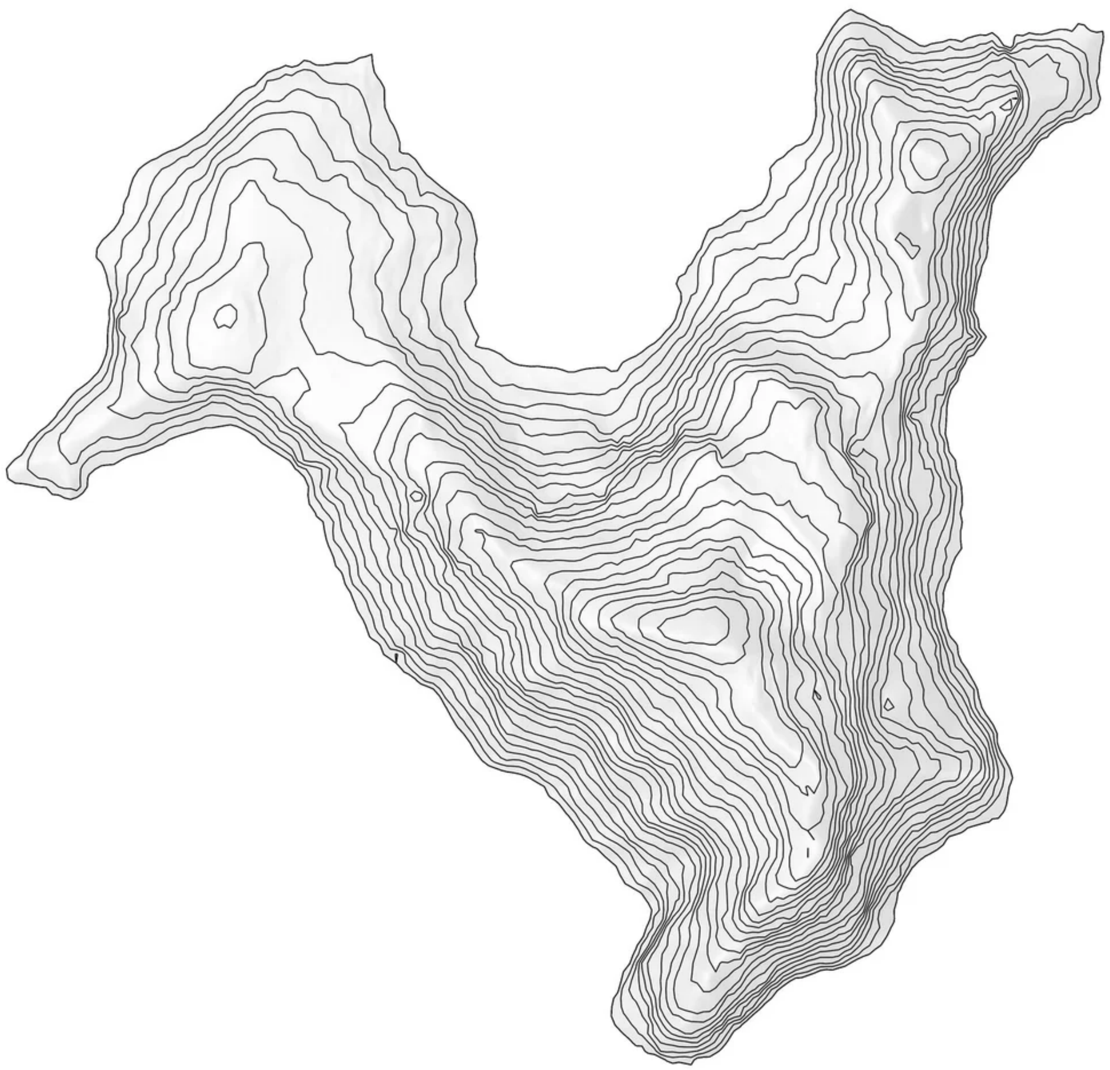


$$R_g \sim L^\nu$$

Segregated vs nested loops



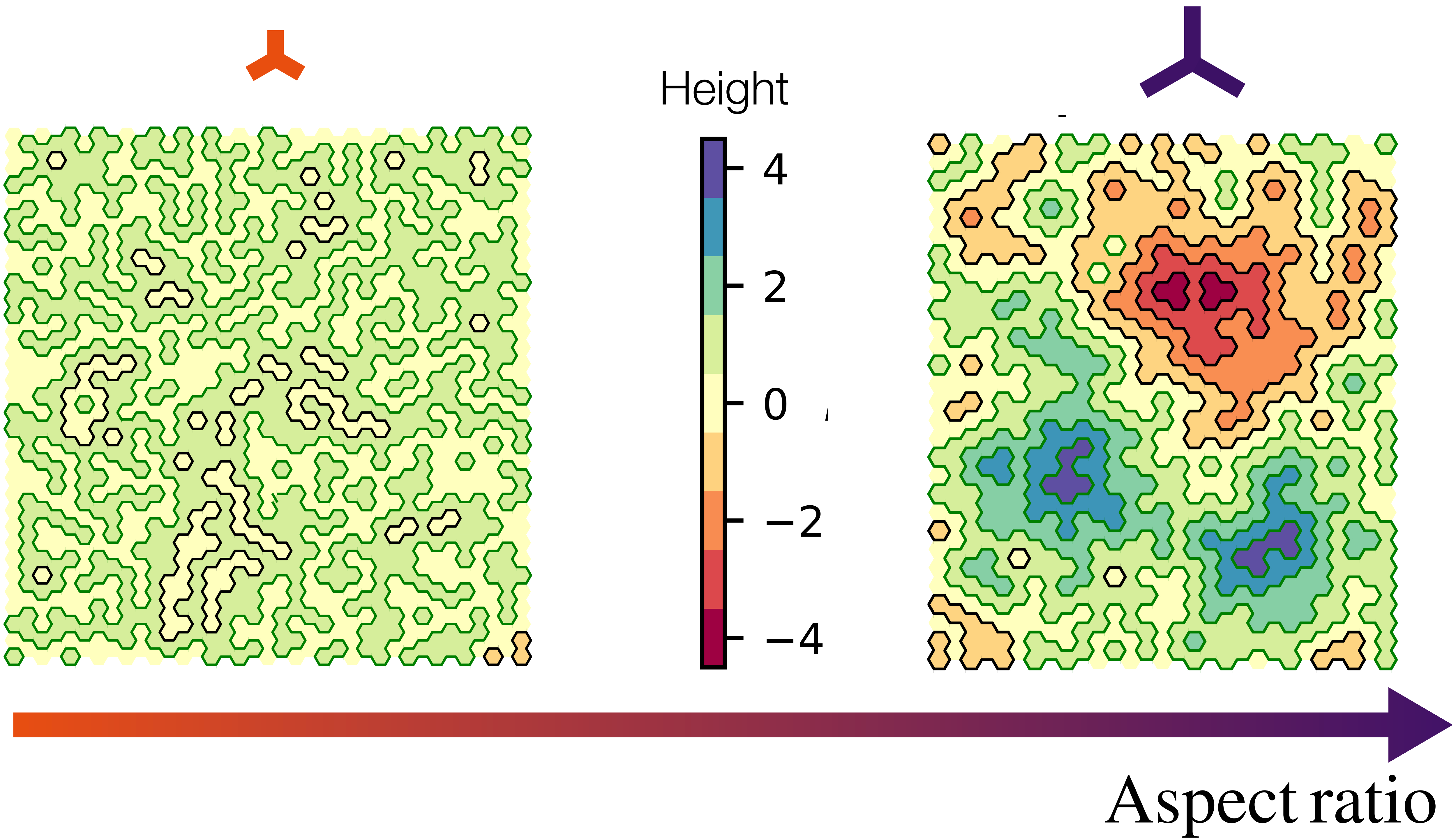
Steamlines as a landscape's contour map



Mont Blanc

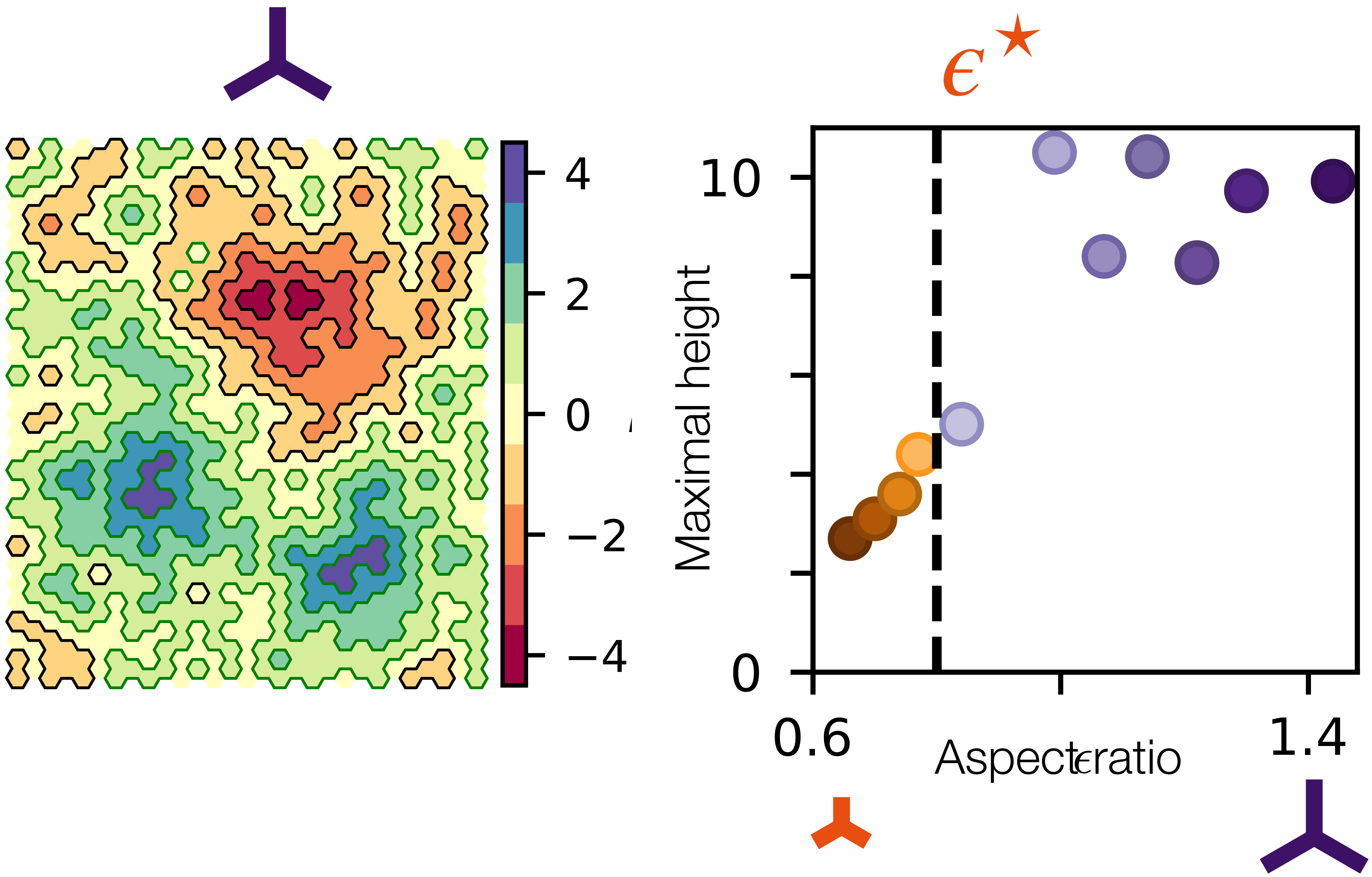
4,808m | 15,777ft

Steamlines as a contour map

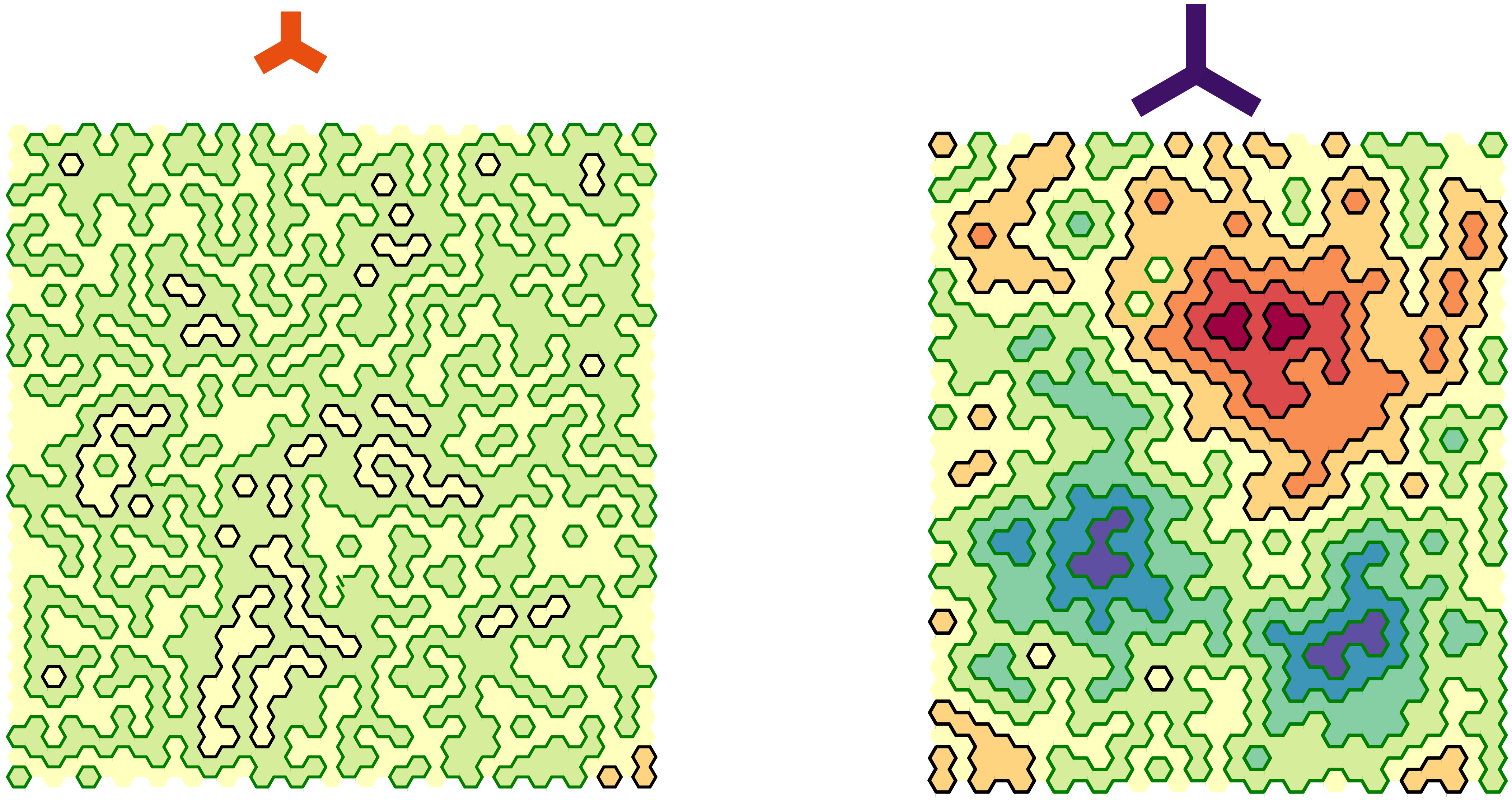


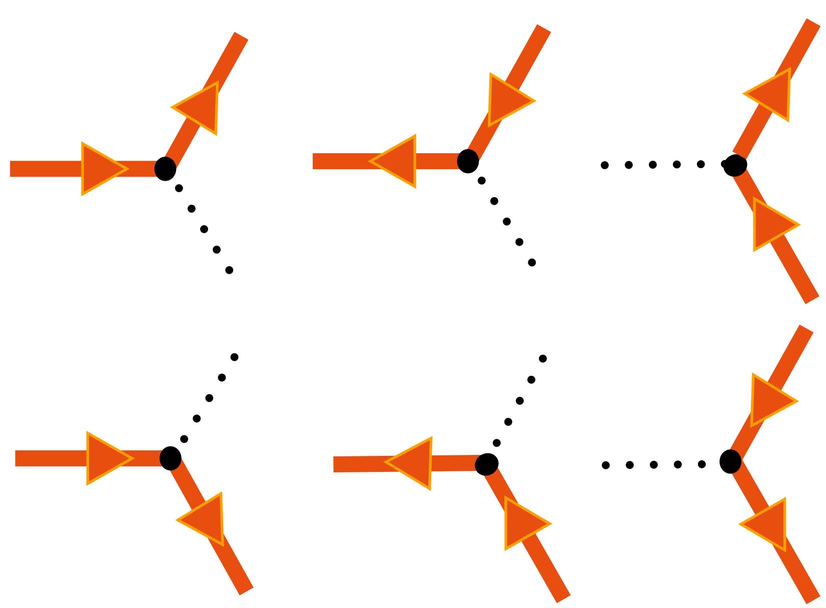
Nienhuis 1980's

Nesting Increases



Structural Diversity ??

