Outline

Lecture 1

1. Isotropic interactions and polar active dynamics

dynamical clustering and phase separation of purely repulsive particles

2. Polar interaction and polar active dynamics

Lecture 2

3. Isotropic active gels and emergence of spontaneous flows

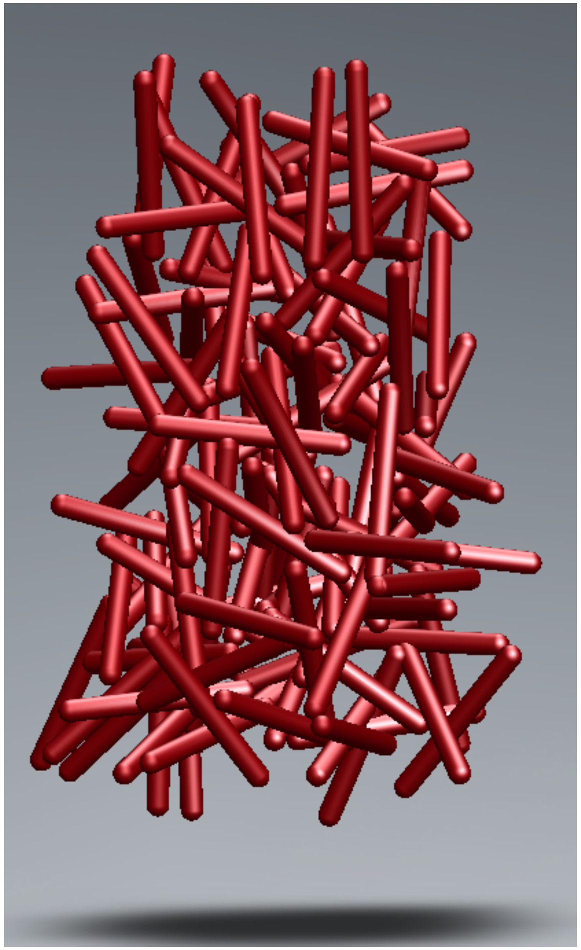
Today:

4. Apolar interaction and nematic active dynamics

- **complex living organisms (dry)**
- **simple shaken granular rods (dry)**
- **active nematics reconstituted from biochemical components (wet)**

Liquids crystals: isotropic-nematic phase transition

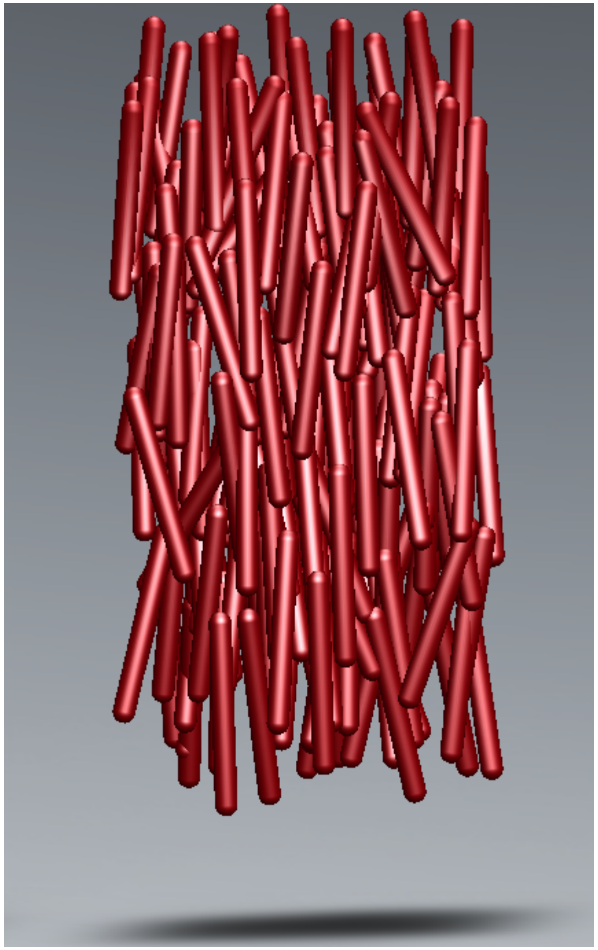
isotropic phase



short-range positional
and orientational order

rod
concentration →

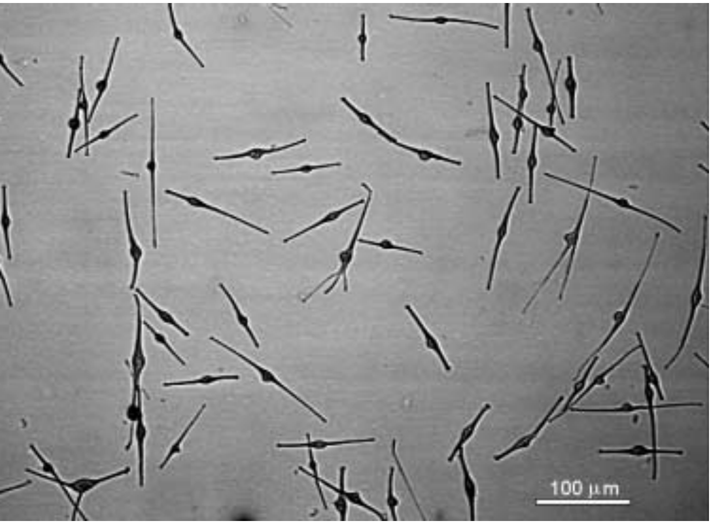
nematic liquid crystal



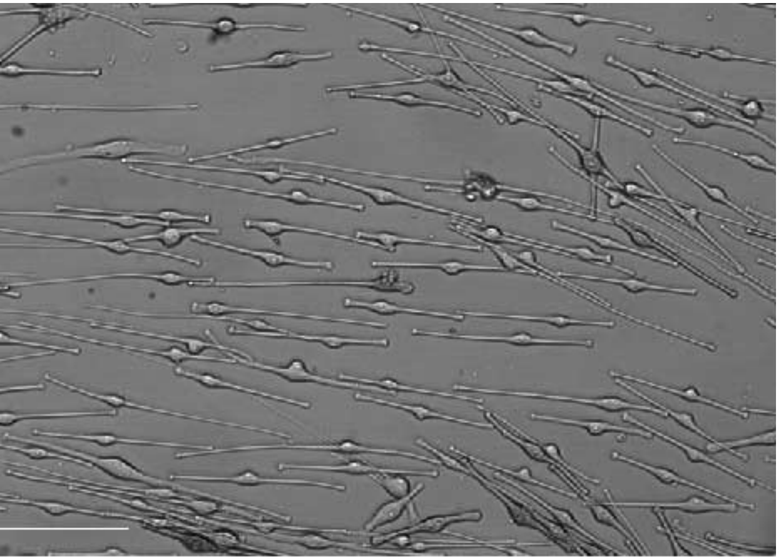
long-range orientation order
short-range positional order

rods equally likely to point up or down nematic (quadripolar) order

Cellular active nematics

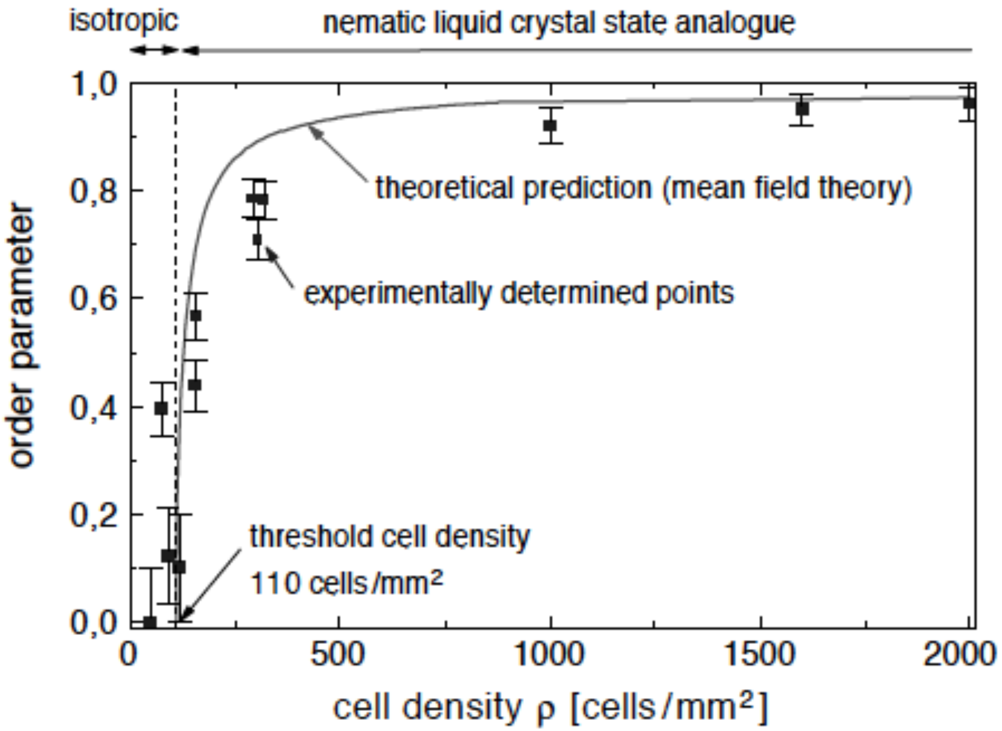


low density – isotropic phase



high density – nematic phase

Motile human melanocytes on a plastic surface:

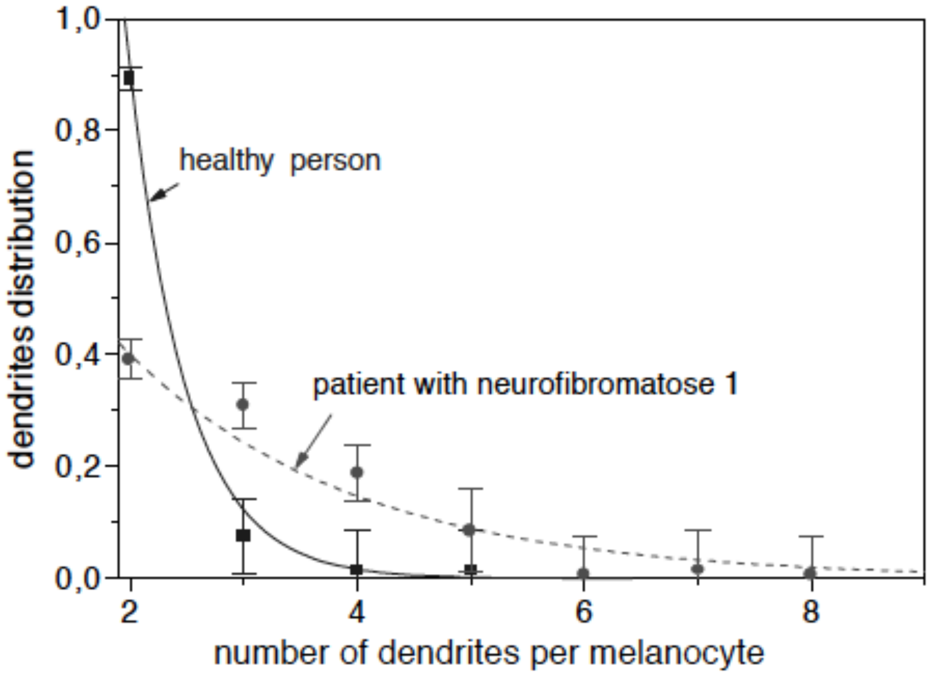


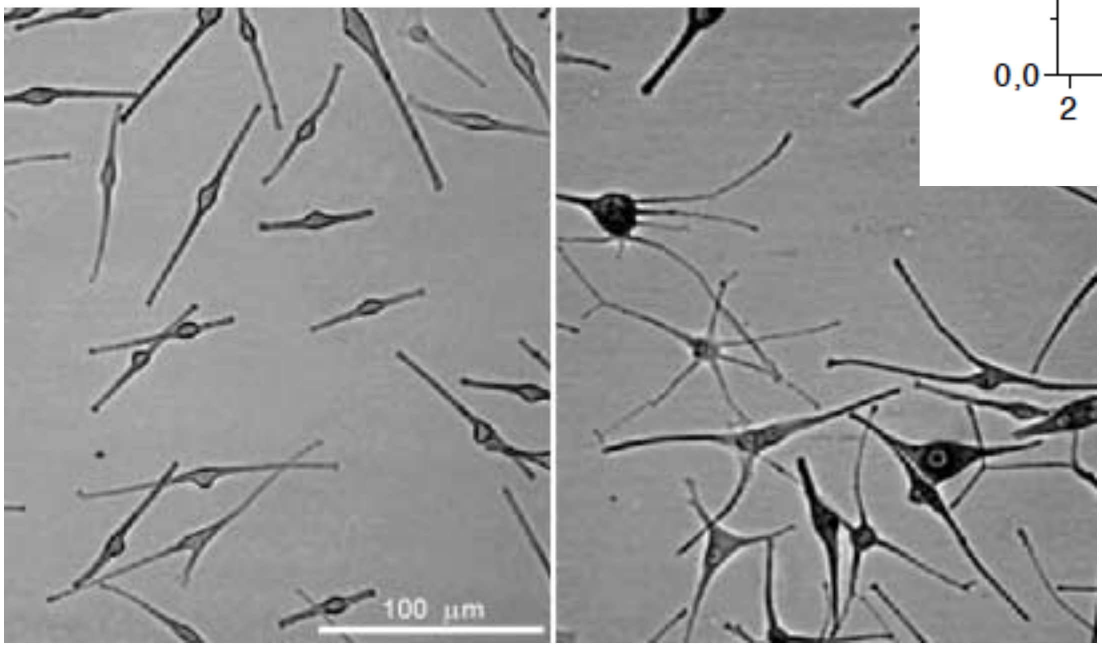
Theoretical interpretation in terms of equilibrium statistical mechanics -probably not correct.

Hans Gruler et. al. 2000

Cellular active nematics

- melanocytes with patients with neurofibromatose (genetic disease)
- different symmetry of the building blocks
- absence of orientational order





Another kind of topological defect

DERMATOGLYPHIC TOPOLOGY

By Prof. L. S. PENROSE, F.R.S.
Galton Laboratory, University College, London

THE ridges which form the dermatoglyphic patterns on the ventral surfaces of the hands and feet are arranged in lines which are parallel in small fields. Two kinds of discontinuity of pattern are found; these occur at the centres of what are termed loops and triradii. Around the core of a loop (Fig. 1) the direction of the ridges turns through an angle of 180°. The centre of a triradius (Fig. 2) is the point where three different fields of almost parallel ridges meet. The result produces three spokes; the angles between them are greater than 90° and are typically each 120°.

On the fingers and toes a single loop is accompanied by one triradius (see Fig. 3). When two loops are present there are two triradii, and the same applies to a symmetrical whorl in which two loops have become fused.

Fig. 1. Loop pattern

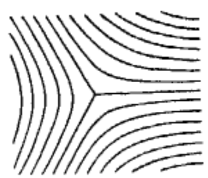


Fig. 2. Triradius

Fig. 3. Configurations on digits; (i) arch, (ii) loop, (iii) whorl

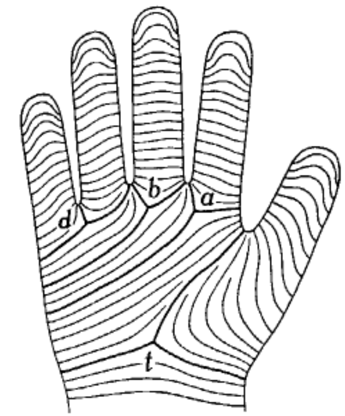


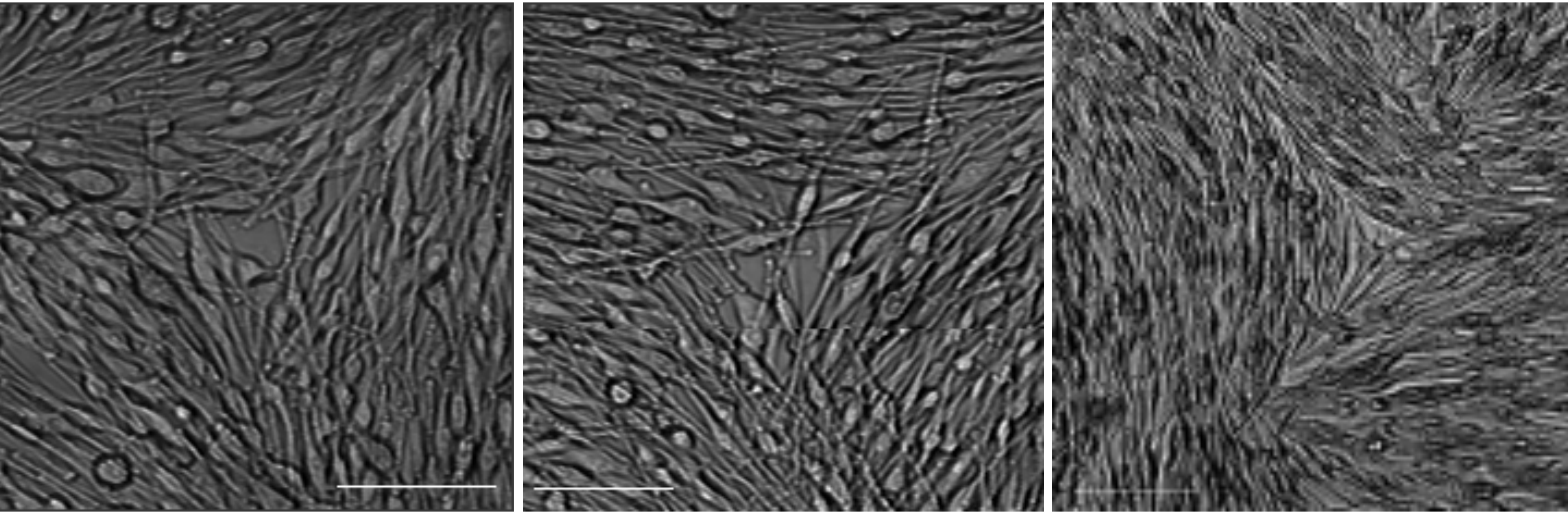
Fig. 4. Minimal number of triradii on hand

Fig. 5. Left hand with multiple ridge patterns

Curvature of the lines which is insufficient to make a loop is called an arch.