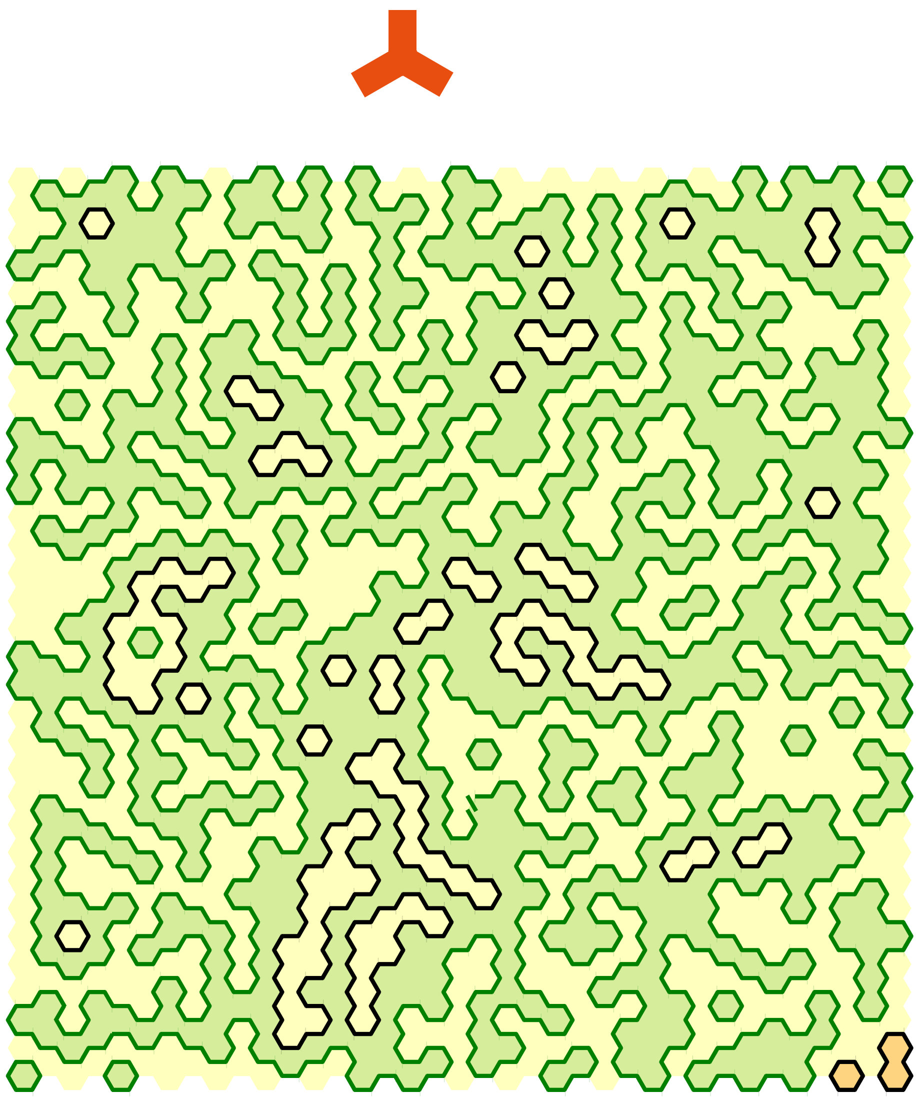


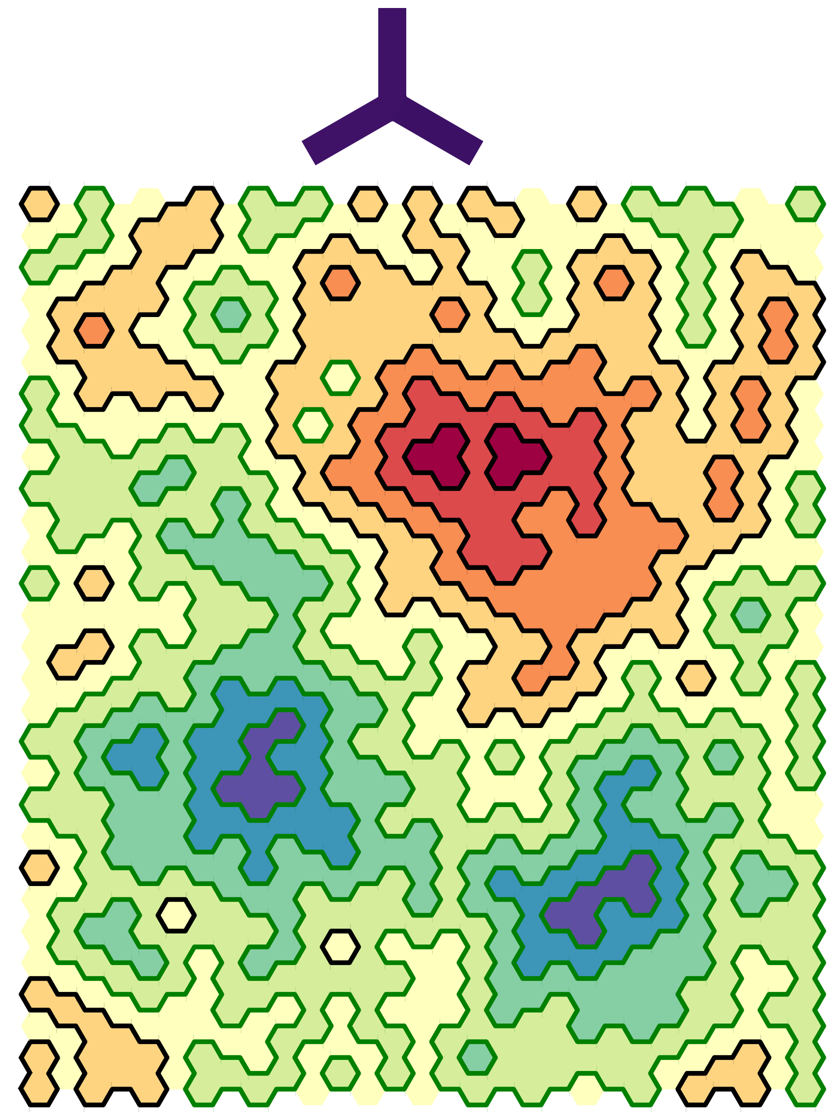


Agnostic to the channels' geometry…

What's missing??

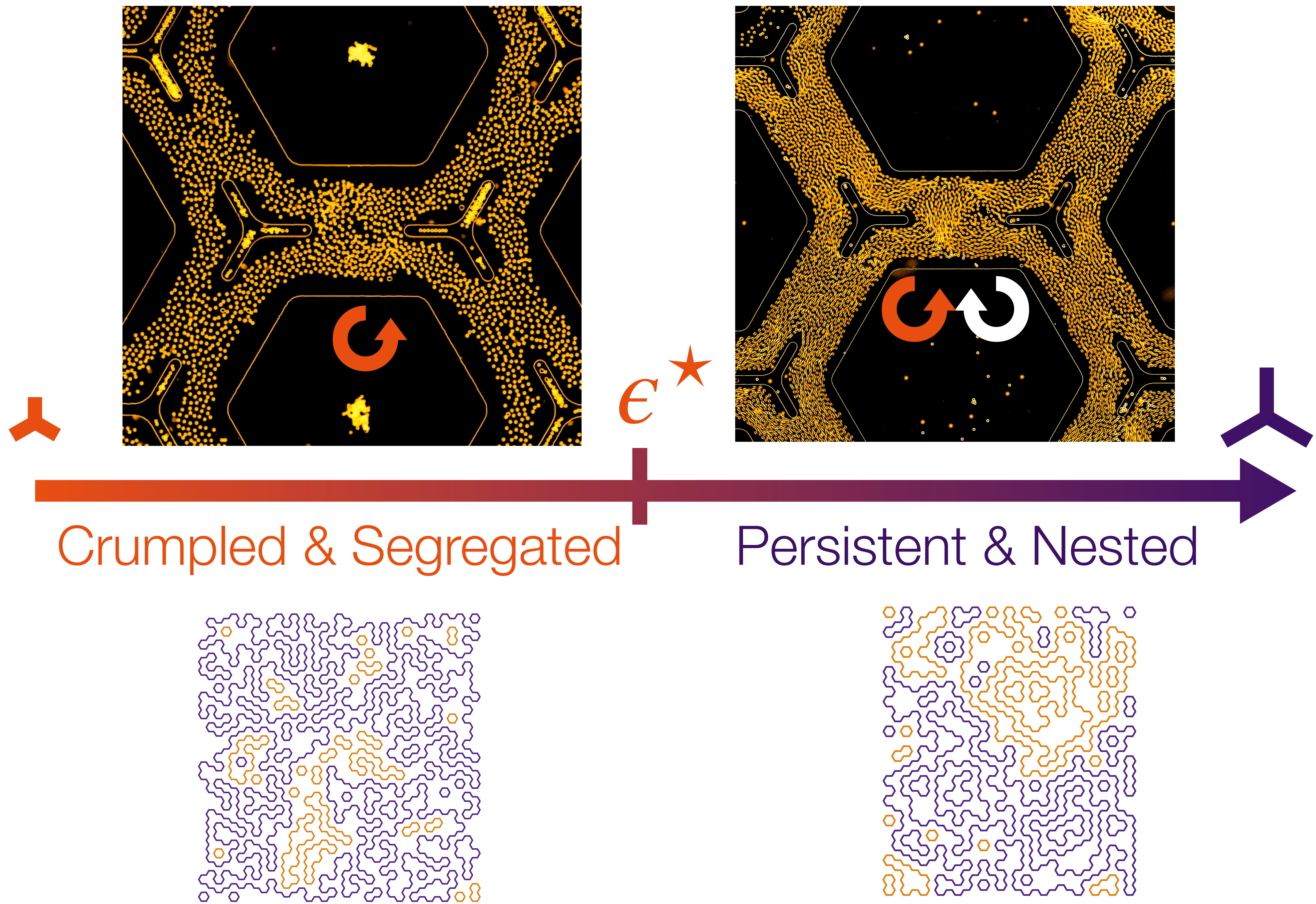
Structural Diversity ??





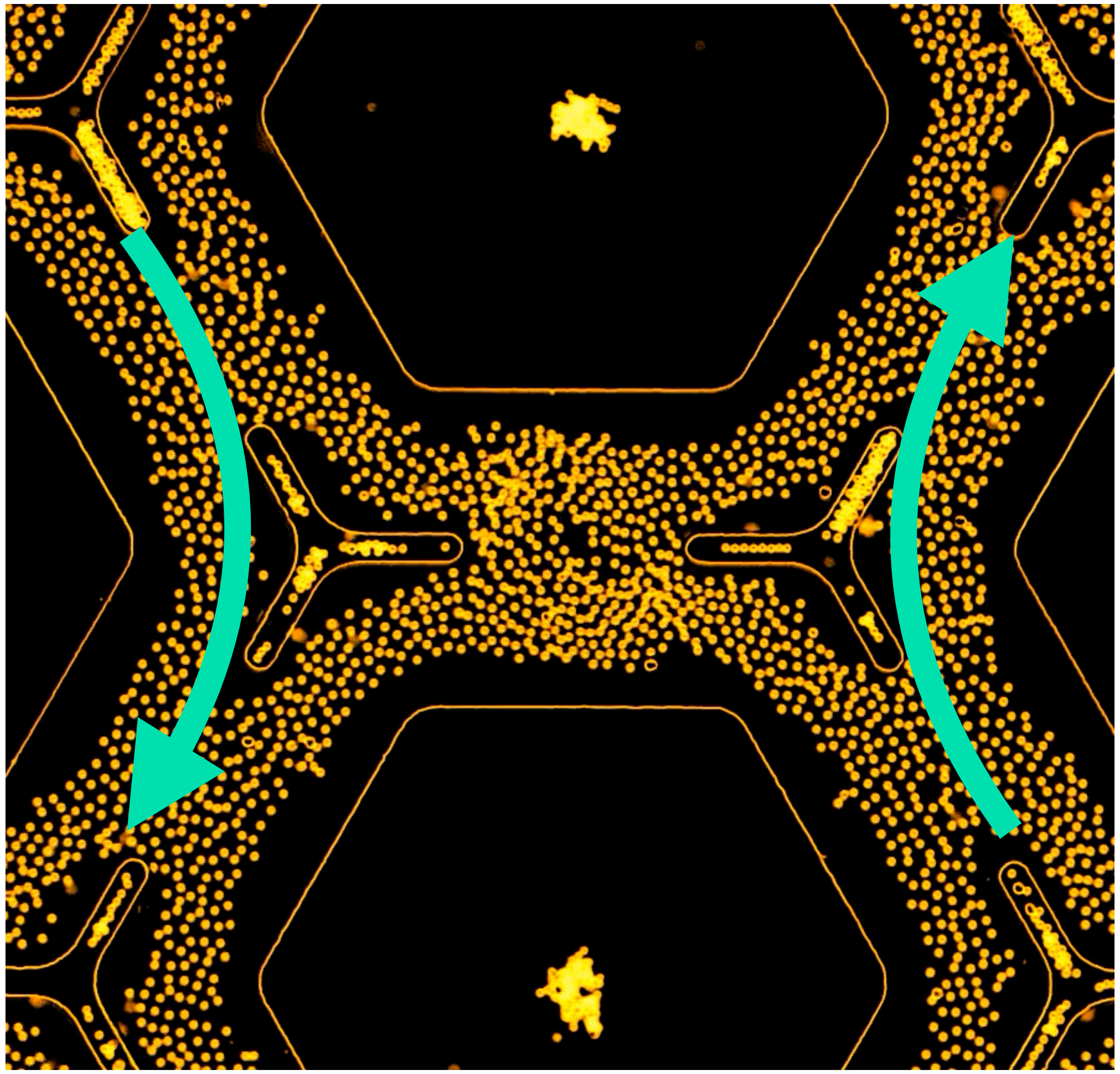
Interactions between stream lines

Structure of the zero-current channels

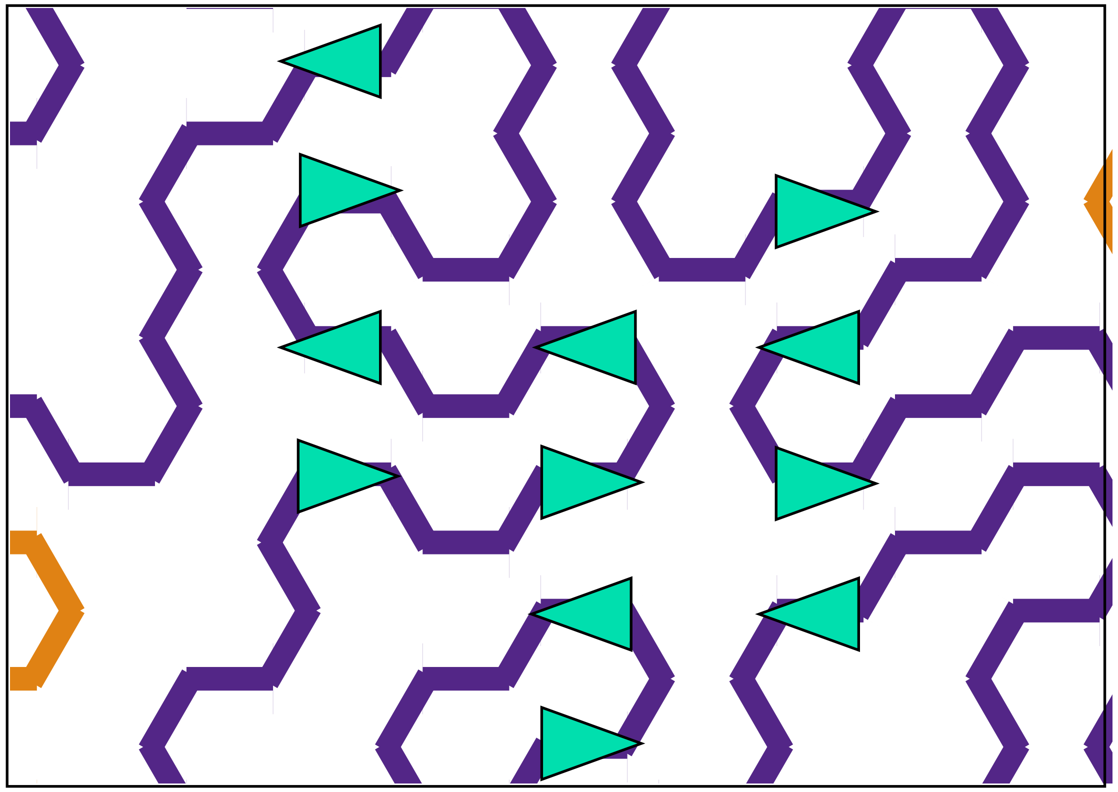


Coupling Symetries

Antiferromagnetic

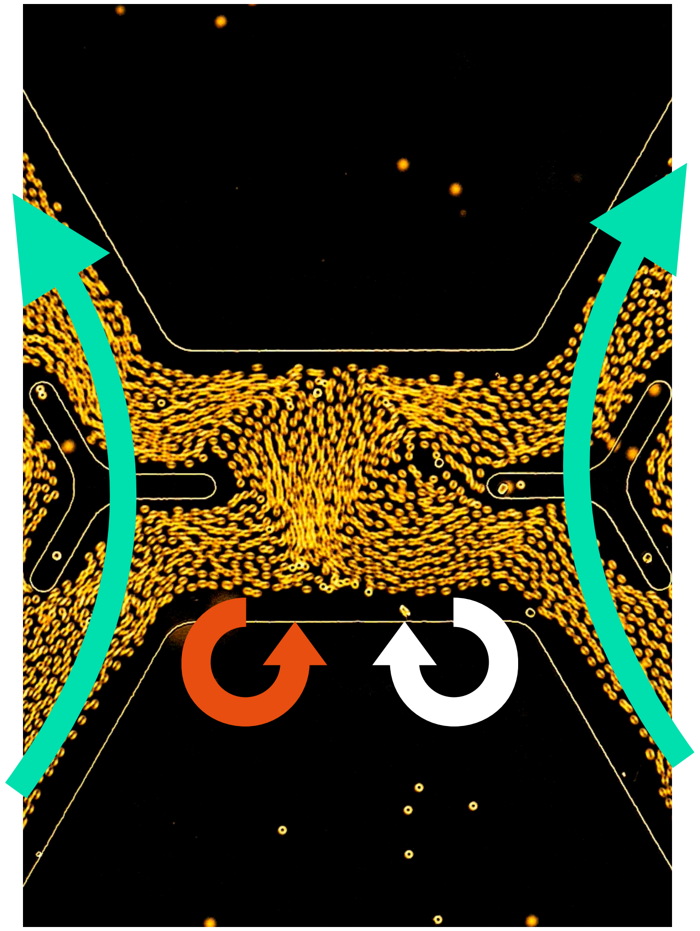


Favors
hairpins & crumples

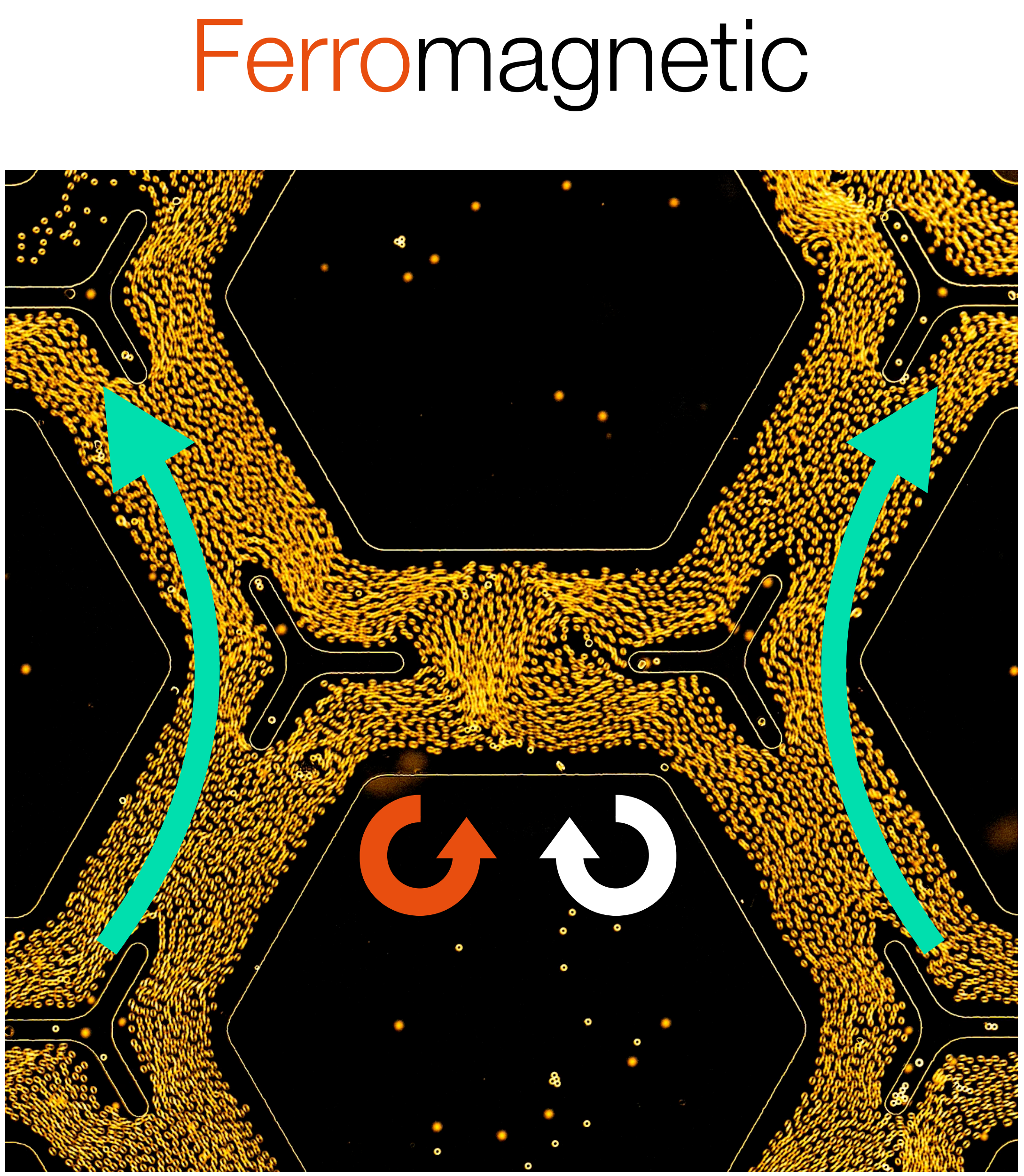


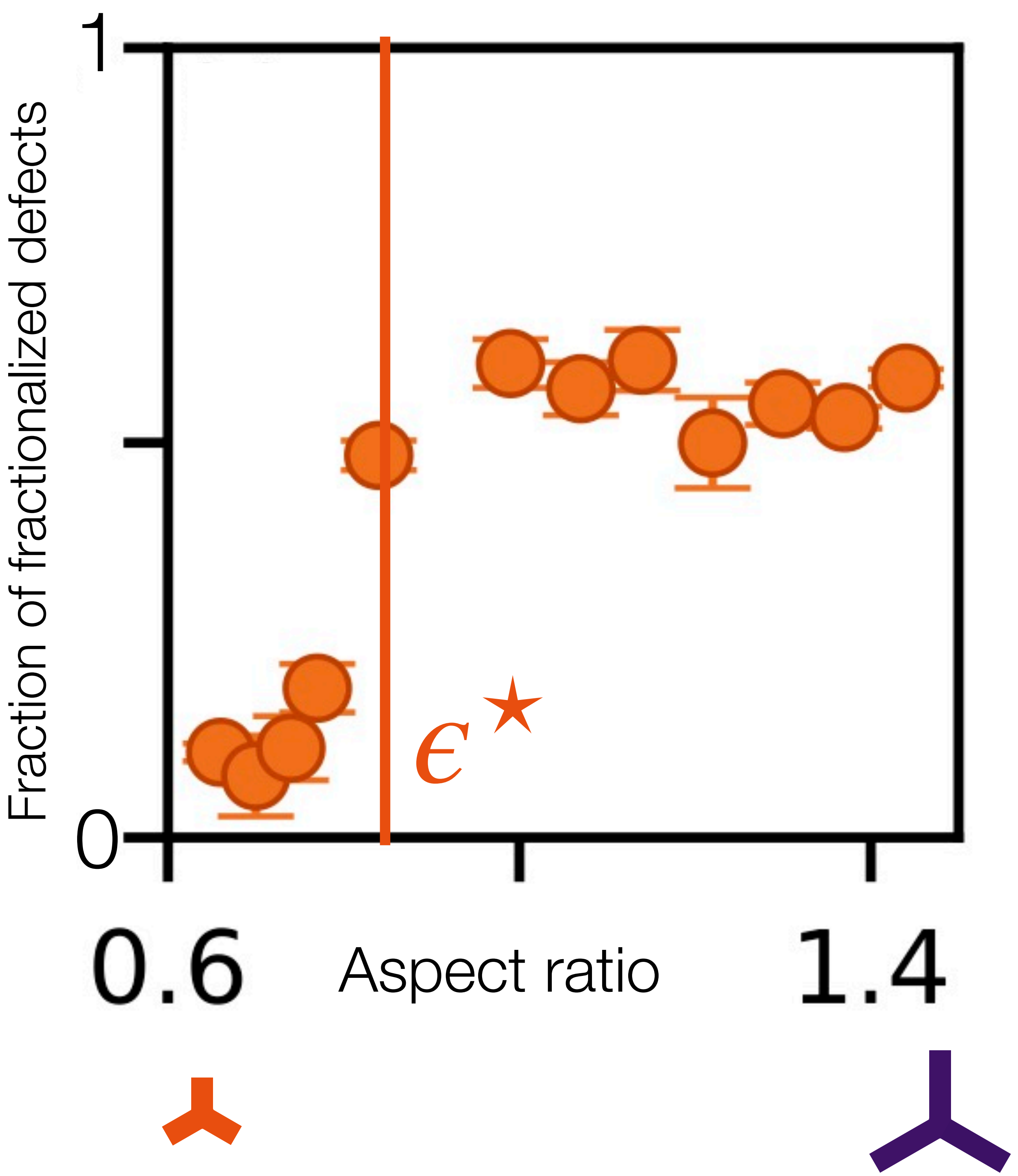
Coupling Symetries?