On the palms the minimal number of triradii is four. These are usually in the positions designated *a*, *b*, *d* and *t* (see Fig. 4). For every loop which occurs on the palm there is another triradius. Moreover, it can be shown empirically that, over the whole hand, including the fingers, the number of triradii exceeds the number of

Cellular active nematics (defects)

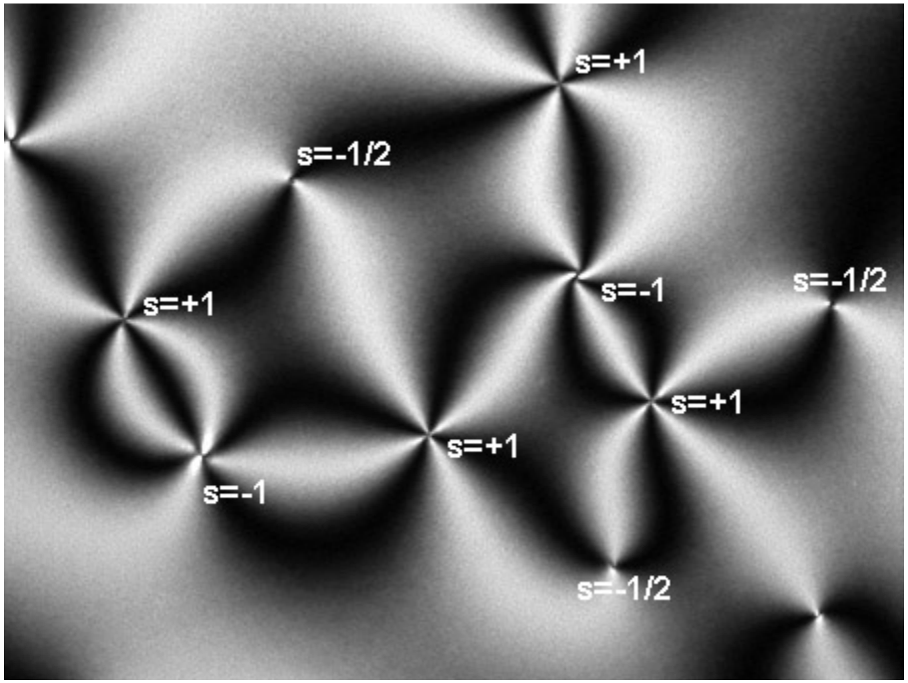


- nematic order in melanocyte active nematic is not uniform
- existence of singular point where nematic order vanishes – topological defects

Nemato in Greek means thread-like due to appearance of ubiquitous defects lines

Defects in equilibrium nematics

Eliminating defects to create monodomain LC samples is essential for fundamental studies and technological applications



polarization microscopy image of a defect ridden quasi-2D nematic liquid crystal

rubbing machine – creates anchoring conditions appropriate for LC displays

disclination defects in equilibrium nematics

topological charge Q= +1

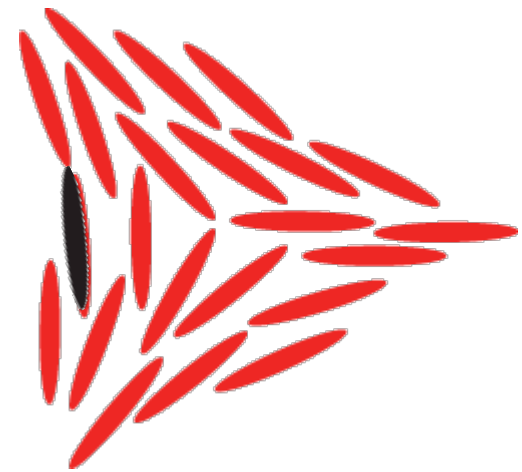
traversing the defect core
requires 360° rotation

topological charge Q= ½

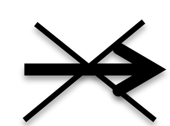
traversing the defect core
requires 180° rotation

Q = +½

Q = -½



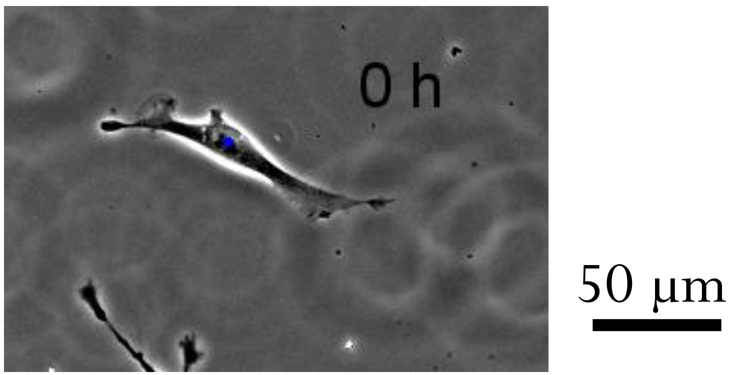
- +½ and -½ defects can annihilate to create defect free nematic
- thermal fluctuations could drive formation of a defect pair in a monodomain sample – thermal barrier to large
- ½ defect can only form in a system with nematic symmetry (arrowless bar)

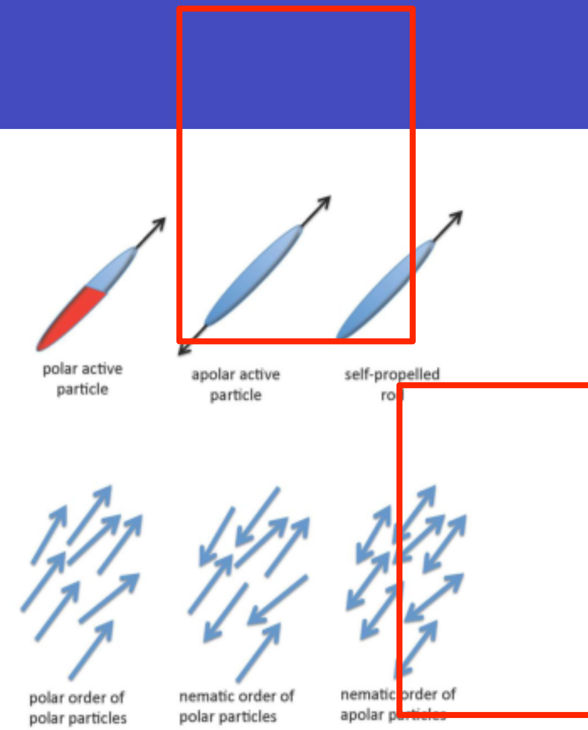


Cellular active nematics

More recent example - spindle-like motile NIH-3T3 fibroblasts cells

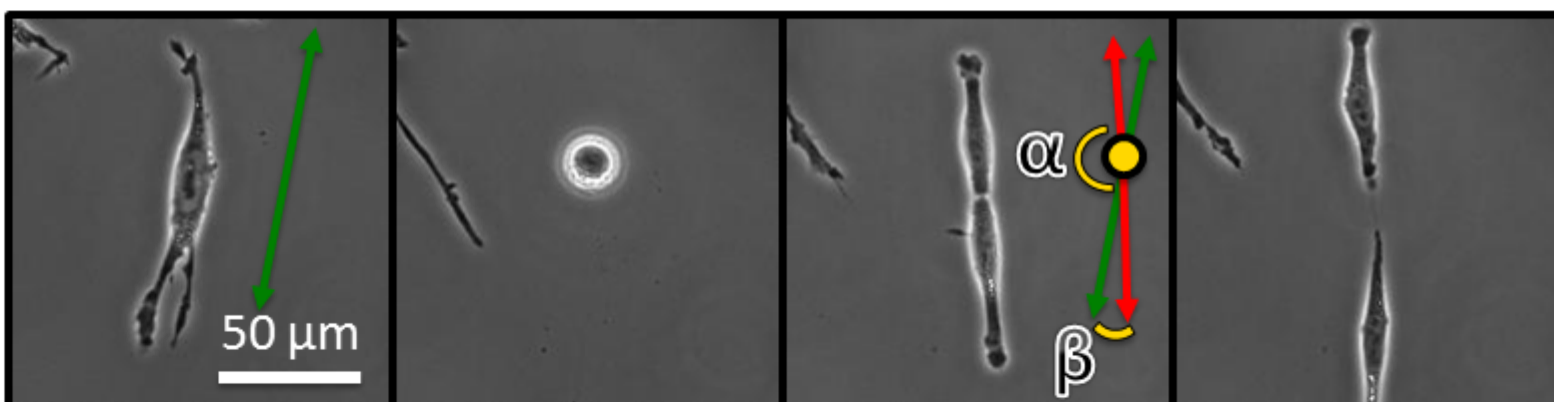
flat glass substrate coated with fibronectin - required for cell adhesion and motiltiy