Ferromagnetic



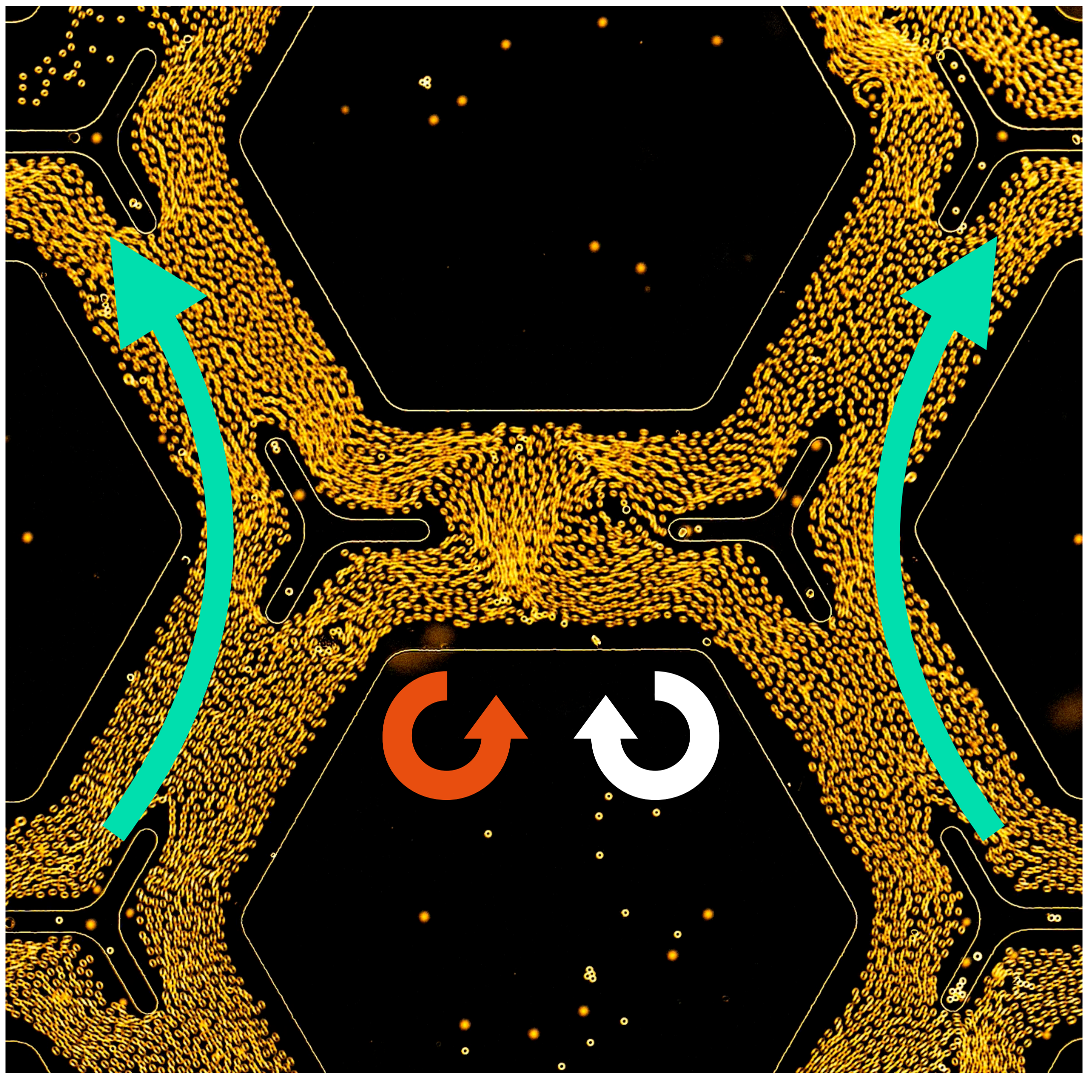
Ferromagnetic interactions prevails





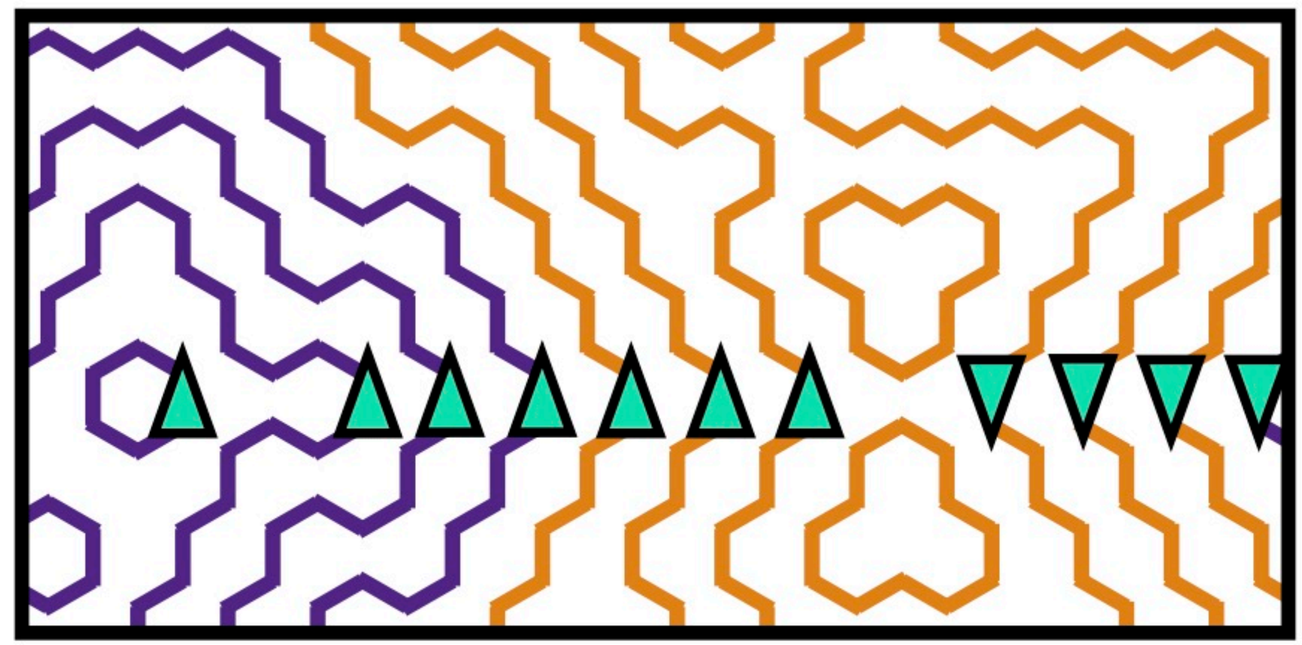
Ferromagnetic interactions prevails

Ferromagnetic



Favors

Persistent & nested loops



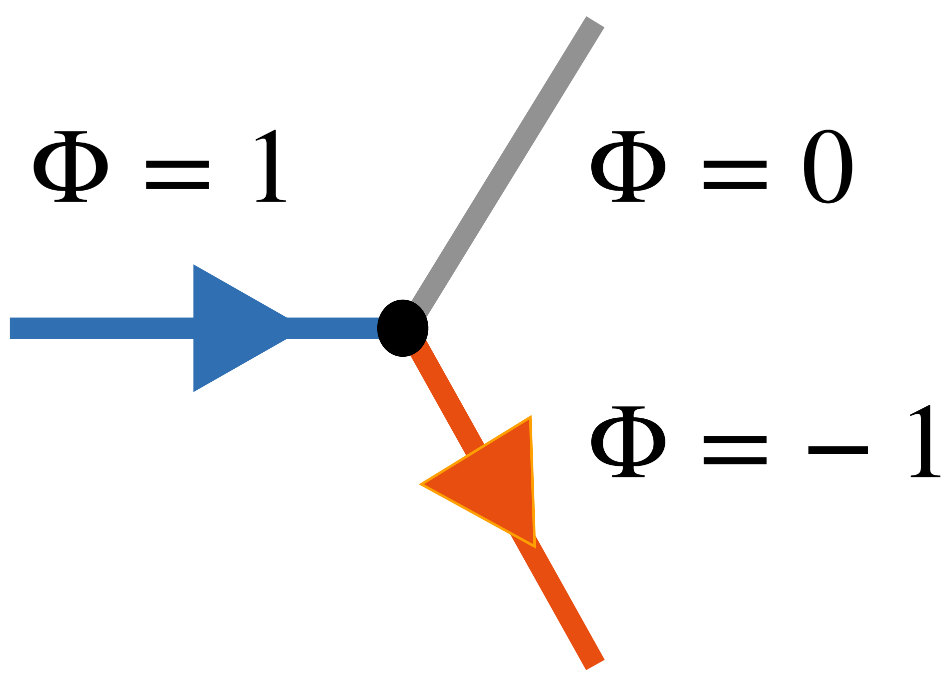
Active Hydraulics

1 — Mass conservation

$$\sum_j \Phi_{ij} = 0$$

2 — Spontaneous flows

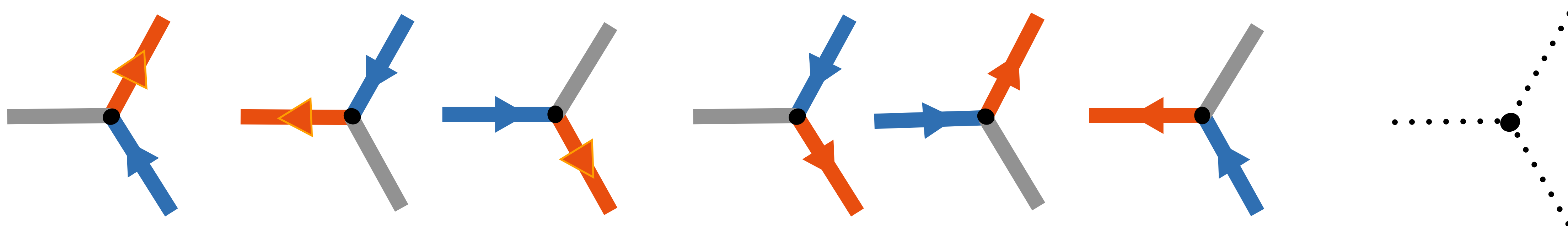
$$\Phi_{ij} = \pm \Phi_0, 0$$



Active Hydraulics

1— Mass conservation

2—Spontaneous flows

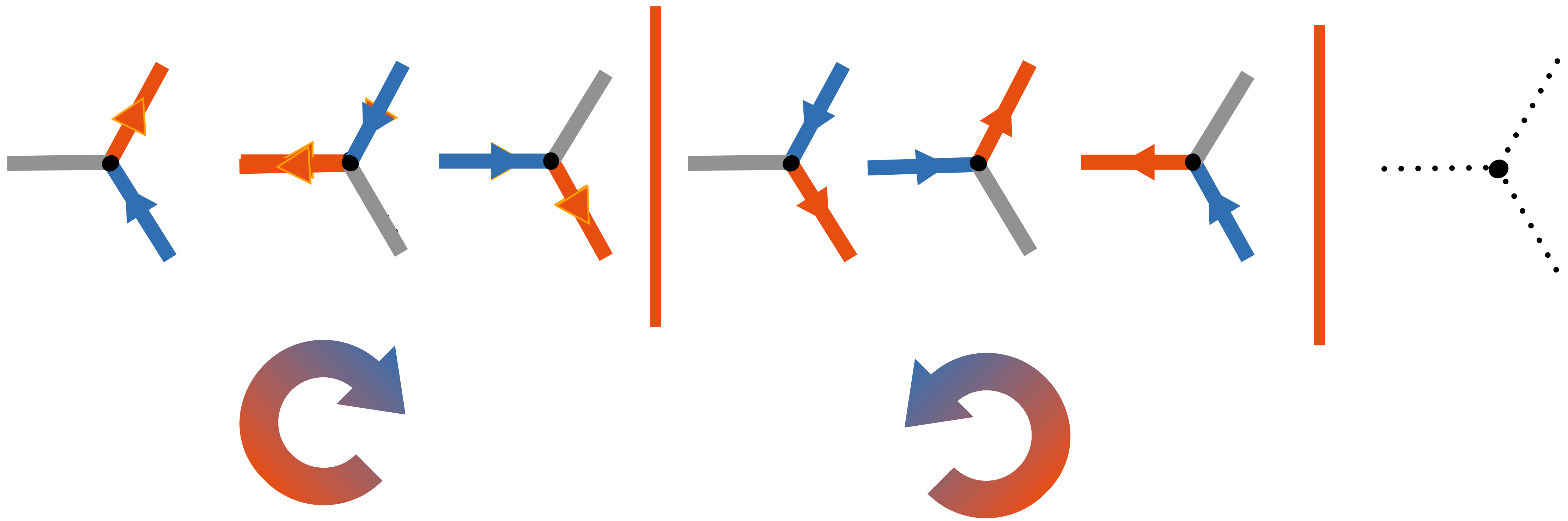


3— Topological-defect-mediated interactions

Three Coloring model

1 — Mass conservation

2 — Spontaneous flows

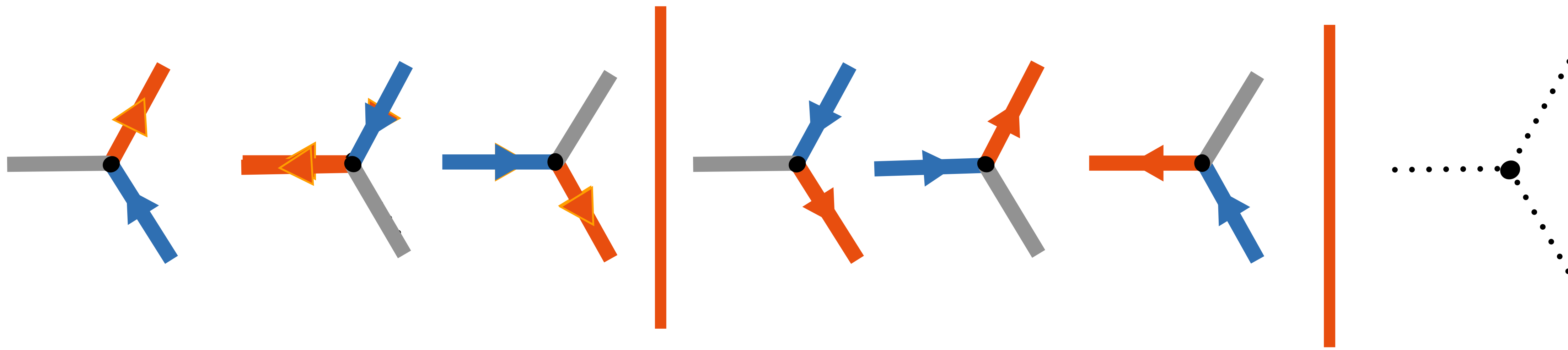


$\sigma = +1$ $\sigma = -1$ $\sigma = 0$

Active Hydraulics

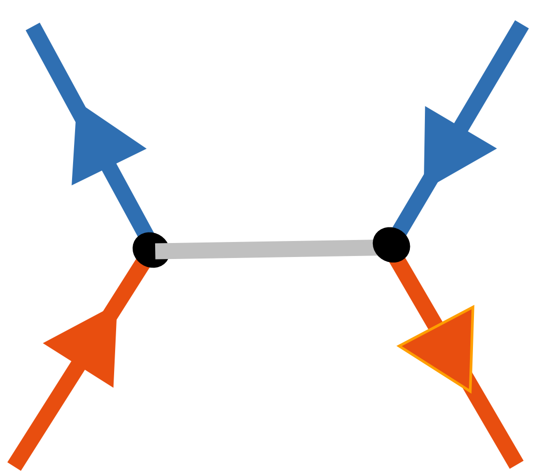
1— Mass conservation

2—Spontaneous flows

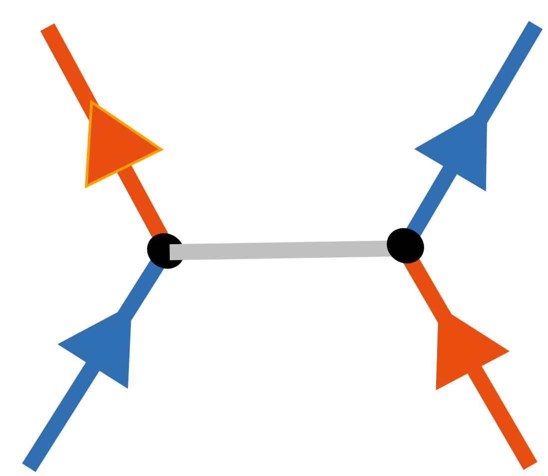


3— Topological-defect-mediated interactions

$\sigma_1\sigma_2 = -1$



$\sigma_1\sigma_2 = +1$



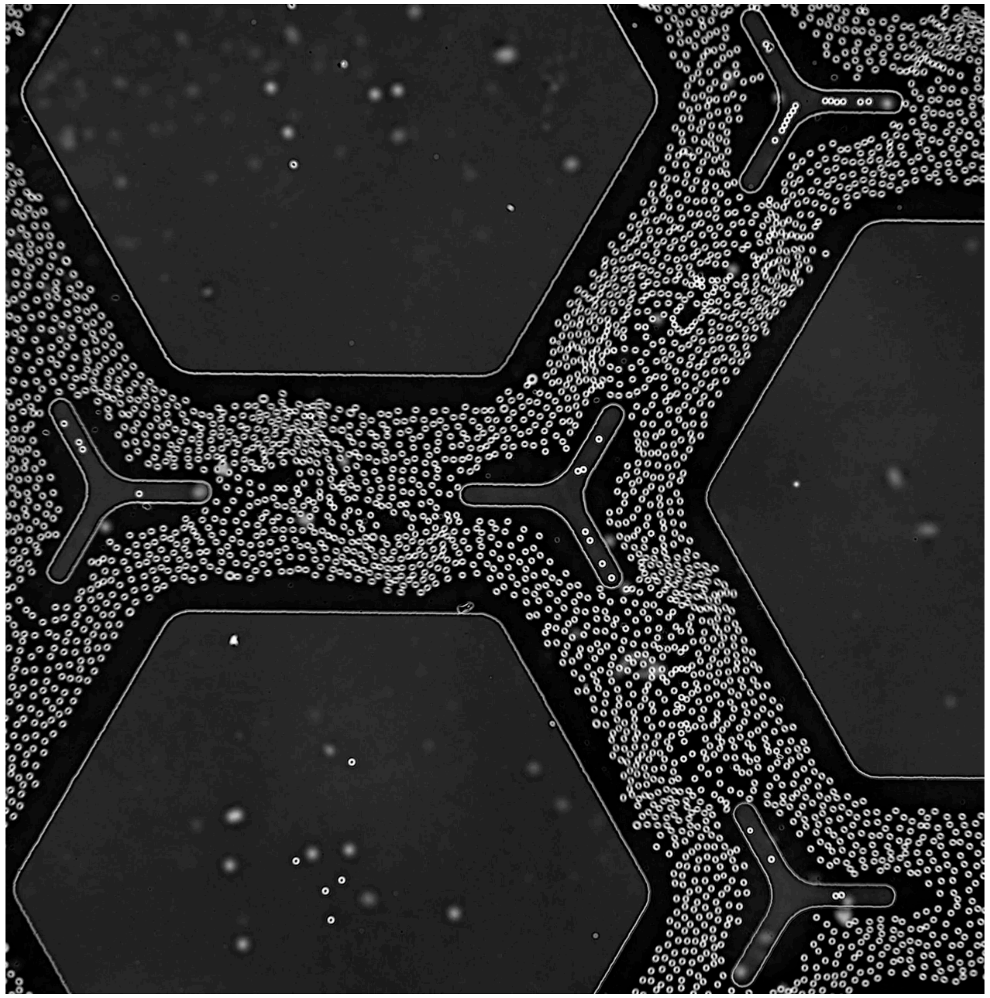
Predicting flow patterns

Edge current: $\Phi_{ij} = \pm 1{,}0$

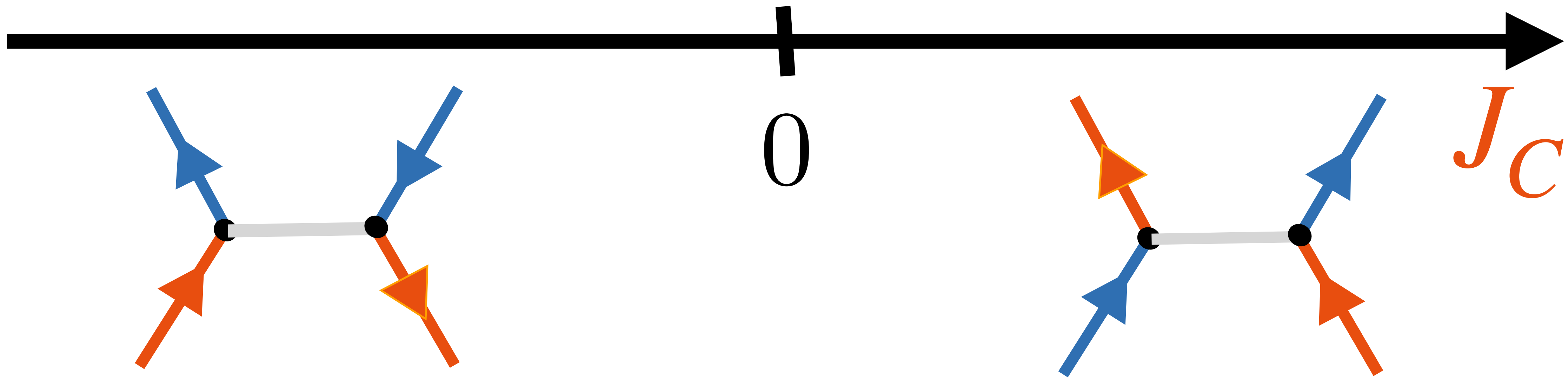
Node handedness $\sigma_i = \pm 1{,}0$

Promote Spontaneous flows

$$\mathcal{H} = -J_{\mathrm{A}} \sum_{\langle i,j \rangle} \Phi_{ij}^2$$



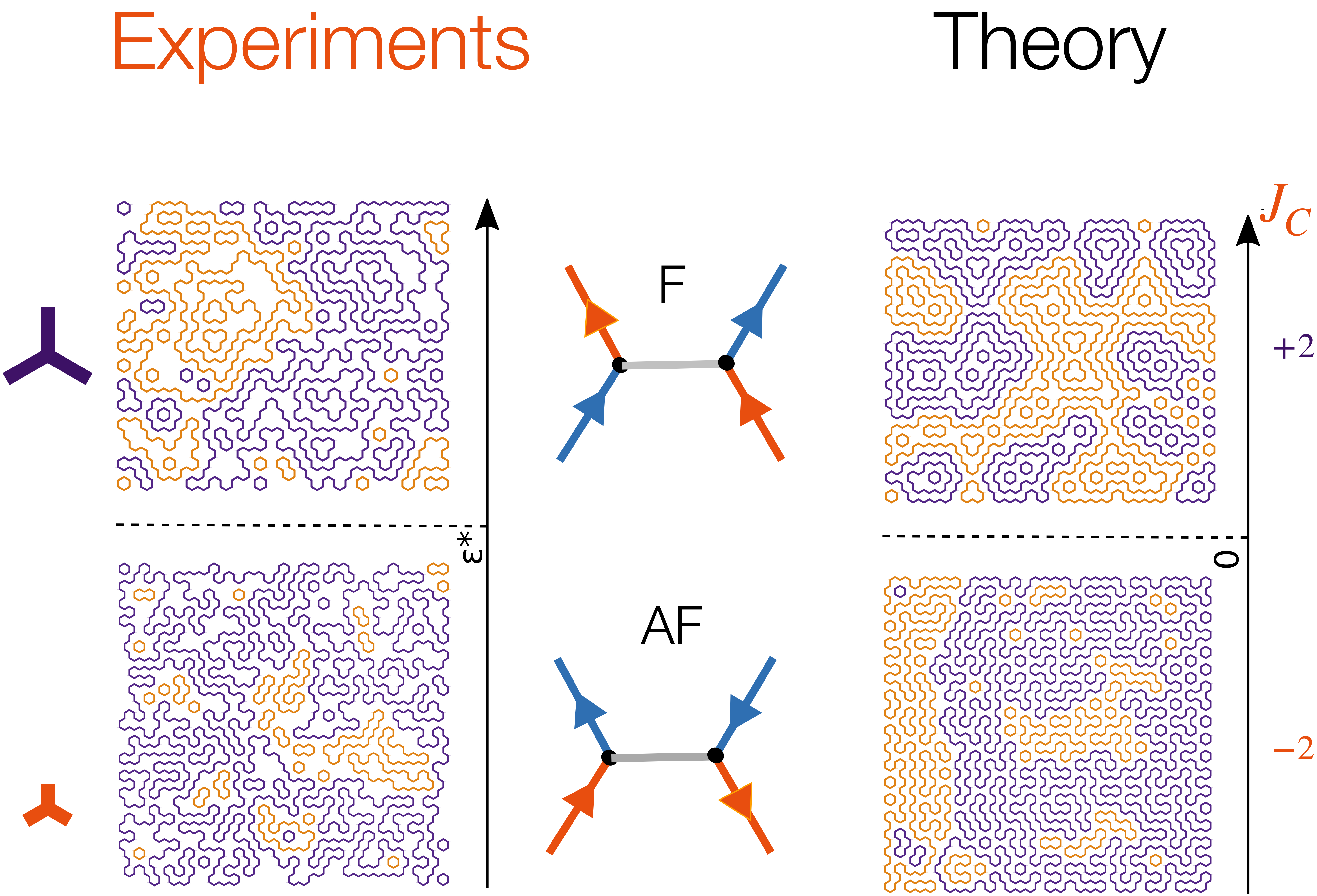
Stramline Interactions



$$\mathcal{H} = -J_{\mathrm{A}} \sum_{\langle i,j \rangle} \Phi_{ij}^2 - J_C \sum_{\langle i,j \rangle} \delta_{\Phi_{ij},0} \sigma_i \sigma_j .$$

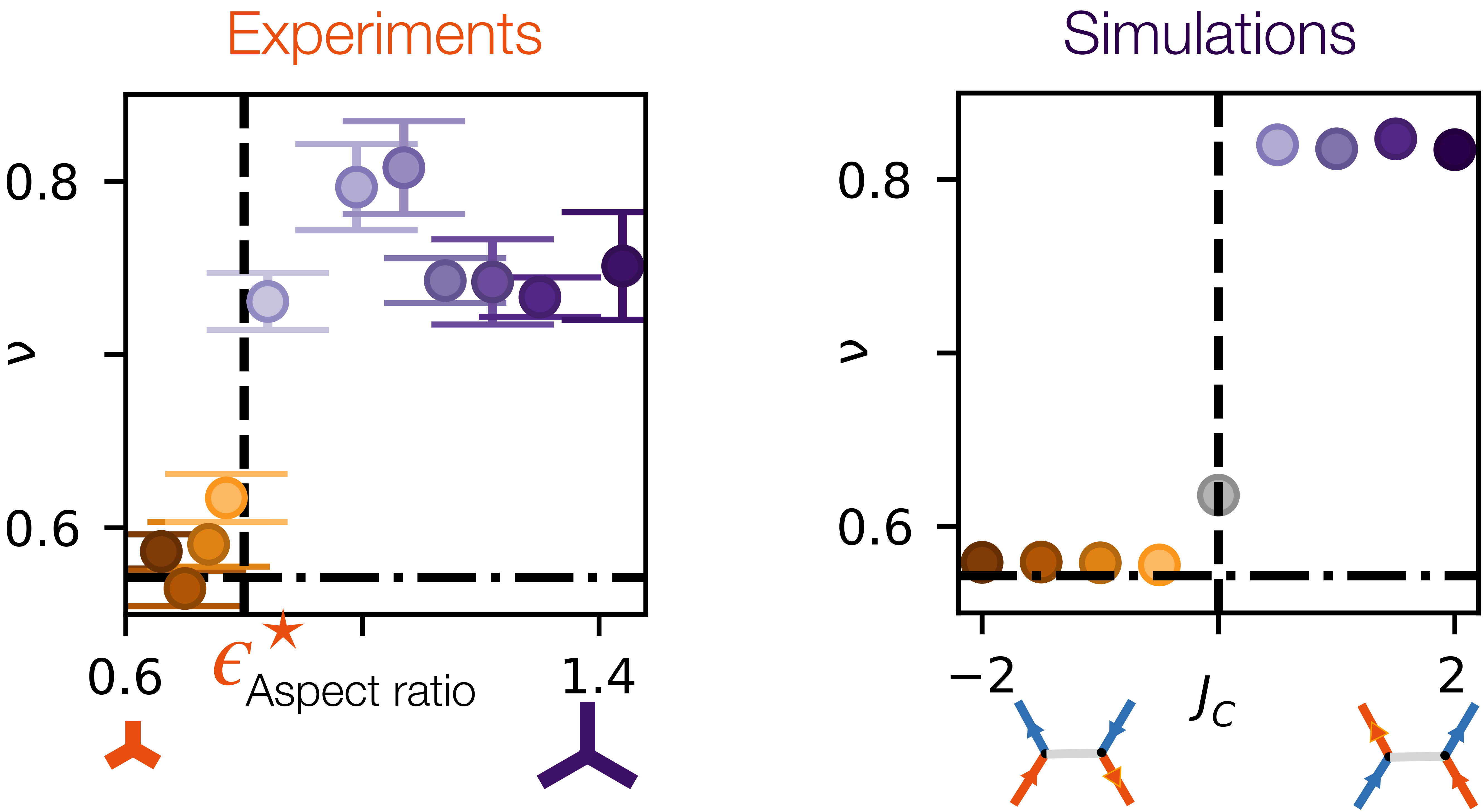
Minimize given the mass-conservation constraint

$$\sum_j \Phi_{ij} = 0$$



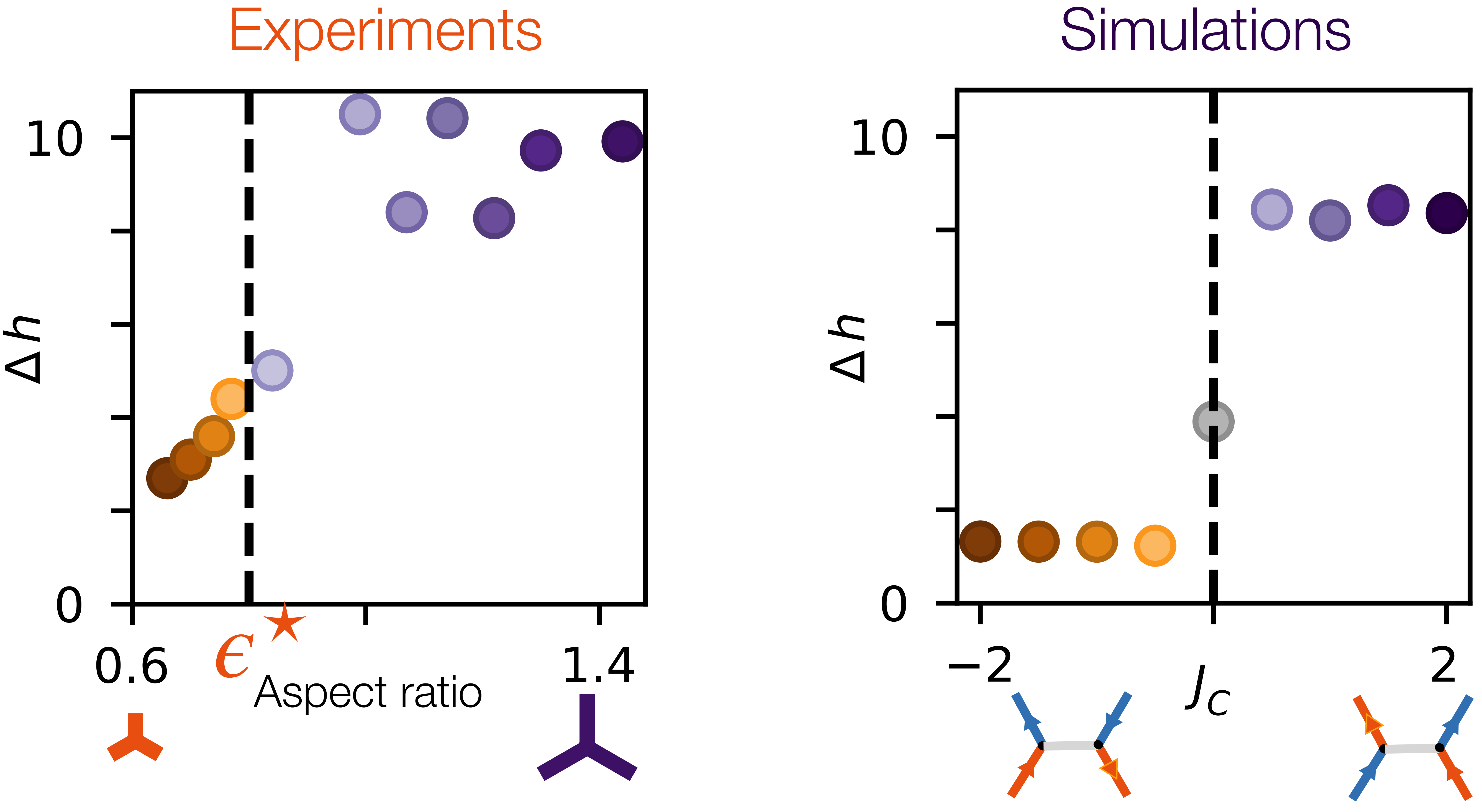
Experiments
Theory
F
AF
ε^*
J_C
+2
0
−2

Crumpling of the stream lines



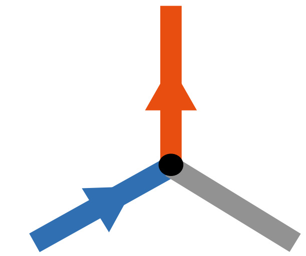
$$R_g \sim L^\nu$$

Nesting of the stream lines



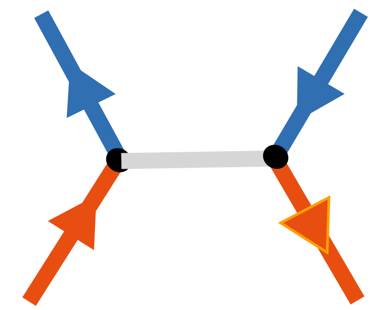
Active Hydraulics

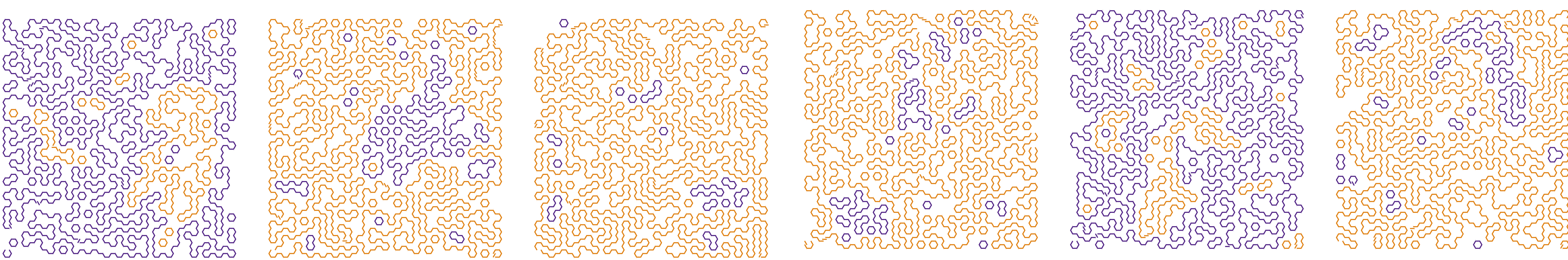
1 — Mass conservation $\sum_{\text{node } i} \mathbf{J}_i = 0$