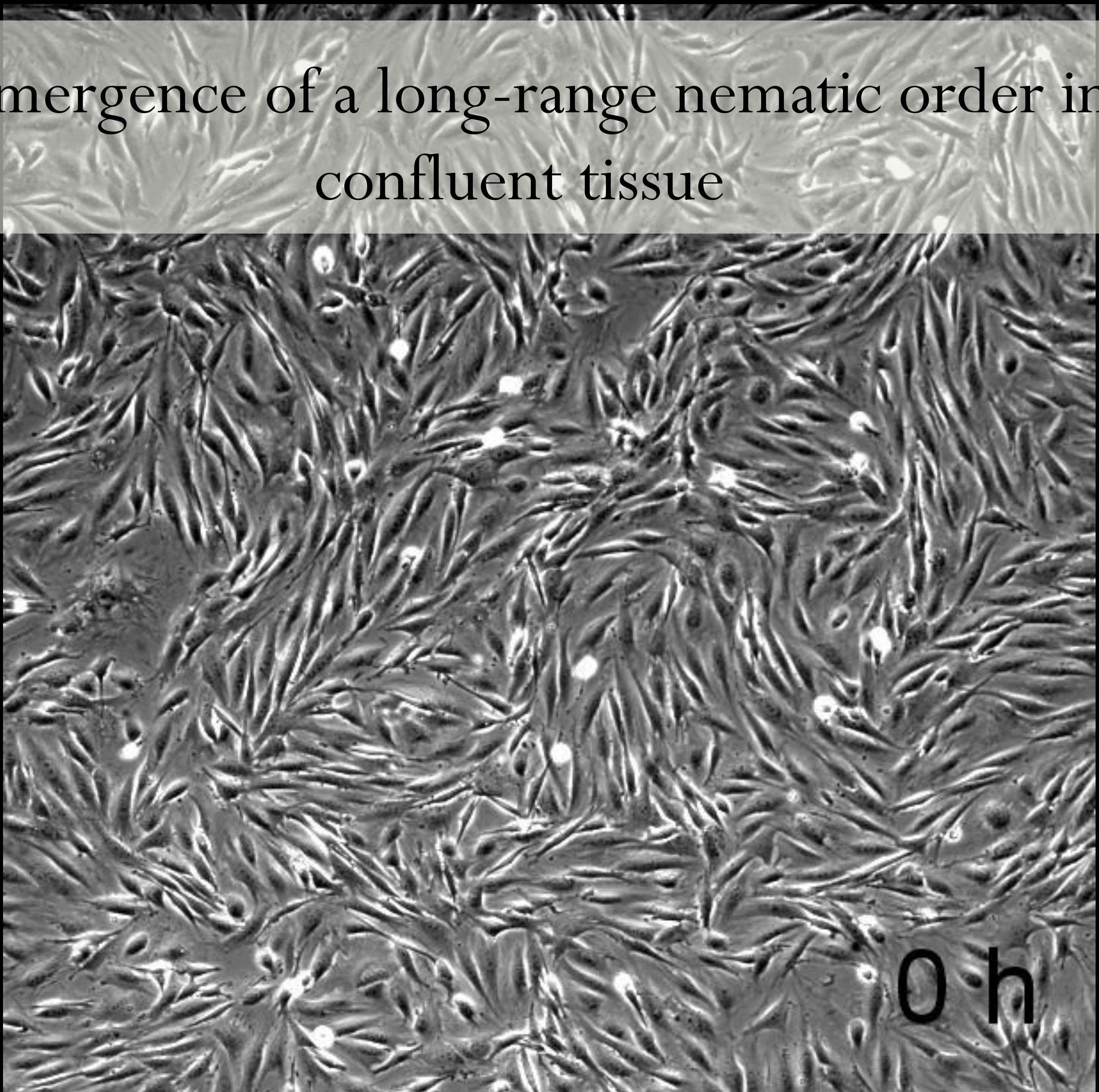
Baskaran and Marchetti, *EurPhysJ E Soft Matter*. 2012
Self-regulation in self-propelled nematic fluids.

Cell division :



Duclos et al, "Perfect nematic order in confined monolayers of spindle-like cells", *Soft Matter* 2014

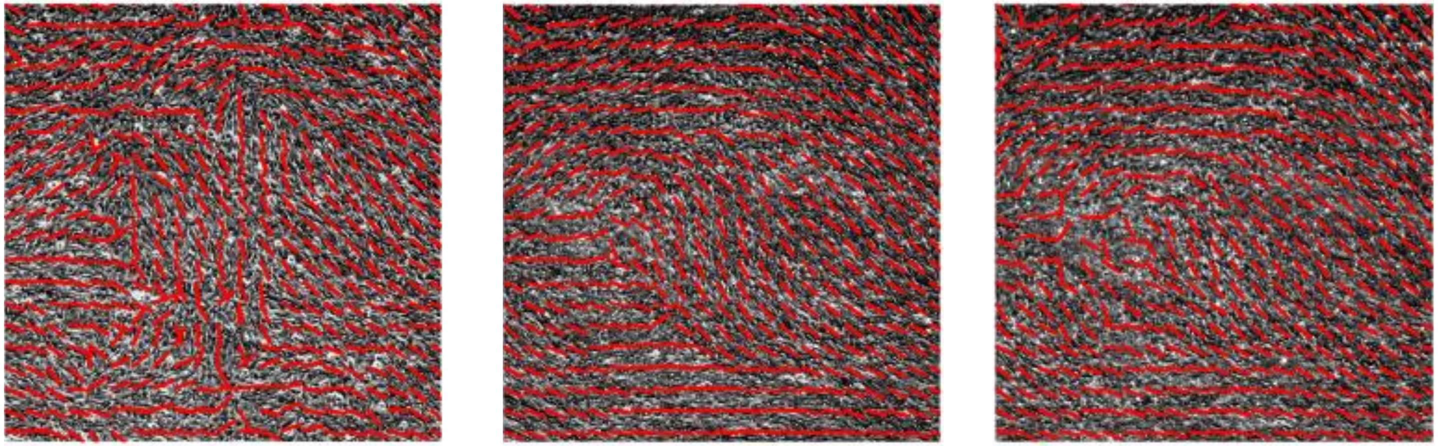
1. Emergence of a long-range nematic order in a confluent tissue

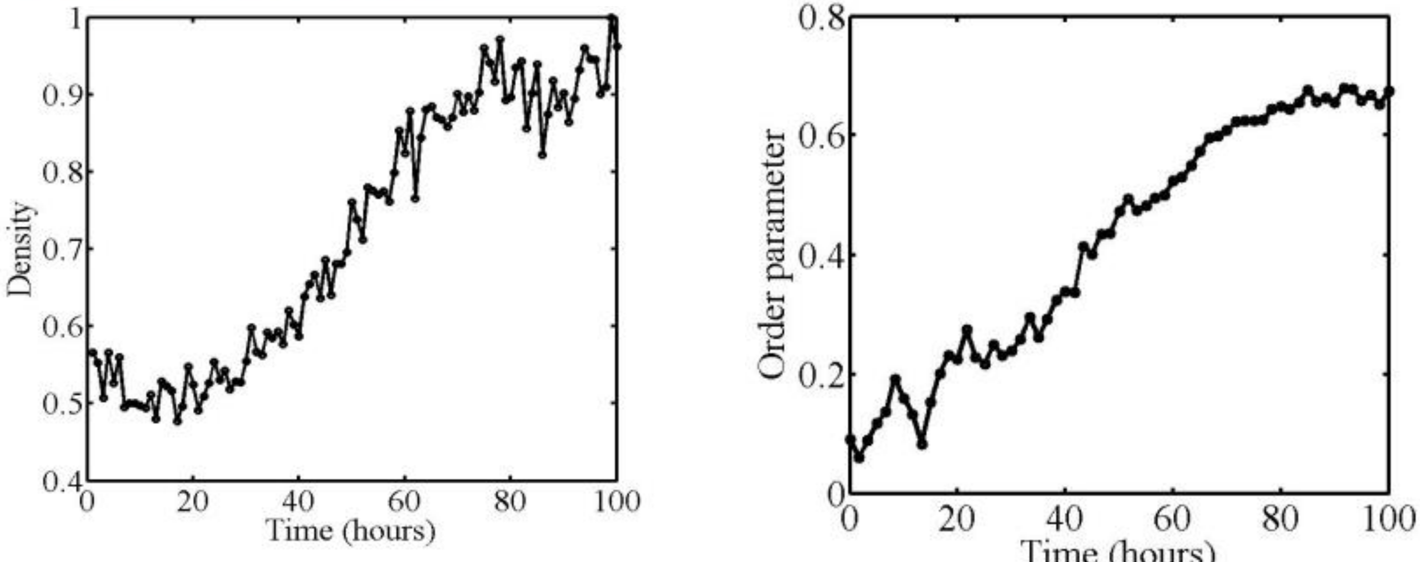


200 μm

Cellular active nematics

Transition from a low-density disordered state to a high-density nematic





two different forces drive nematic non-equilibrium dynamica: cell motility and cell division

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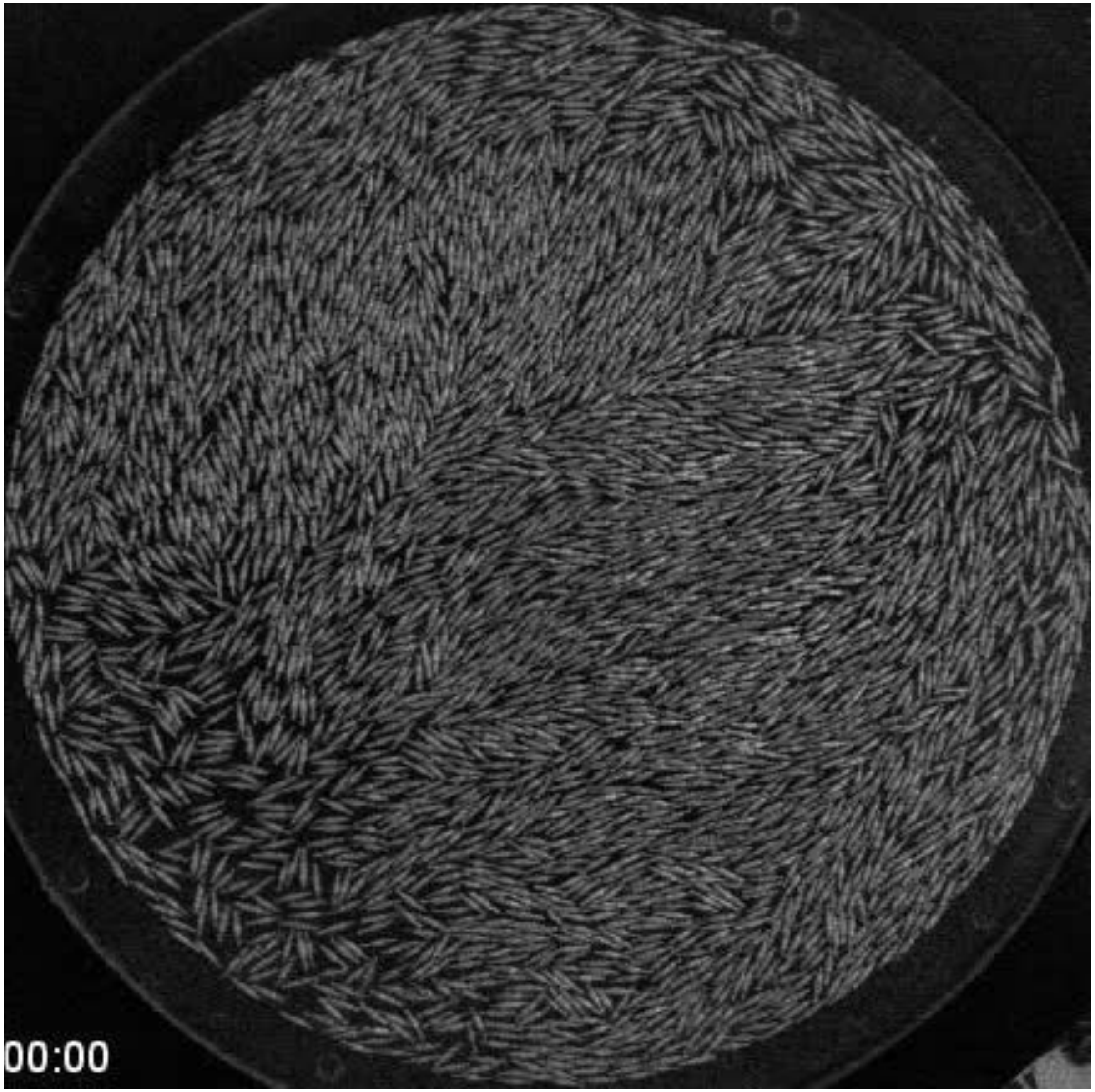
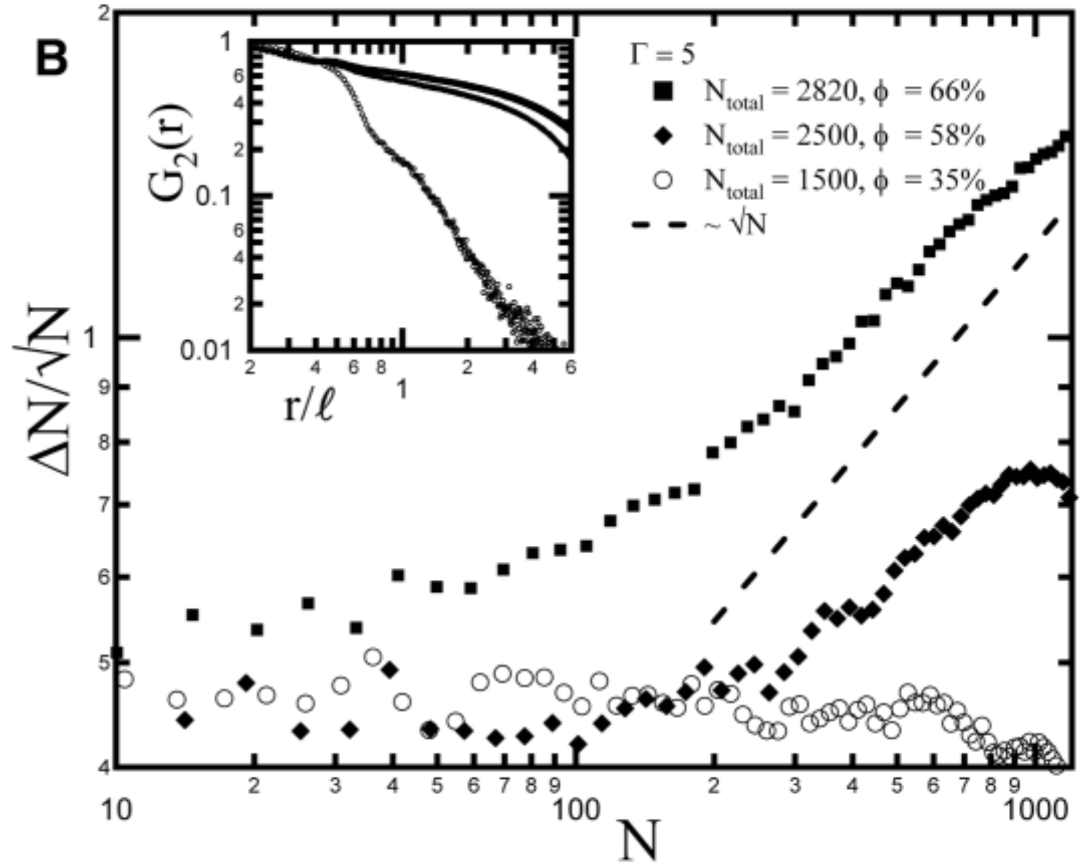
- **complex living organisms (dry)**
- **simple shaken granular rods (dry)**
- **active nematics reconstituted from biochemical components (wet)**