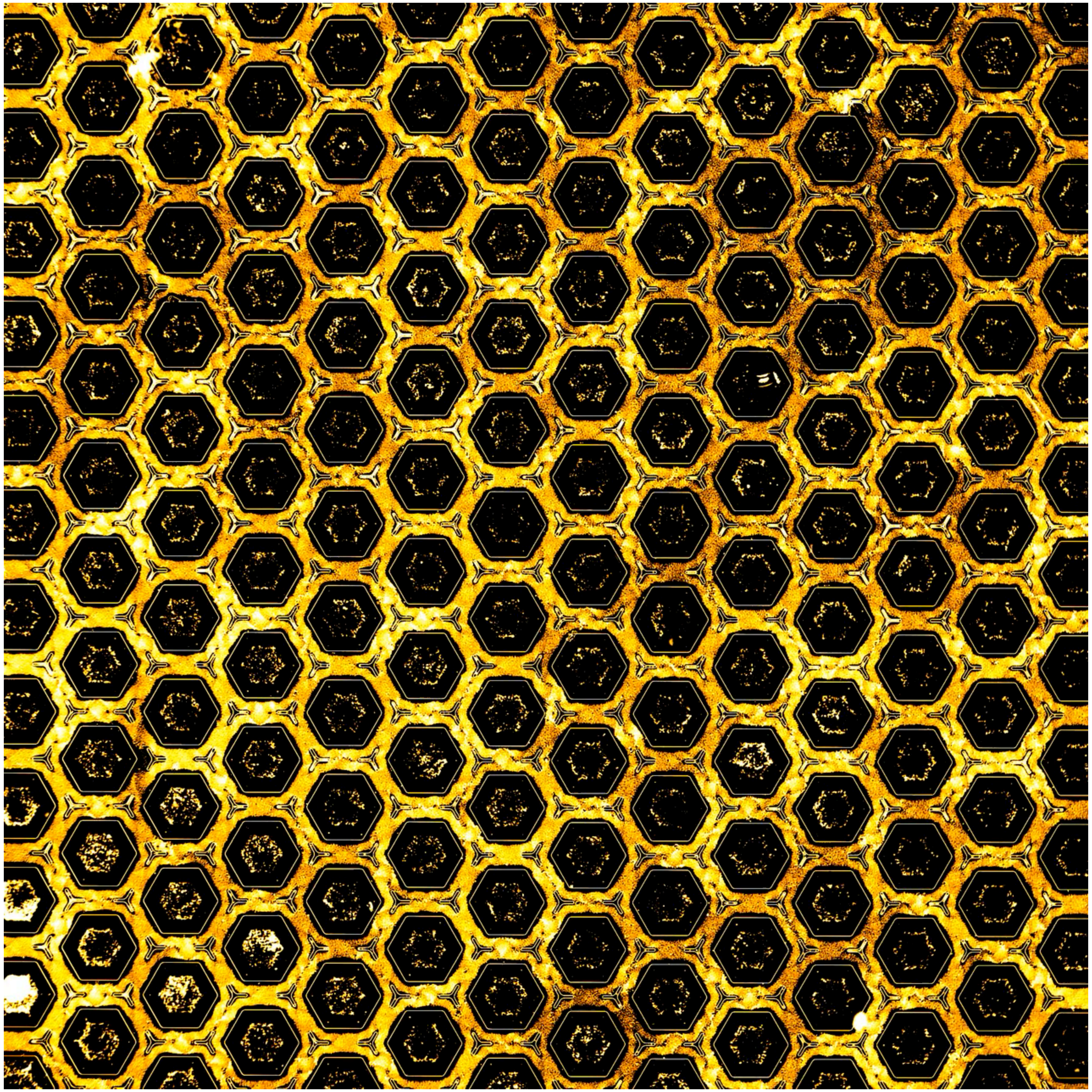
2 — Spontaneous flows $J_i = \pm J_0, 0$

3 — Defect-mediated interactions





Active Hydraulics



Crowd Hydrodynamics

Without any assumption
about pedestrian behavior

Crowds as continua

Conservation laws

&

Constitutive relations

Experimental measurements

Controled perturbations

2,000 runners

Response to a boundary perturbation

↓

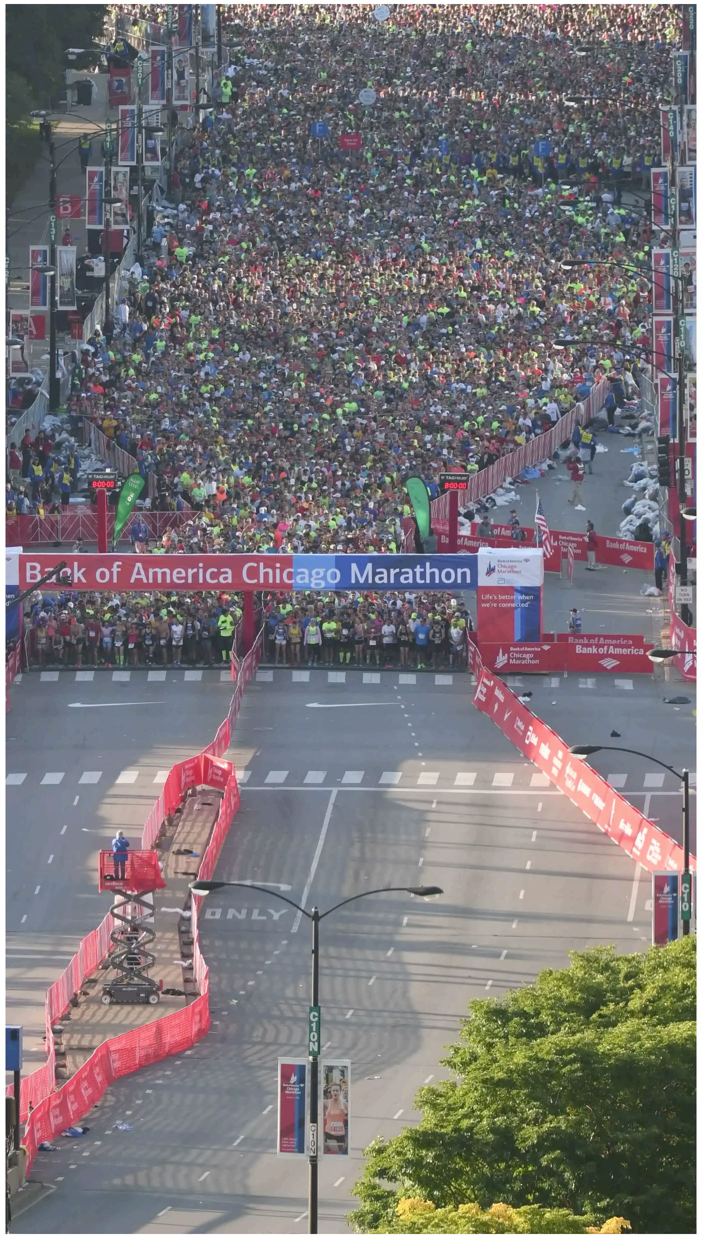
Hydrodynamic model

Chicago marathon

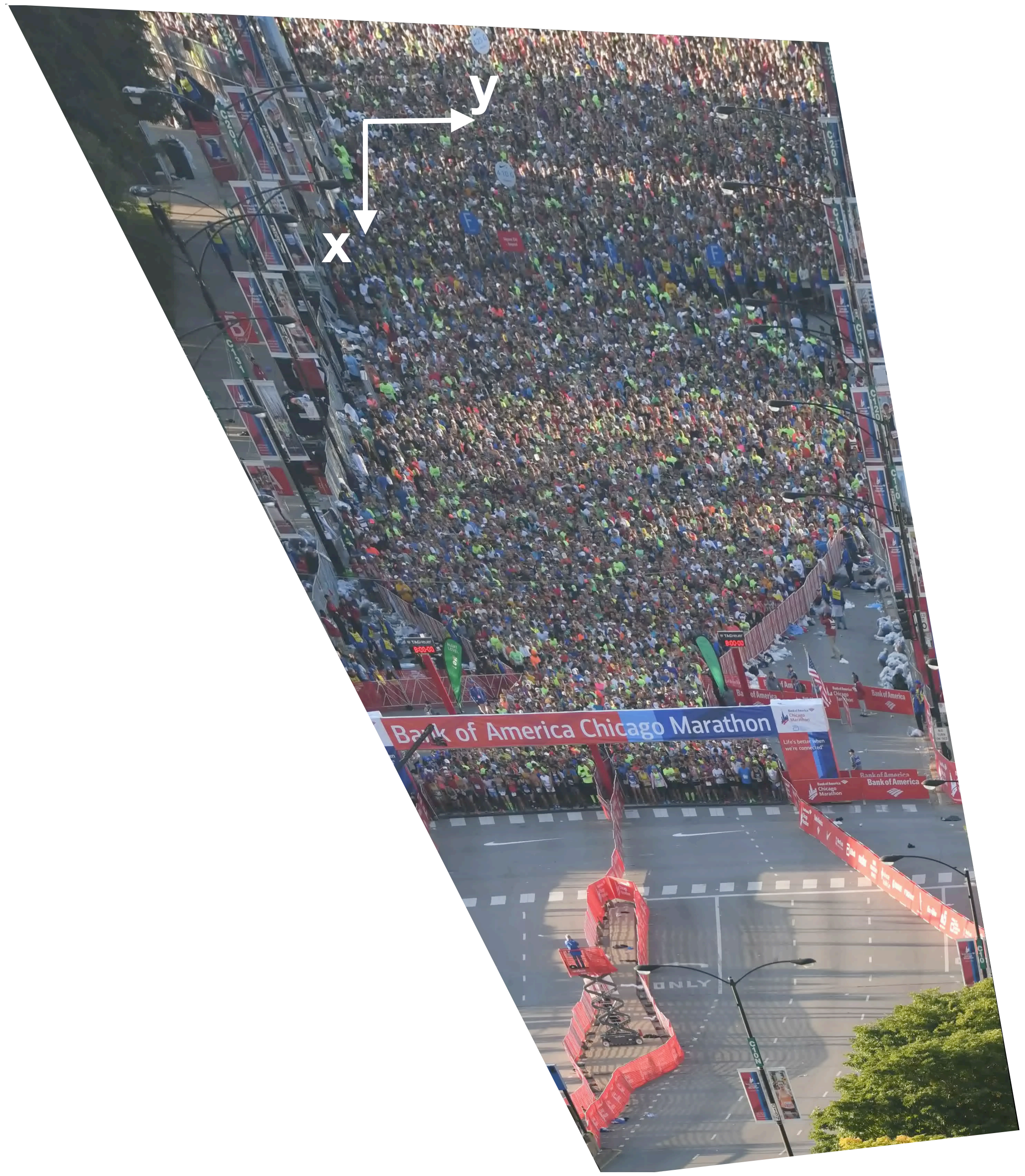
Chicago marathon

Image correction

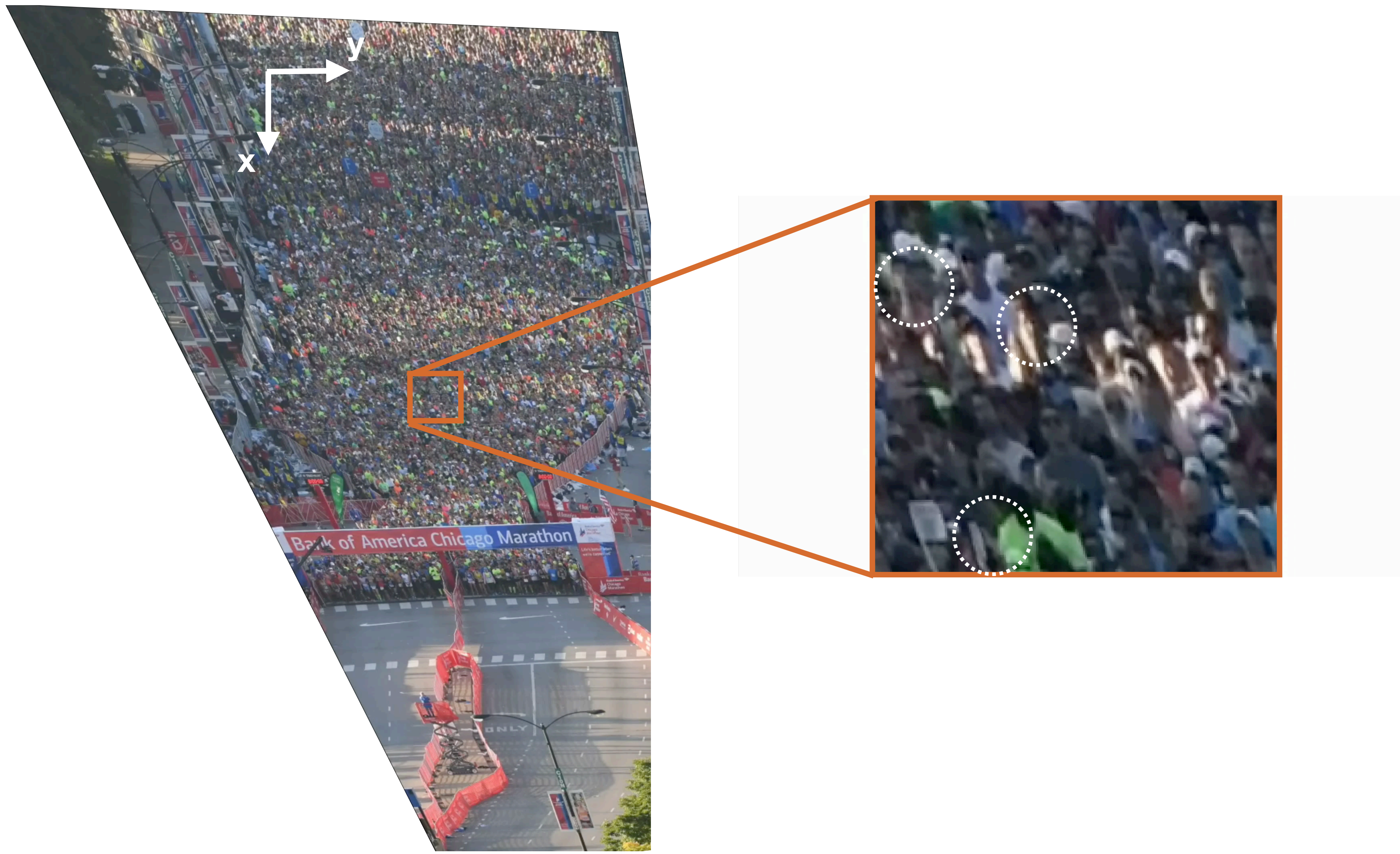
Raw image



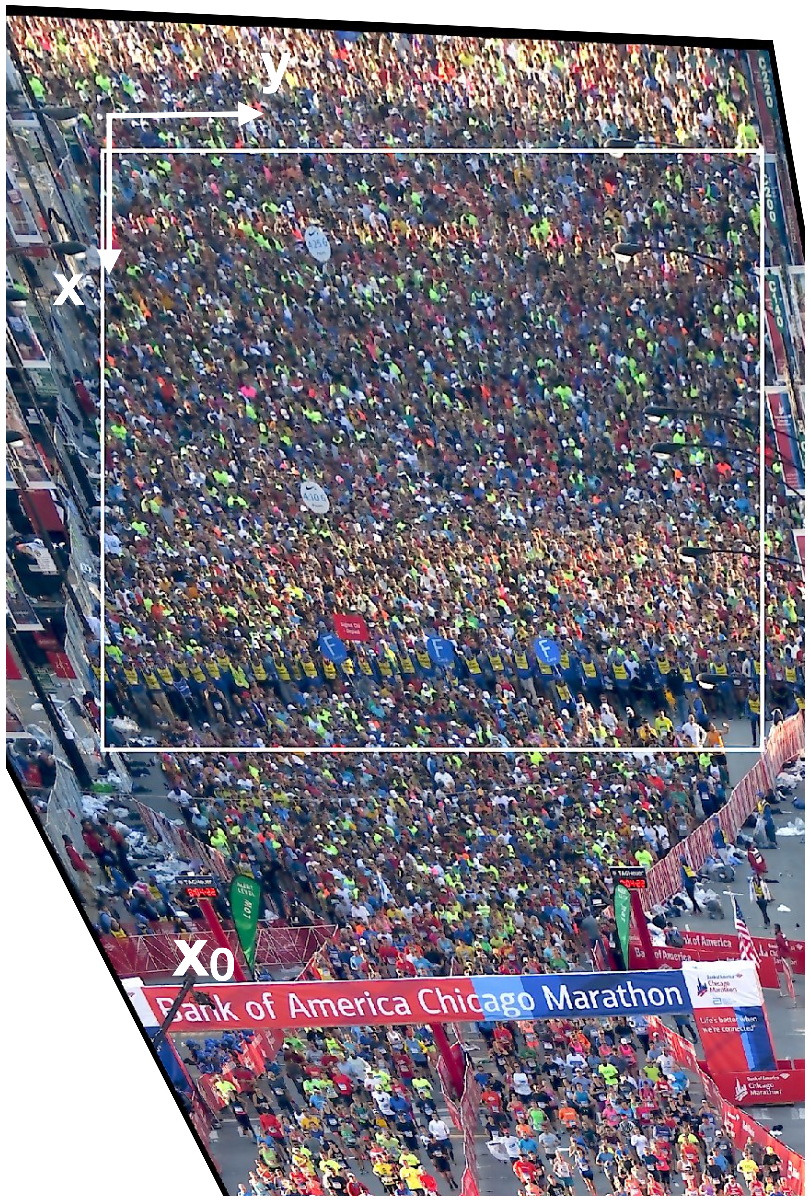
Corrected image

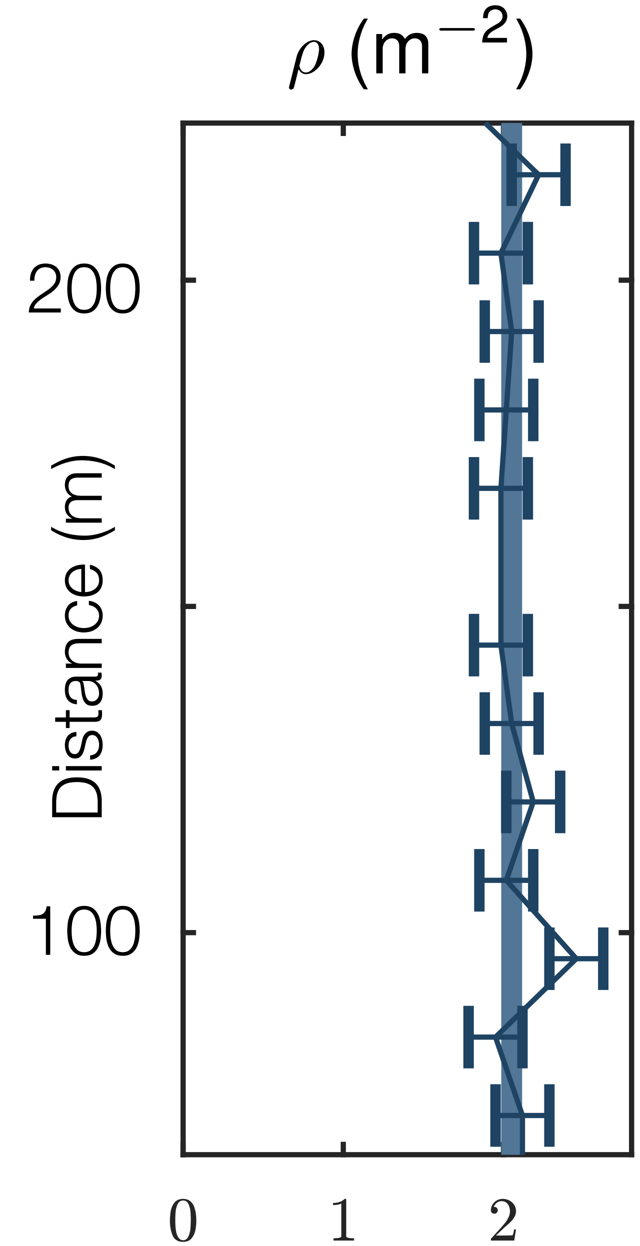


Density field



Crowd hydrostatics





Constant uniform density

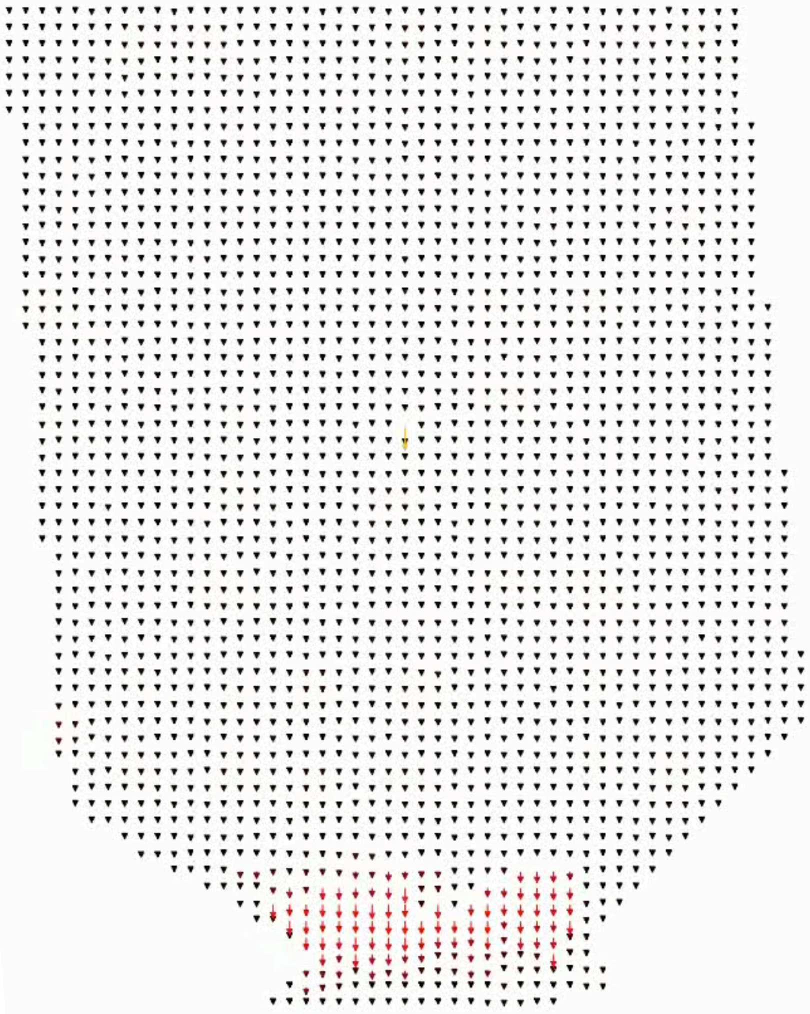
(although unbounded)