Granular active nematics

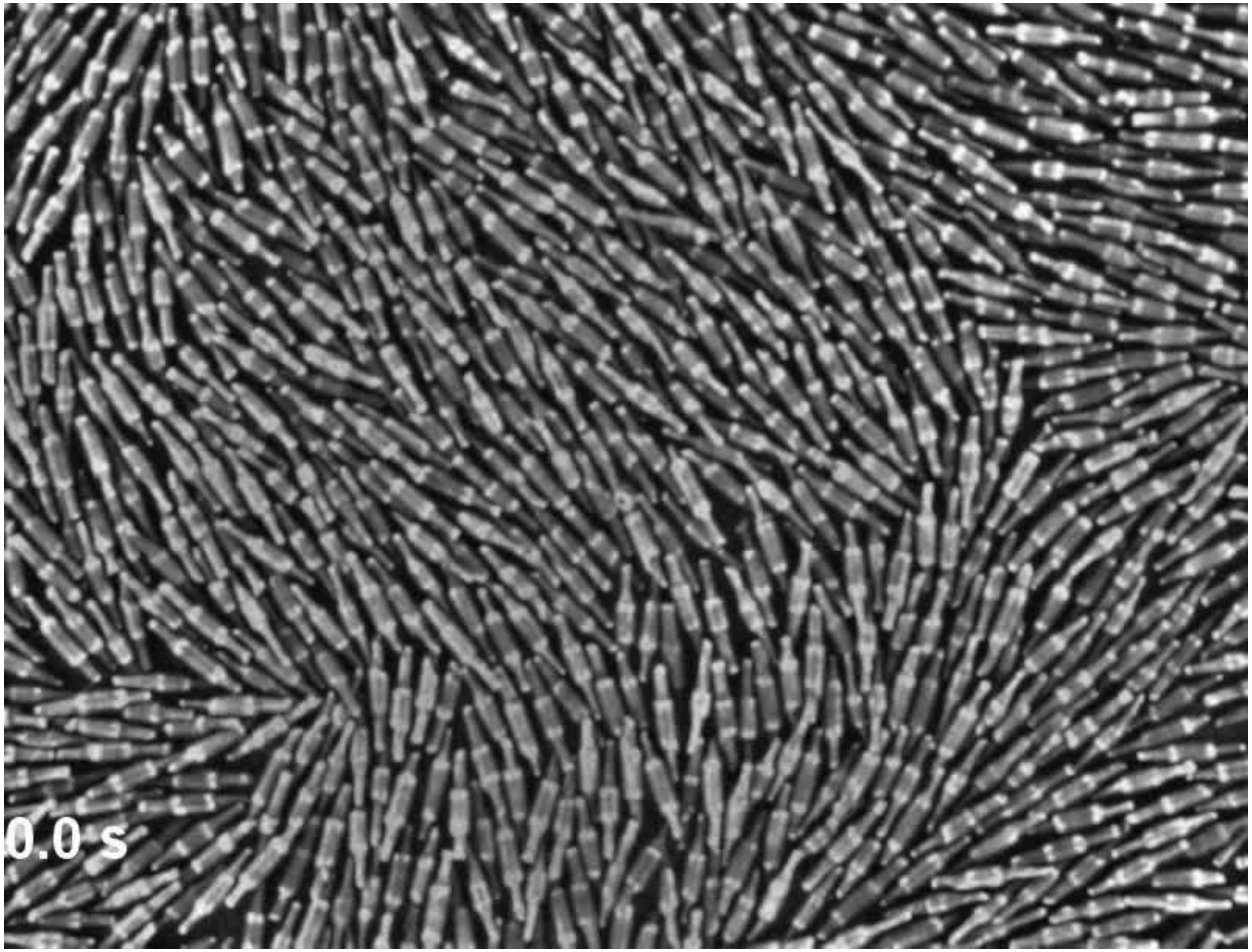


Granular active nematics

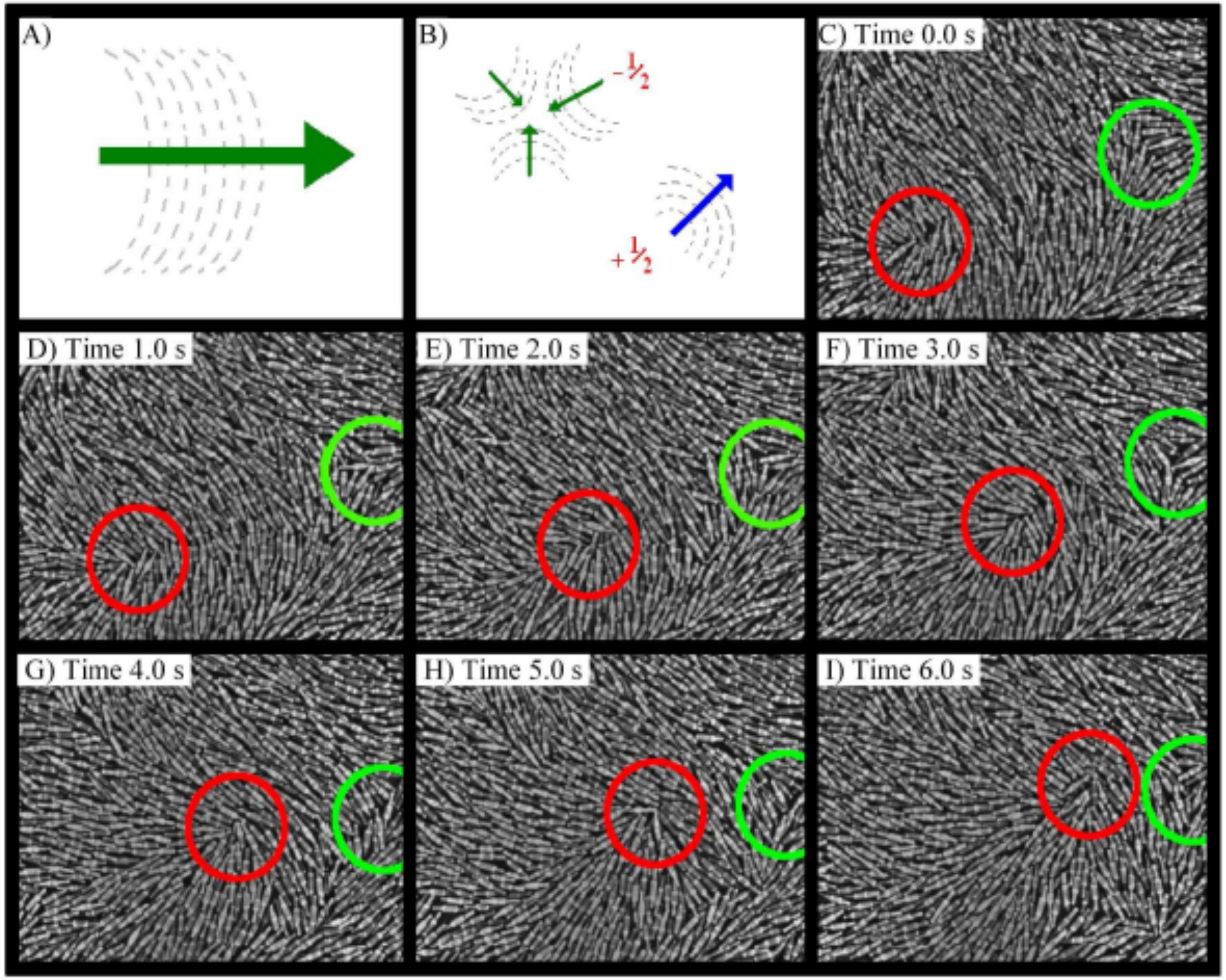


Active nematic – giant number fluctuations

Granular active nematics



Granular active nematic



+1/2 topological defect are motile,- ½ defects are passive

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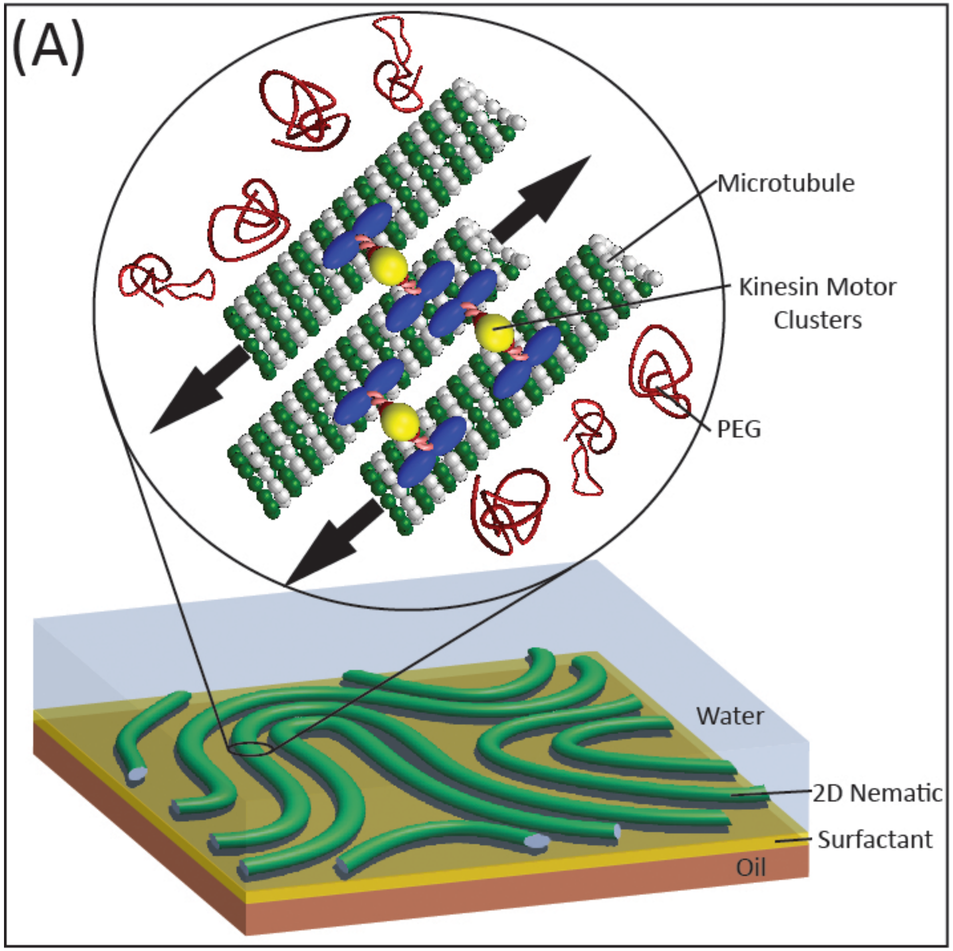
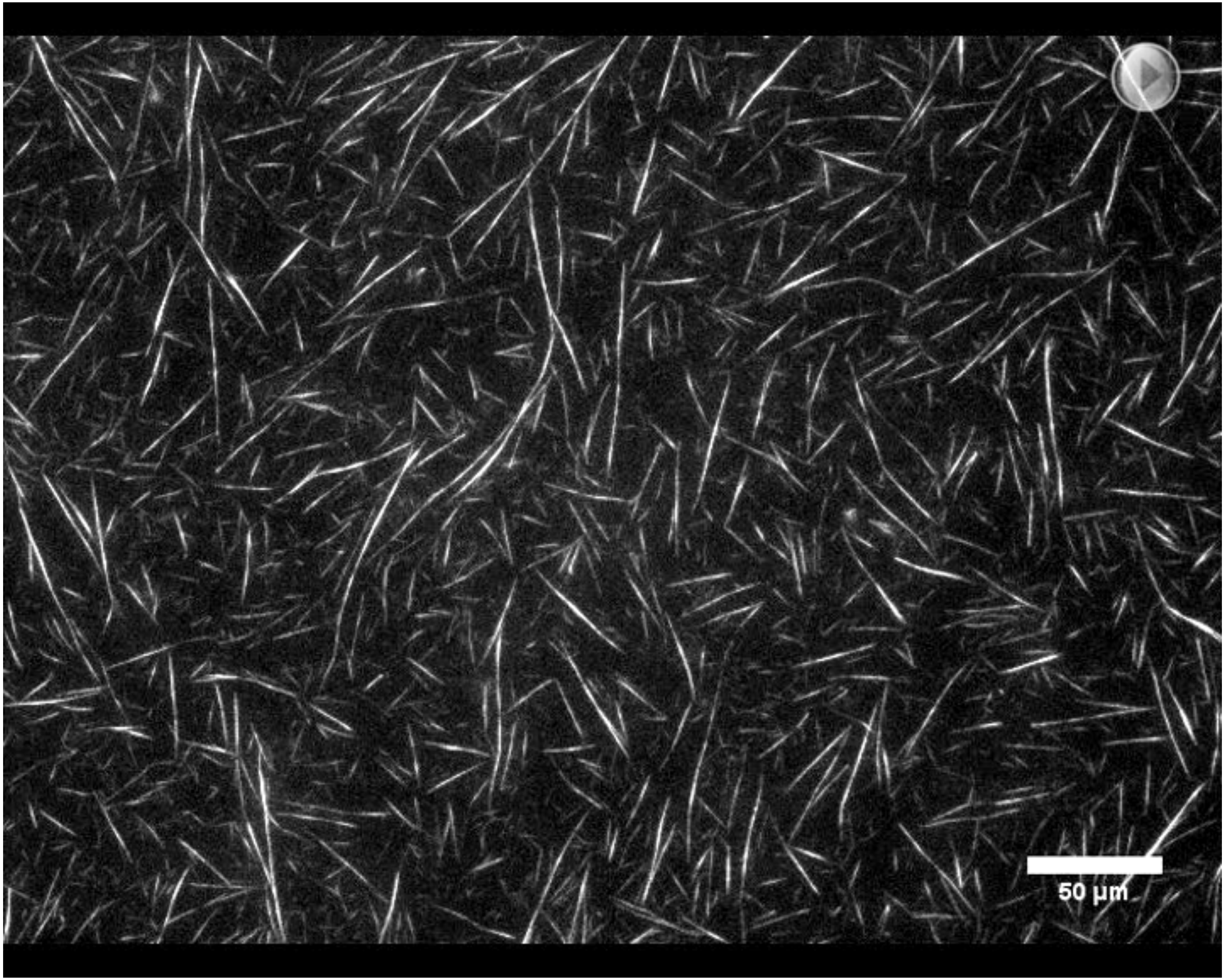
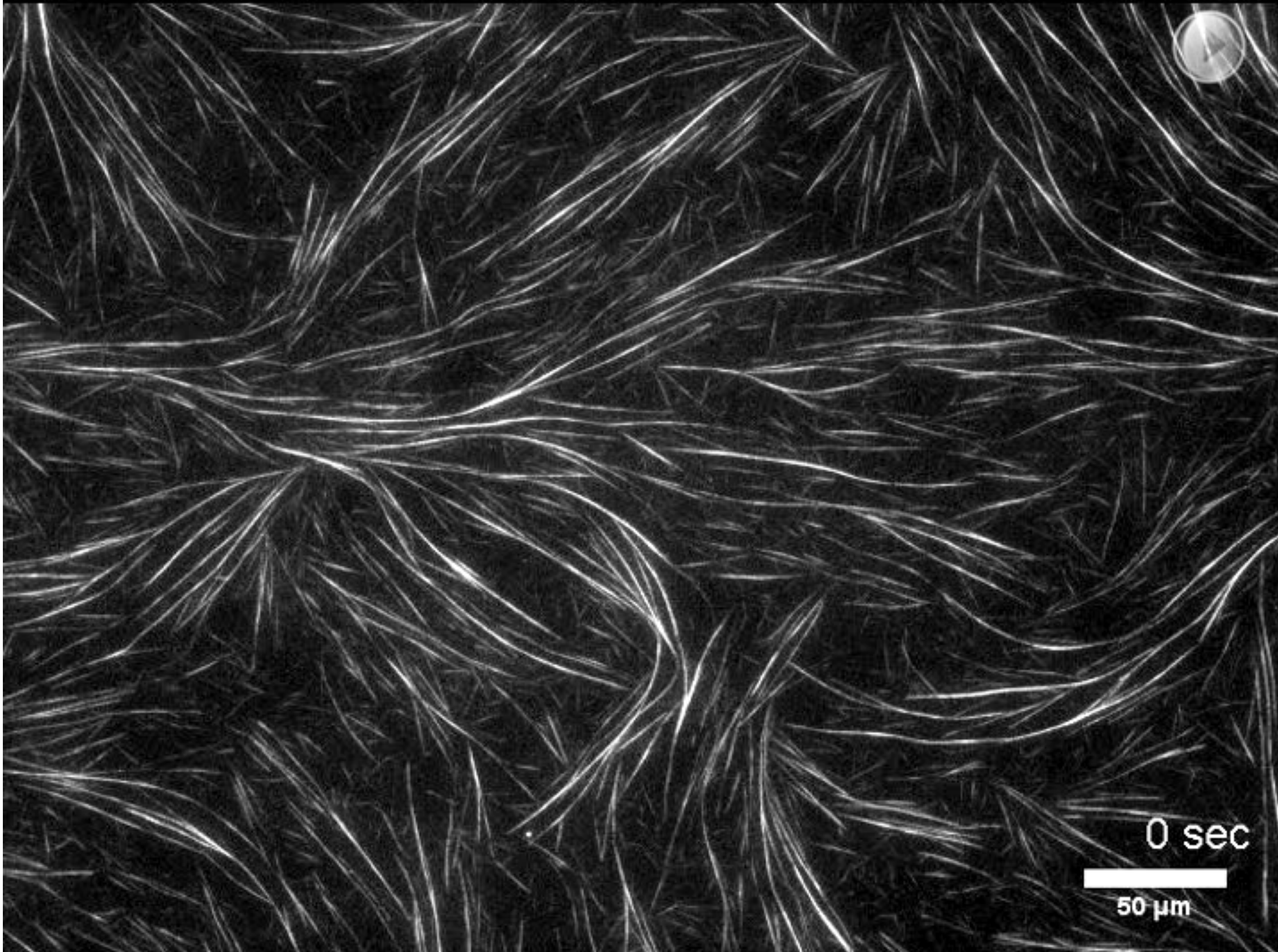
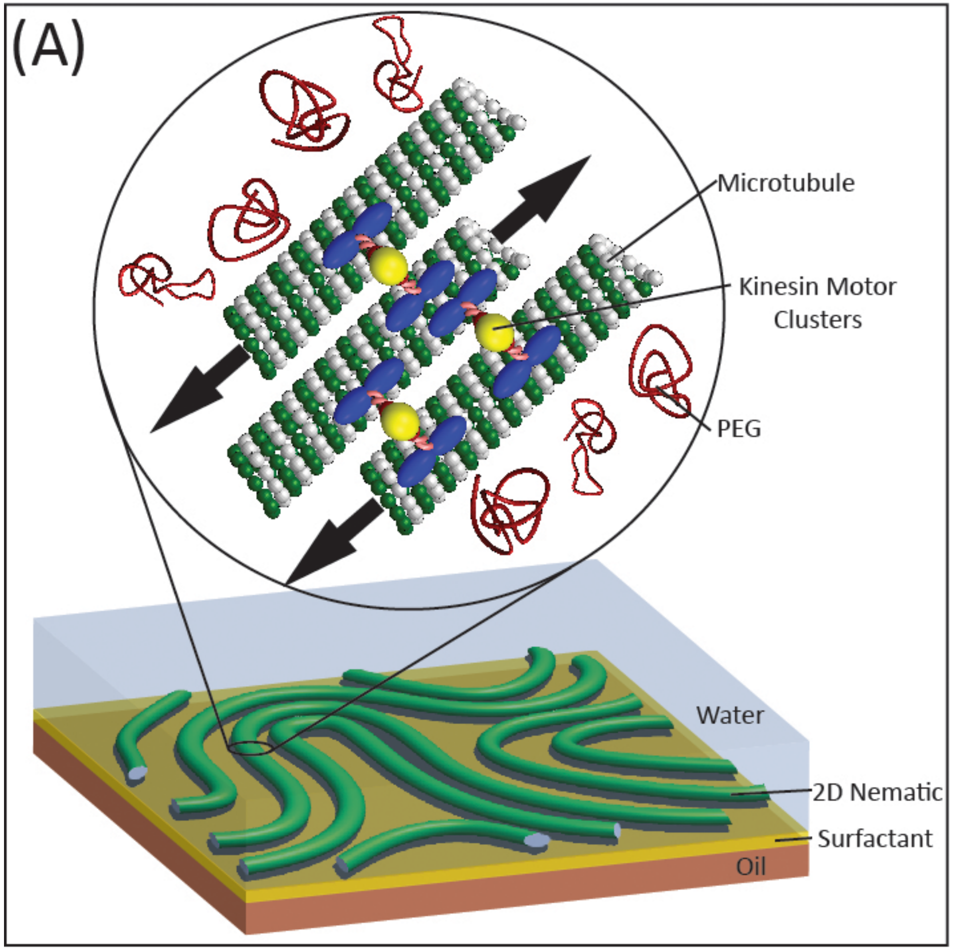
2D active nematics on oil-water interface