$\rho_0 = 2.2 \pm .05\,\mathrm{m}^{-2}$

Crowd dynamics

$10\,\mathrm{m} \times 1\,\mathrm{m}$

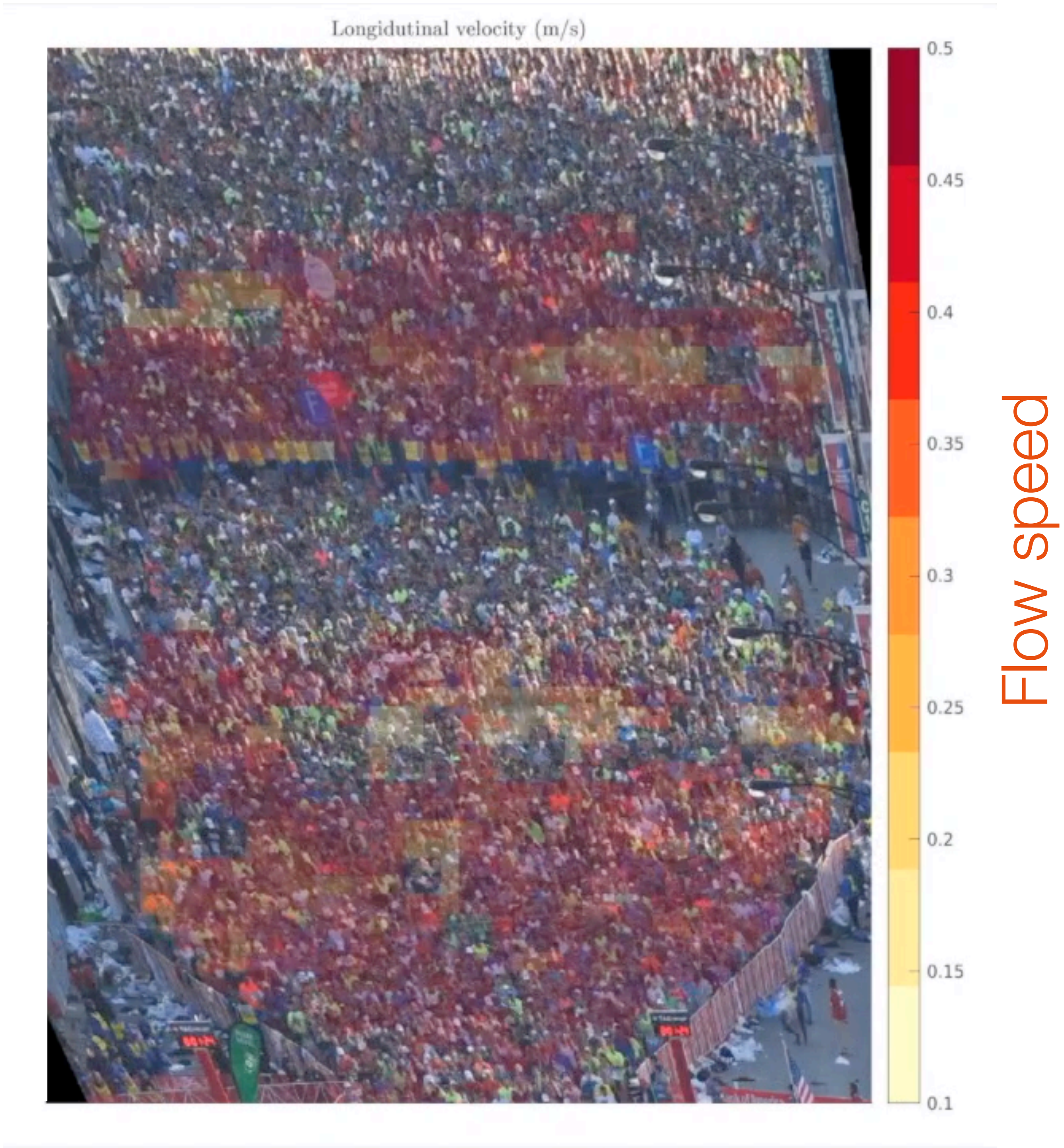
$\delta v \sim 10\,\mathrm{cm/s}$



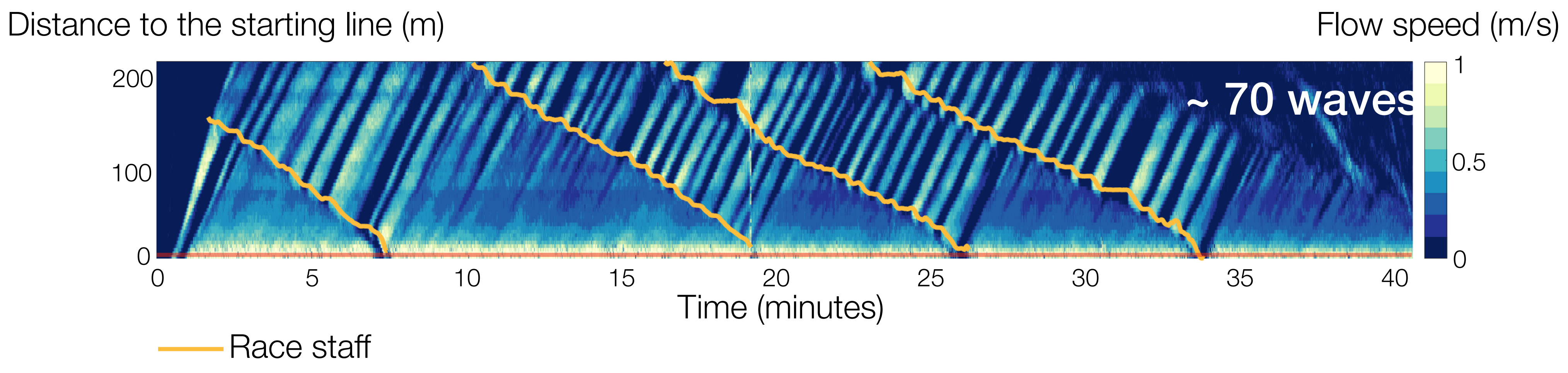
PIV

$\mathbf{v}(\mathbf{x}, t)$

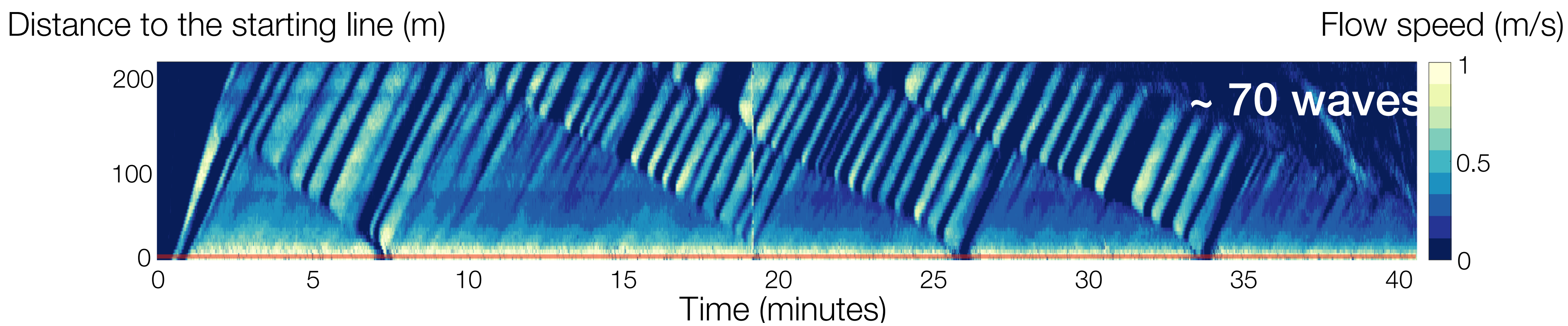
Density-speed waves

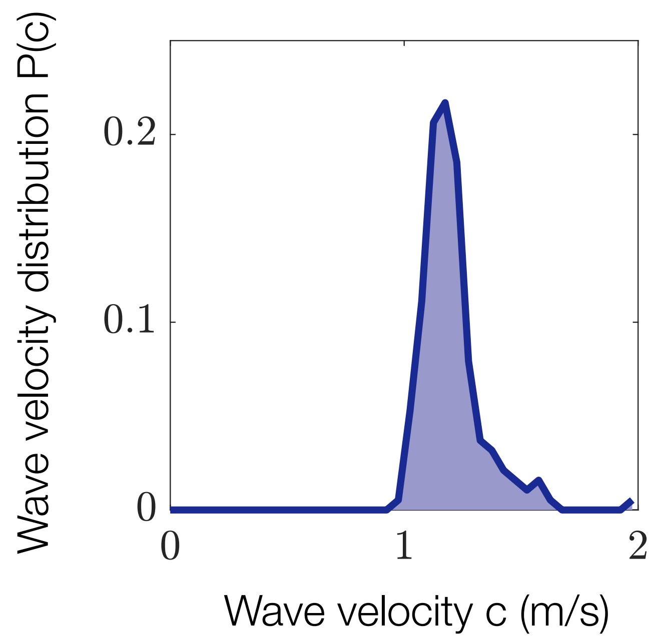


Dynamic response to boundary perturbations



Constant wave speed

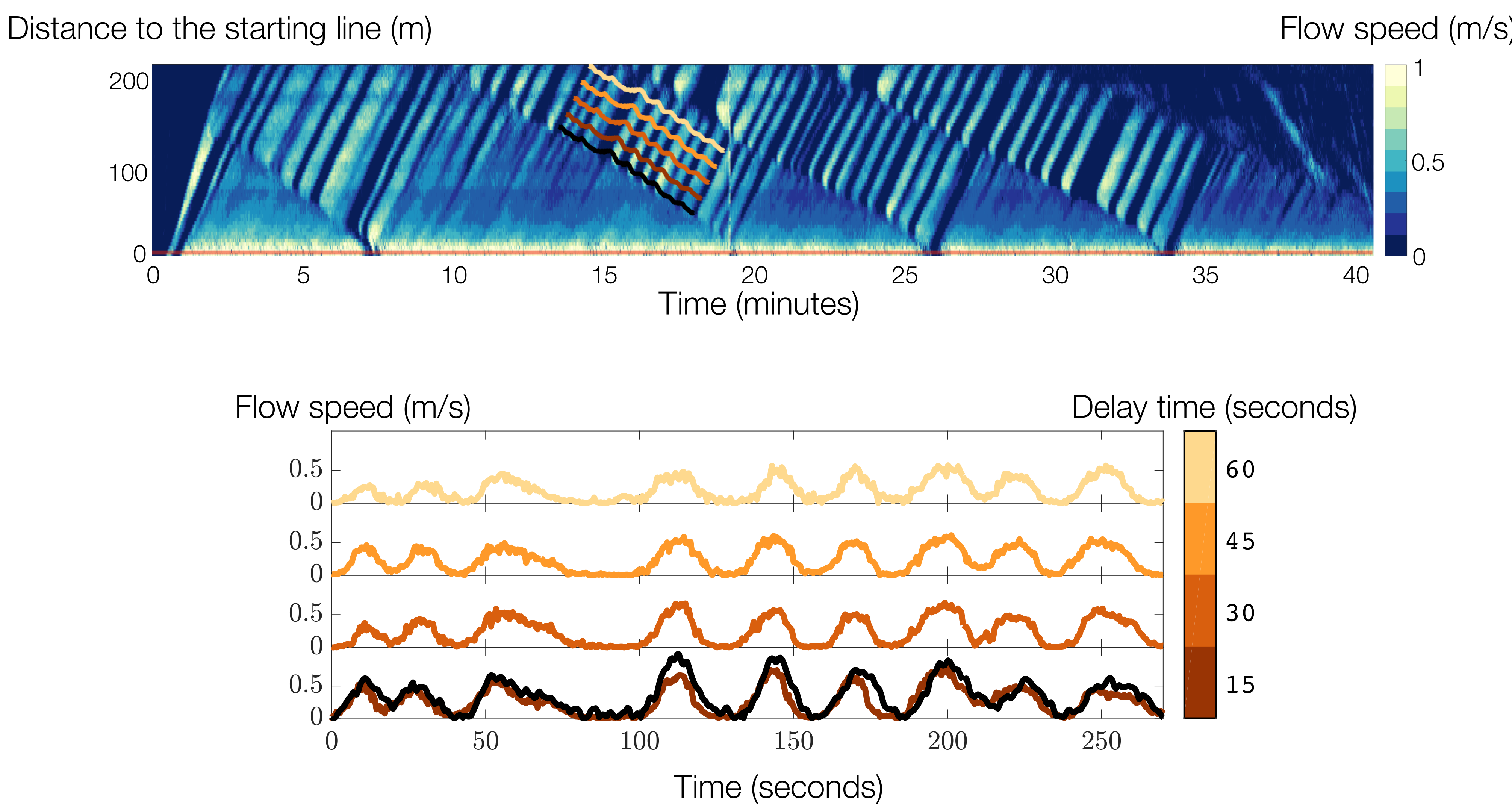




Wave velocity

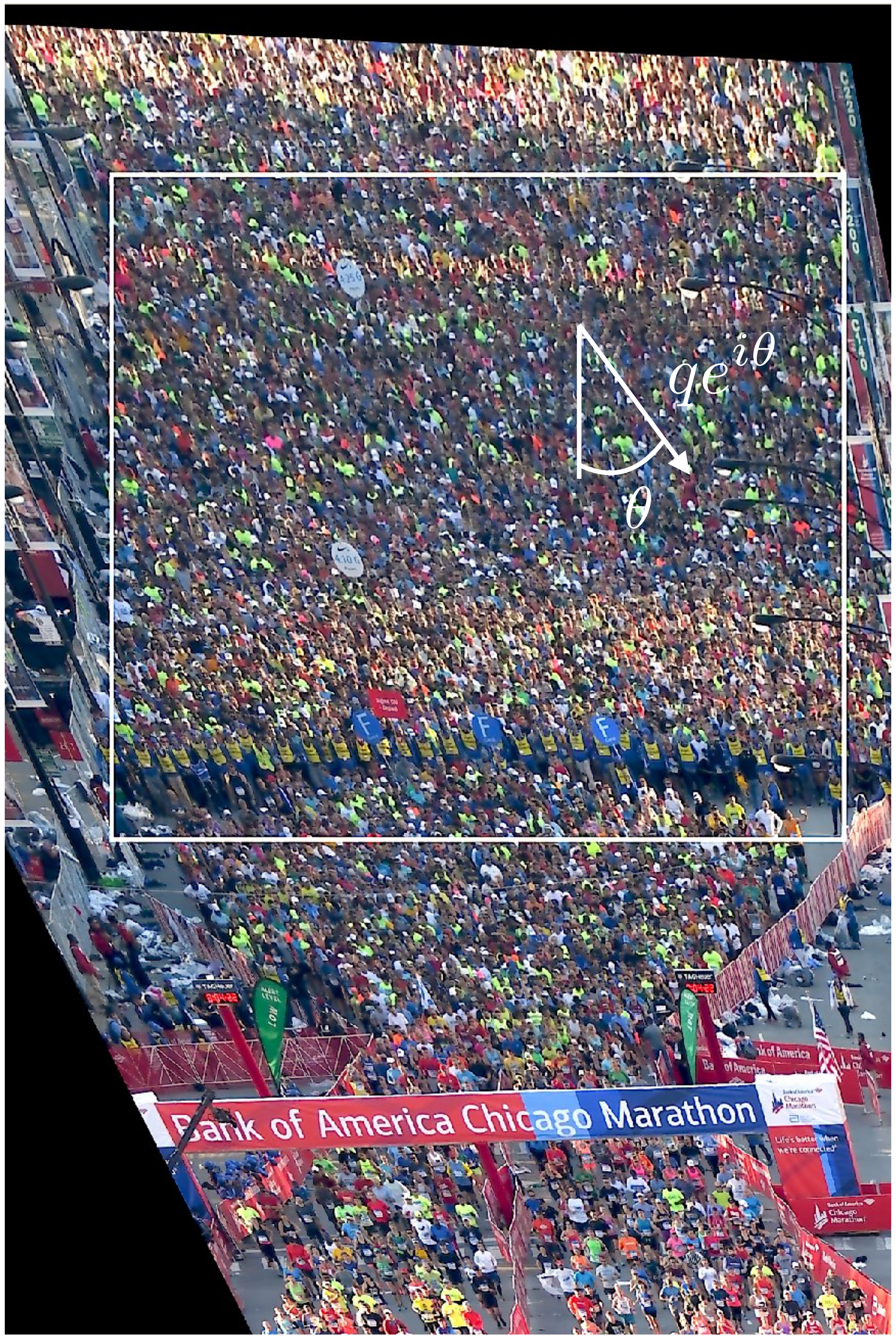
$\langle c \rangle = 1.2 \pm 0.3$ m.s^{-1}

Linear response



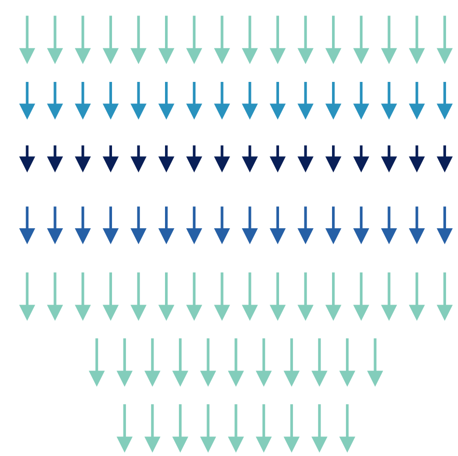
Linear, non-dispersive waves

Spectral analysis



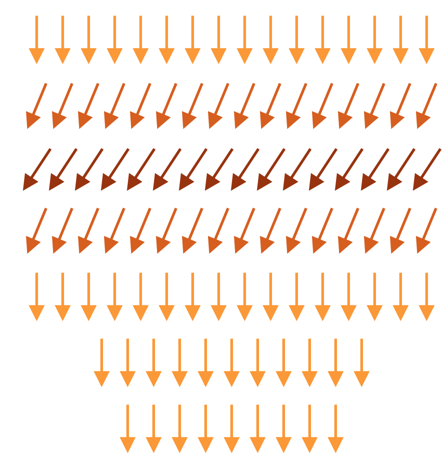
Flow speed

$|\mathbf{v}|$

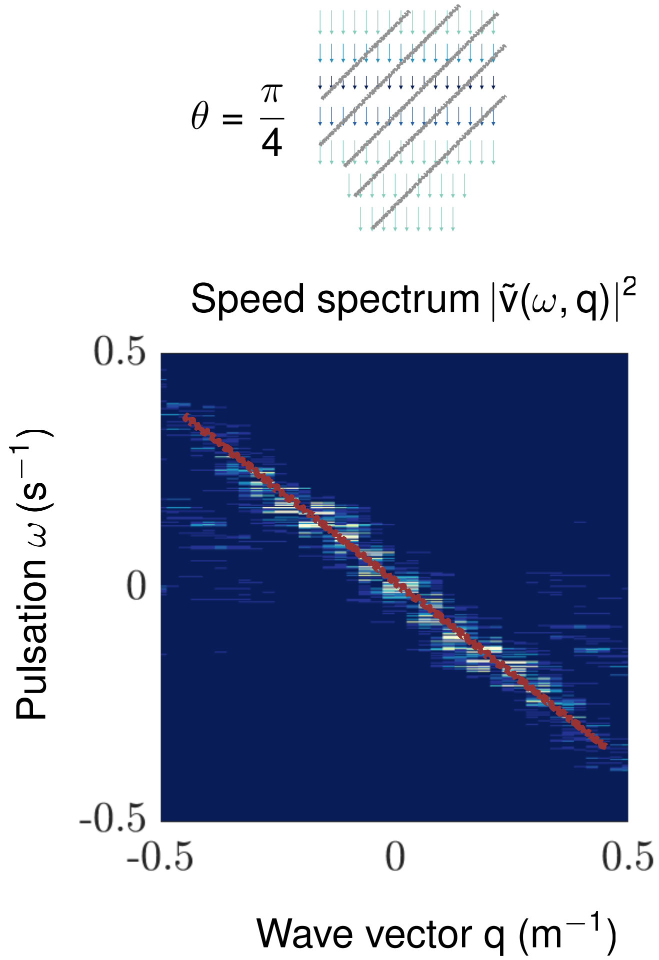


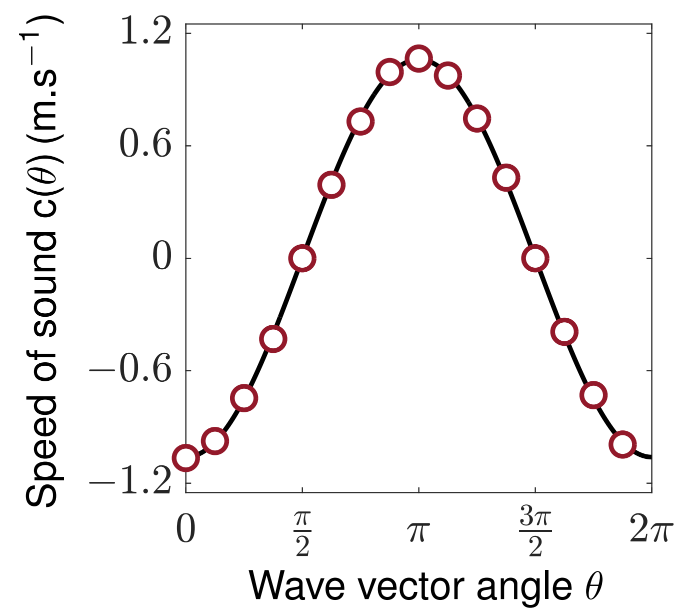
Flow orientation

$\varphi = \arg(\mathbf{v})$



Speed waves





Dispersion relation

$\omega = c(\theta)q$

Angular variations

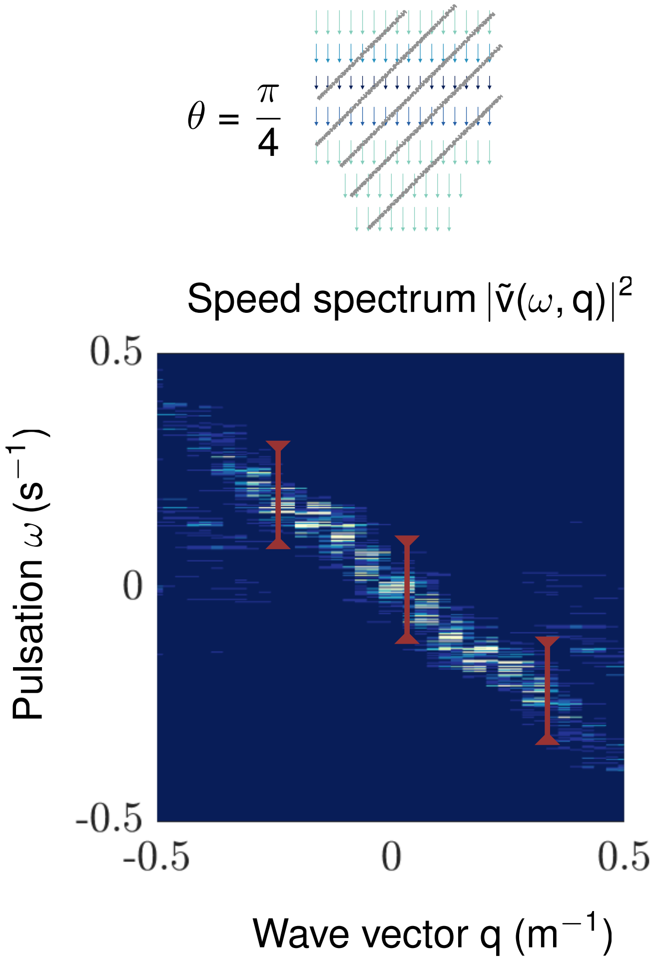
$c(\theta) = -c_0 \cos\theta$

Upstream transport only

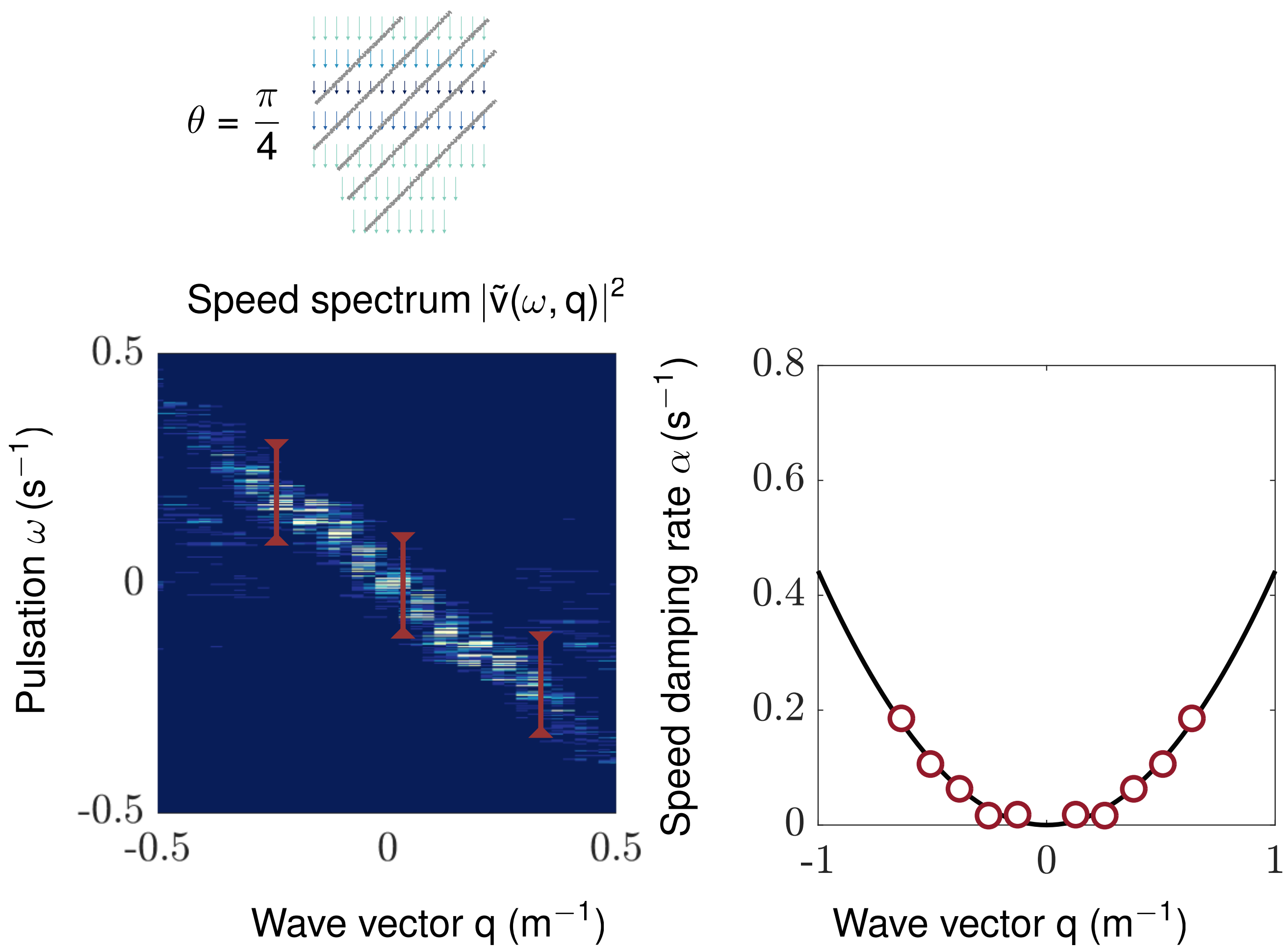
$\omega = -c_0 q_x$

$c_0 = 1.2\,m.s^{-1}$

Flow-speed damping



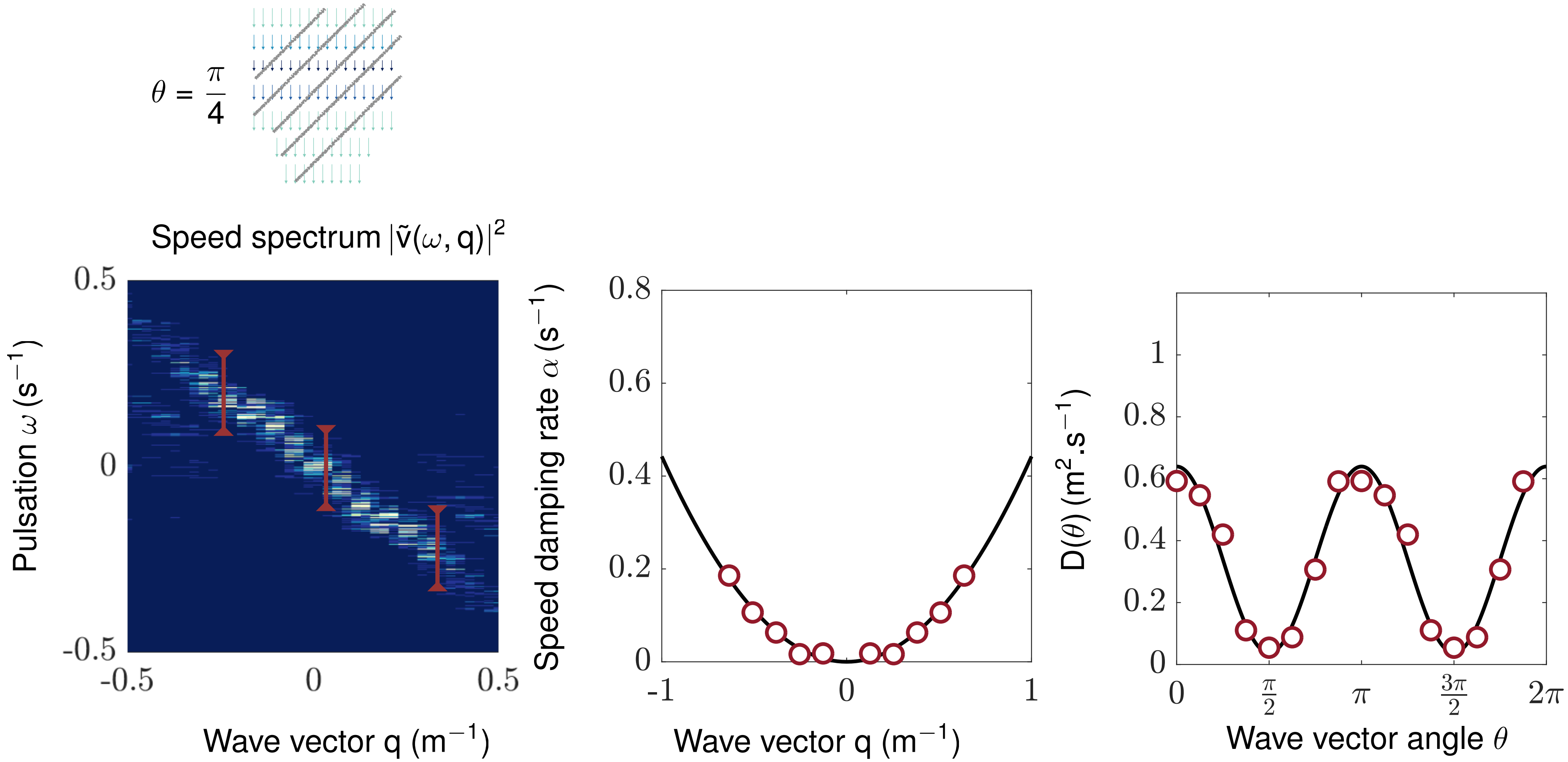
Flow-speed damping



Diffusive damping

$\alpha = D(\theta)q^2$

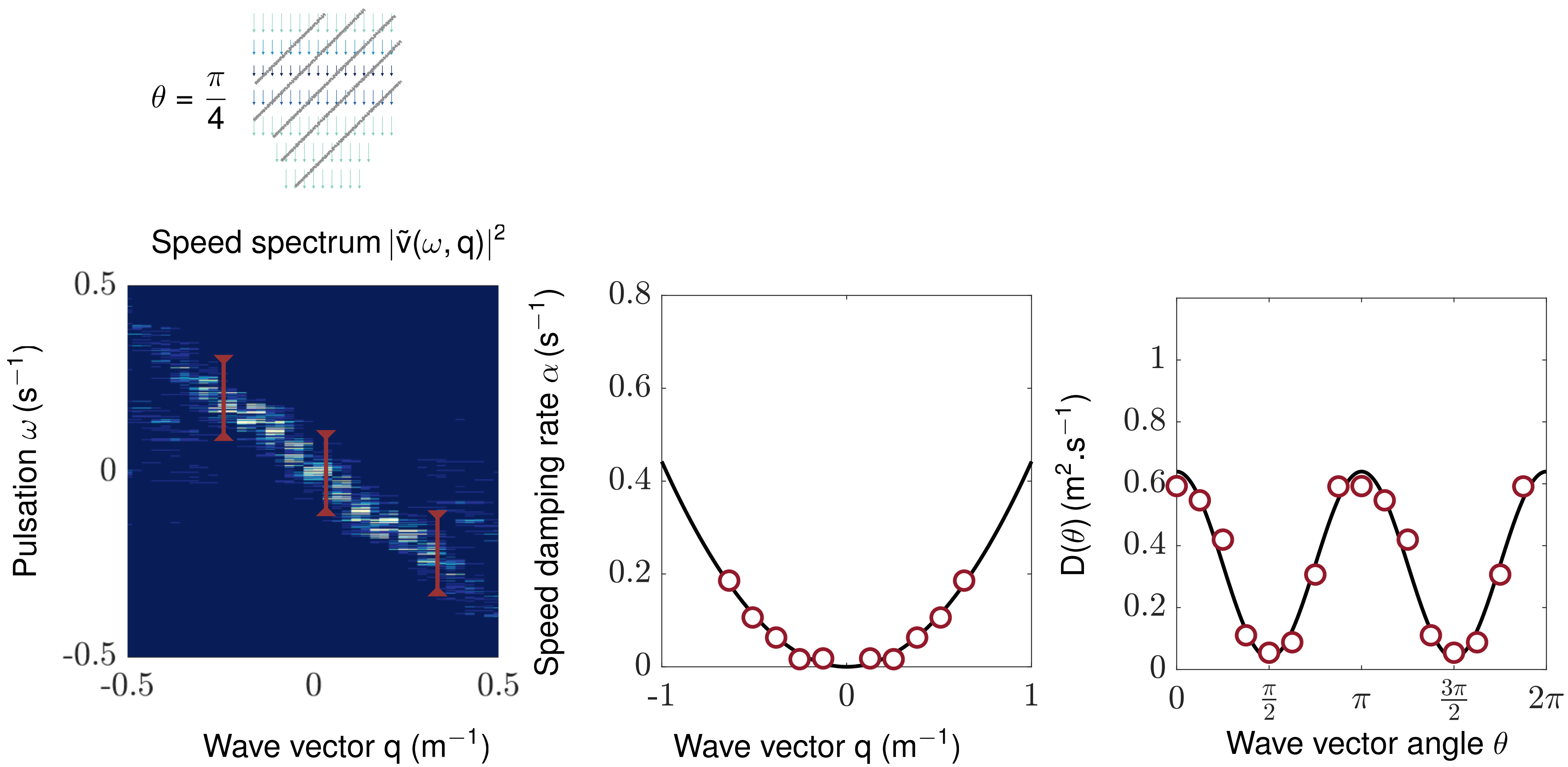
Flow-speed damping



$D(\theta) = D_0 \cos^2 \theta$

$D_0 = 0.6\, m^2.s^{-1}$

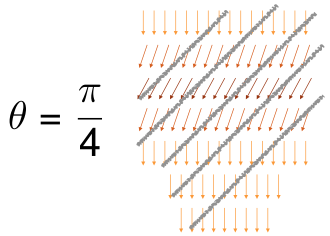
Flow-speed damping

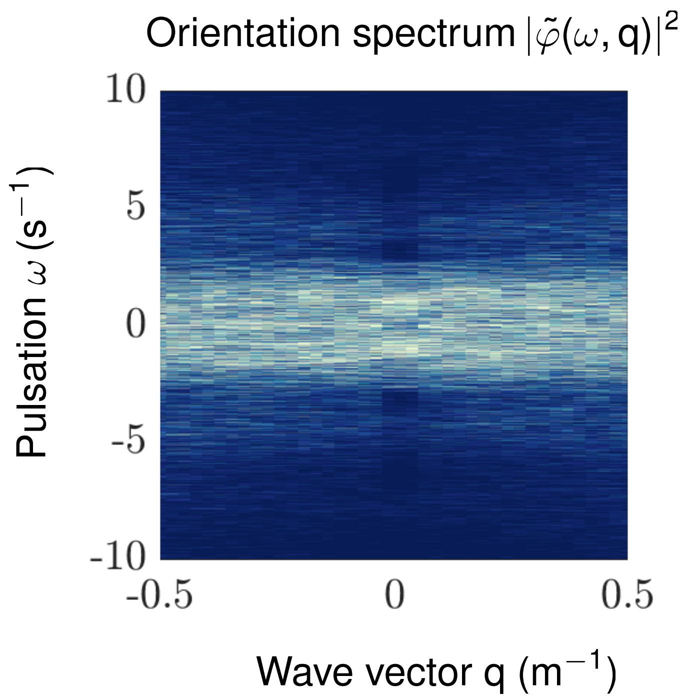


Slow 1D longitudinal dynamics

$$i\omega = -icq_x - D_0 q_x^2$$

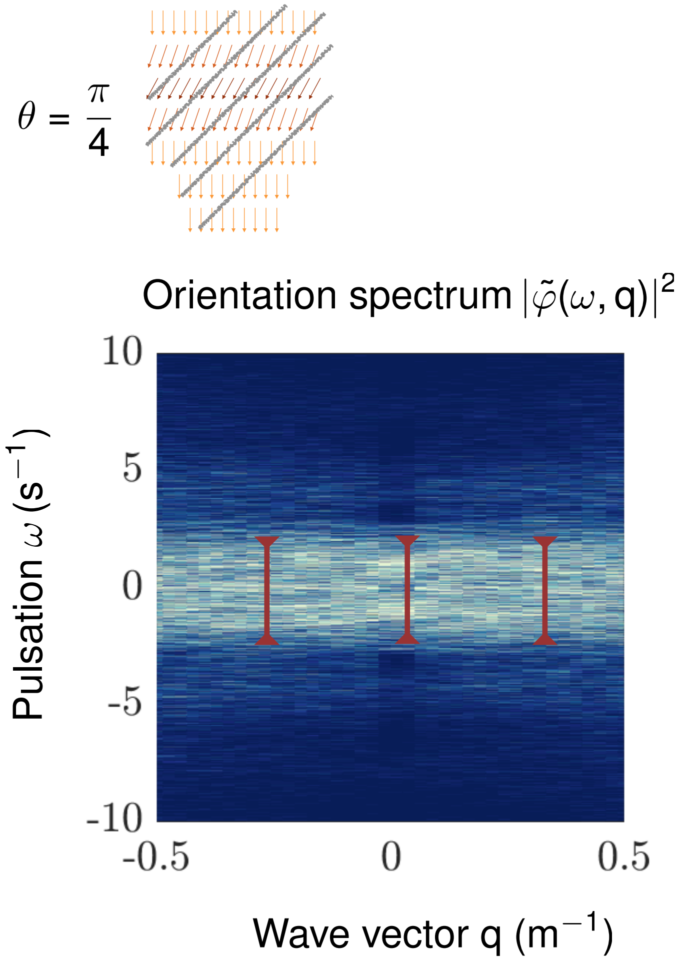
Orientational dynamics

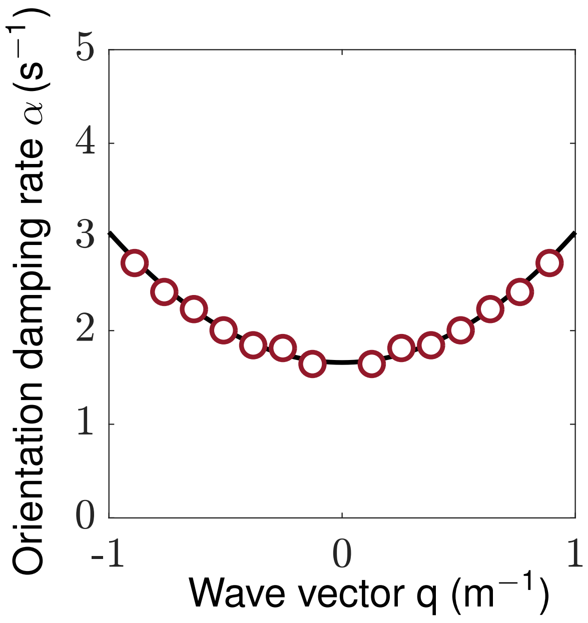




Orientational fluctuations are overdamped

Orientational dynamics

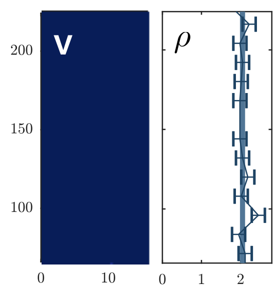




Fast overdamped 2D dynamics

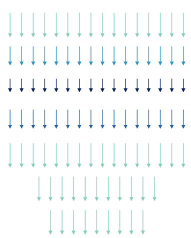
$$i\omega = -\alpha_0 - D_x q_x^2 - D_y q_y^2$$

Polarized crowds



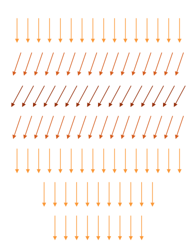
1) Static polarised crowds are homogeneous

$$\mathbf{v} = 0 \longrightarrow \rho = 2.2 \pm .05\,\mathrm{m}^{-2}$$



3) Flow speed: slow 1D dynamics, no intrinsic relaxation scale

$$i\,\omega = -i\,c_0 q_x - D_0 q_x^2$$



4) Flow orientation: fast relation at all scales

$$i\,\omega = -\alpha_0 + \mathcal{O}(q^2)$$

Crowd hydrodynamics

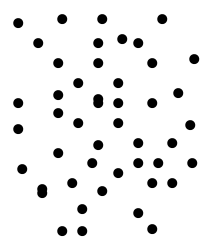
Conservation laws, symmetries & phenomenology

No behavioral assumption

Three fields

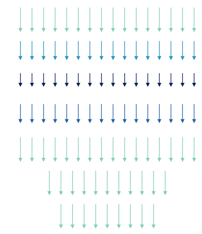
Density

ρ



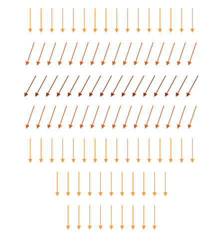
Velocity

$\mathbf{v}$



Polarization

$\mathbf{p}$



Simplifying observation

- People do not walk sideways

$$\hat{\mathbf{v}} = \hat{\mathbf{p}}$$

Conservation laws

Mass conservation:

$$\partial_t \rho + \boldsymbol{\nabla} \cdot (\rho \mathbf{v}) = 0$$

Momentum conservation:

$$\rho \mathrm{D_t} \mathbf{v} = \nabla \cdot \sigma + \mathbf{F}_\mathrm{f}$$

Overdamped angular dynamic

$$\partial_t \mathbf{p} = \mathbf{T}$$

Stress field

Momentum conservation:

$$\rho \mathrm{D_t} \mathbf{v} = \nabla \cdot \sigma + \mathbf{F}_\mathrm{f}$$

Pressure stress

$$\sigma = -P(\rho) + \mathcal{O}(\nabla)$$

Linear response

$$\nabla \cdot \sigma \sim -\beta \nabla \rho$$

Body force

Momentum conservation:

$$\rho \mathrm{D_t} \mathbf{v} = -\beta \nabla \rho + \mathbf{F}_\mathrm{f}$$

Friction Force

Body force

Momentum conservation:

$$\rho \mathrm{D_t} \mathbf{v} = -\beta \nabla \rho + \mathbf{F}_\mathrm{f}$$

Friction Force

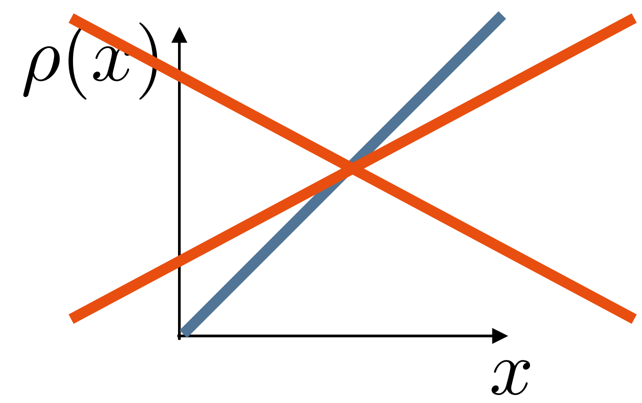
$$\mathbf{F}_\mathrm{f} = -\Gamma \cdot (\mathbf{v} - \nu_0 \mathbf{p}) + \mathcal{O}(\nabla)$$

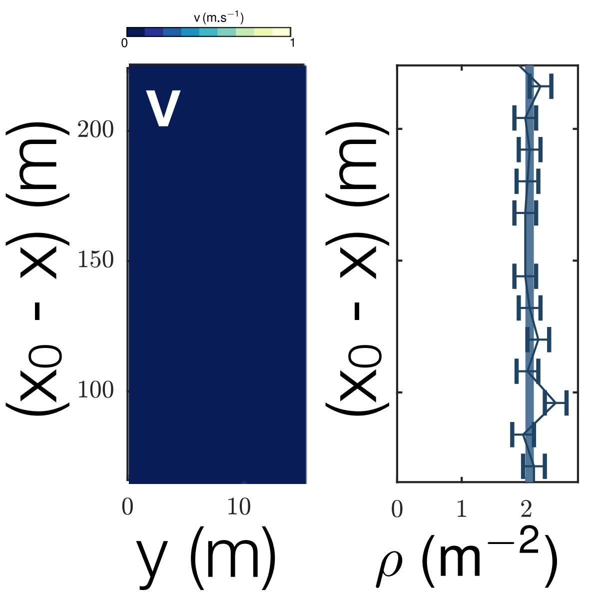
Crowd hydrostatics

Force Balance

$$0 = -\beta \nabla \rho + \nu_0 \mathbf{p}$$

$$\nu_0(\rho_0) = 0$$





Constant & uniform density

$\rho_0 = 2.2 \pm .05\,m^{-2}$

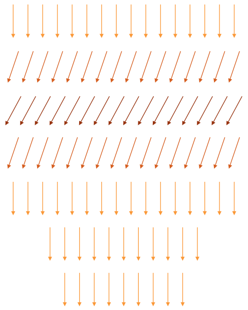
Body torque

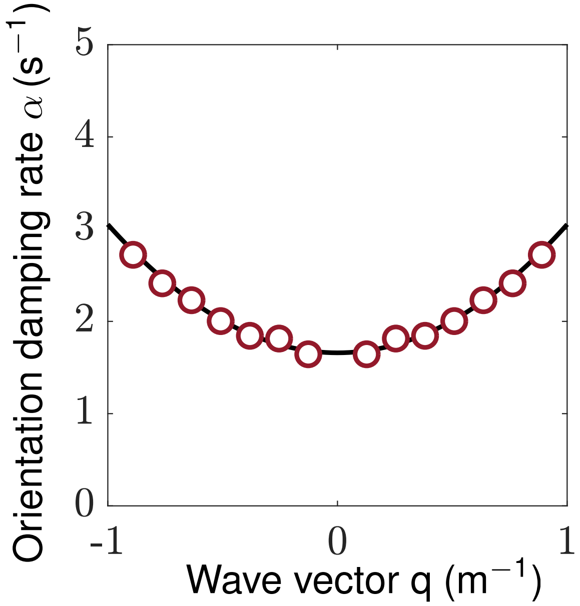
Angular dynamics

$$\partial_t \mathbf{p} = \mathbf{T}$$

Friction Torque

$$\mathbf{T} = -\Gamma_{\mathrm{r}}(\mathbf{p} - h\hat{\mathbf{x}})$$





Polarized crowd hydrodynamics

$$\partial_t v - c_0\, \partial_x v - D_0\, \partial_x^2 v = 0$$

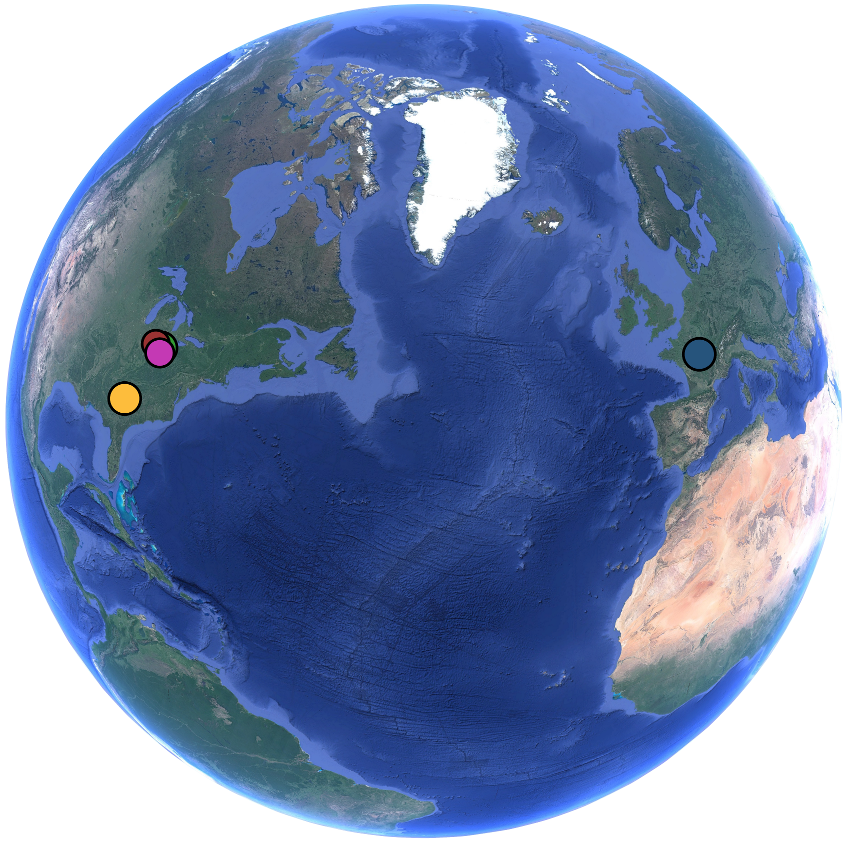
$$c_0 = -\rho_0 \nu_0'(\rho_0) \qquad D_0 = \frac{\rho_0 \beta}{\Gamma_x}$$

Active friction

Compressibility

Predictive theory?

$$\partial_t v - c_0\,\partial_x v - D_0\,\partial_x^2 v = 0$$



2016 Chicago Marathon

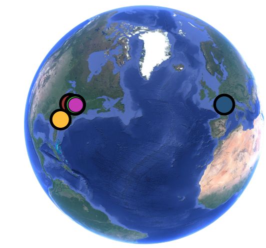
2017 Chicago Marathon

2017 Paris Marathon

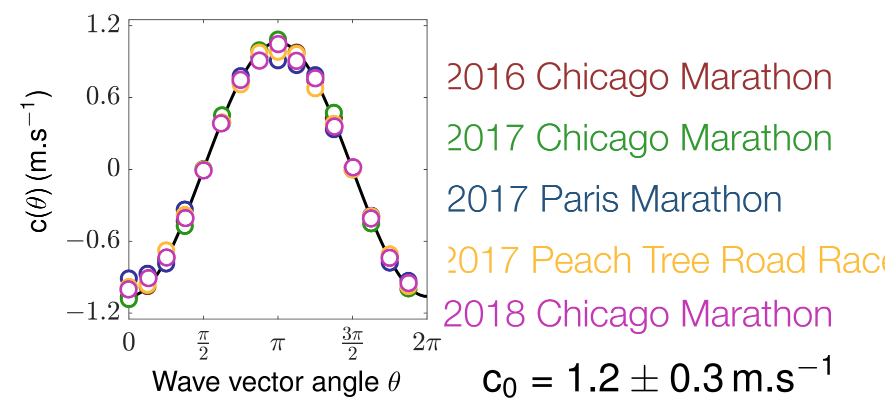
2017 Peach Tree Road Race

2018 Chicago Marathon

Predictive theory

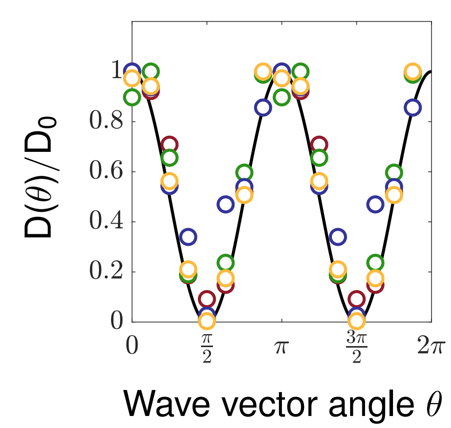


Wave speed



$c_0 = 1.2 \pm 0.3\,\mathrm{m.s^{-1}}$

Diffusive damping



$D_0 = 1 \pm 0.5\,\mathrm{m^2.s^{-1}}$

Camille Jorge

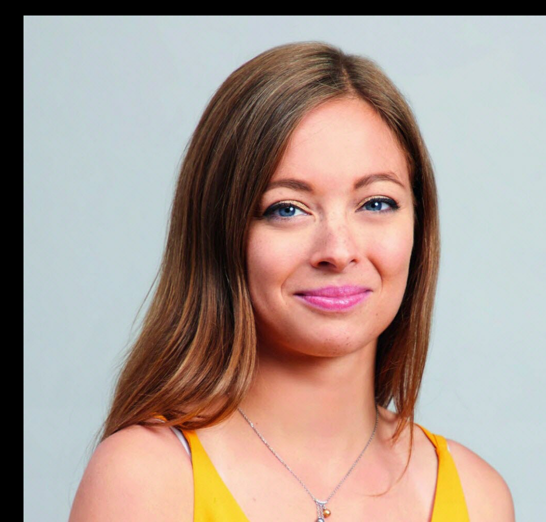
Amélie Chardac

Alexis Poncet

Nicolas Bain

Alexandre Morin

Delphine Geyer



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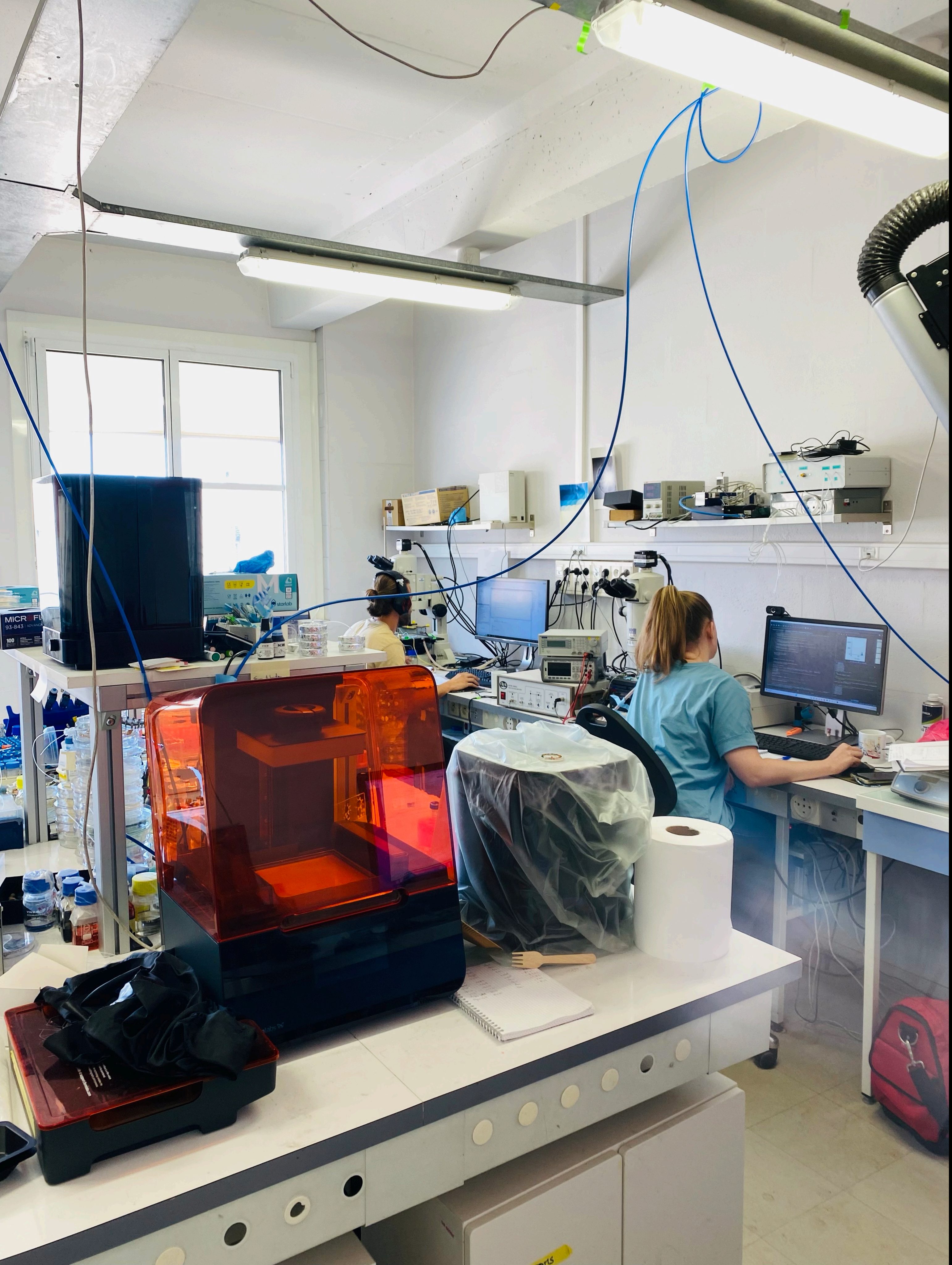

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