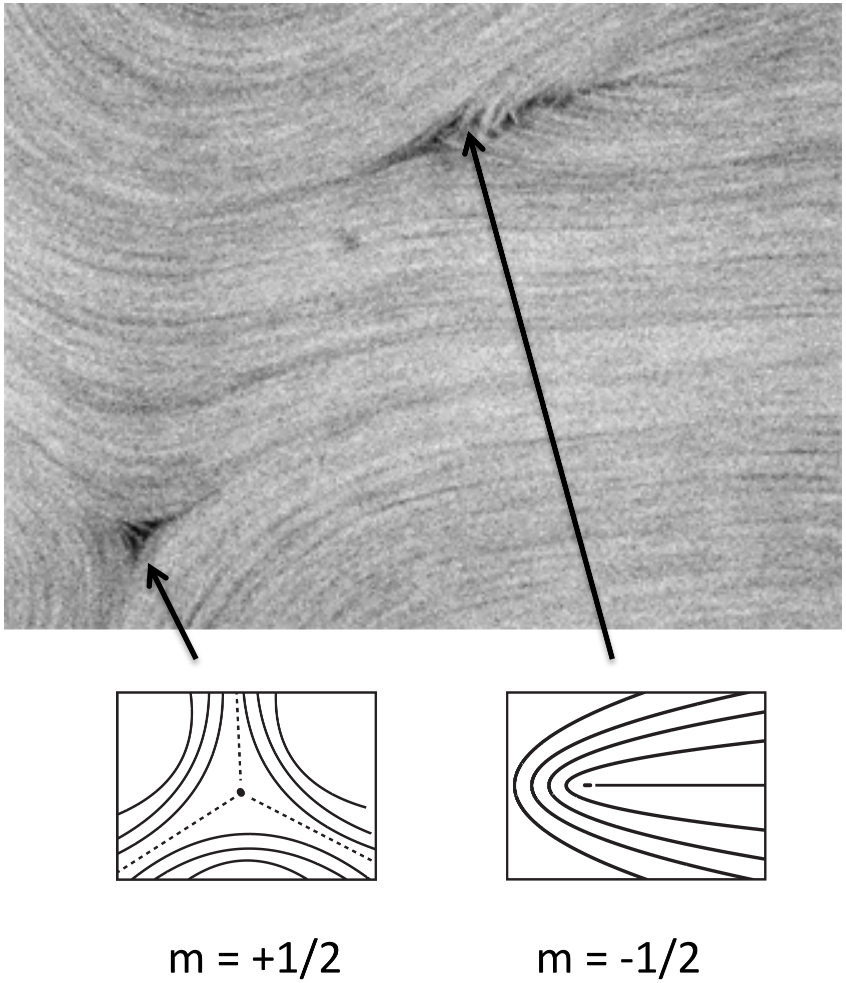



50 µm

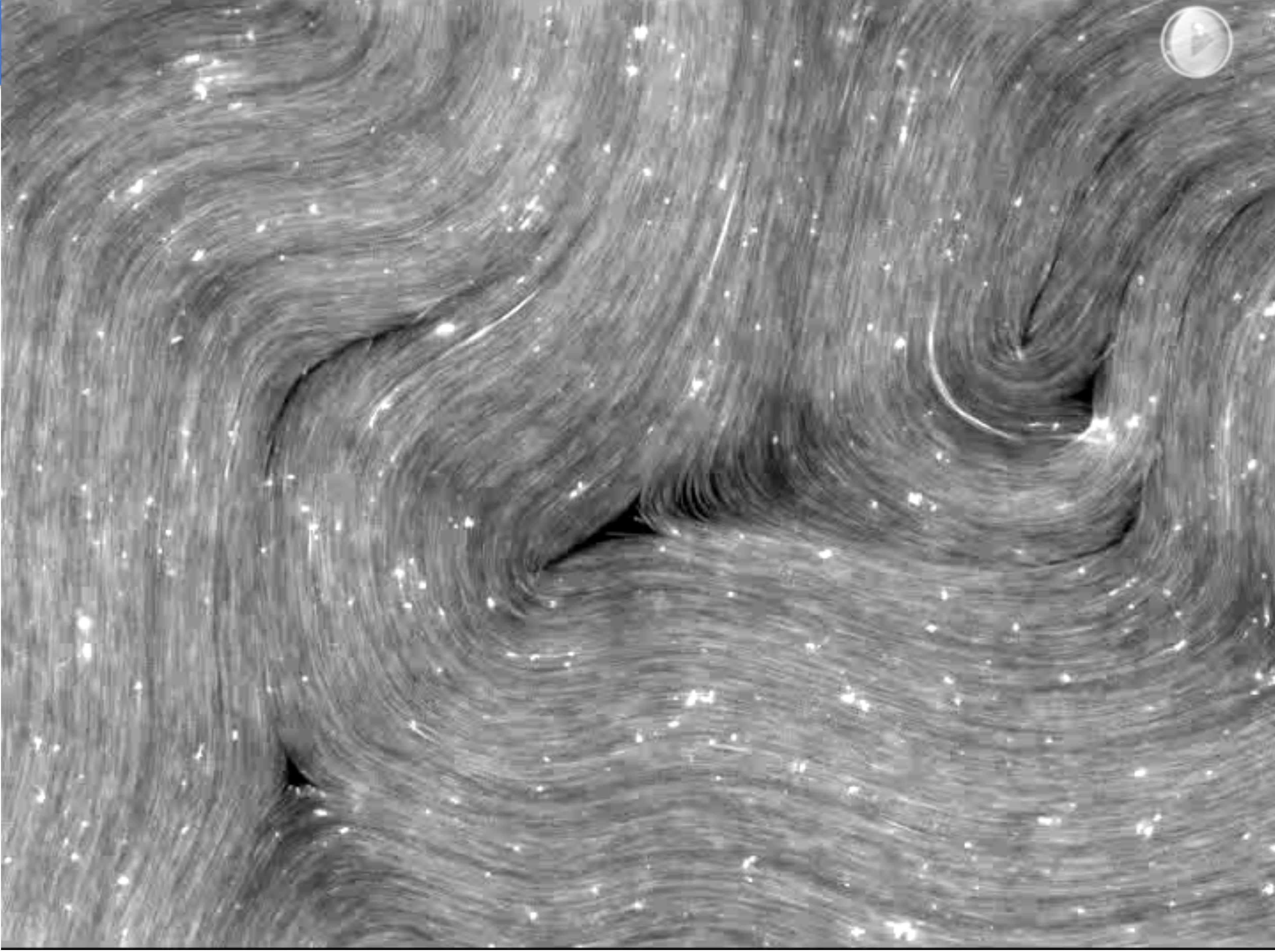

0 sec
50 µm

2D active nematics on oil-water interface

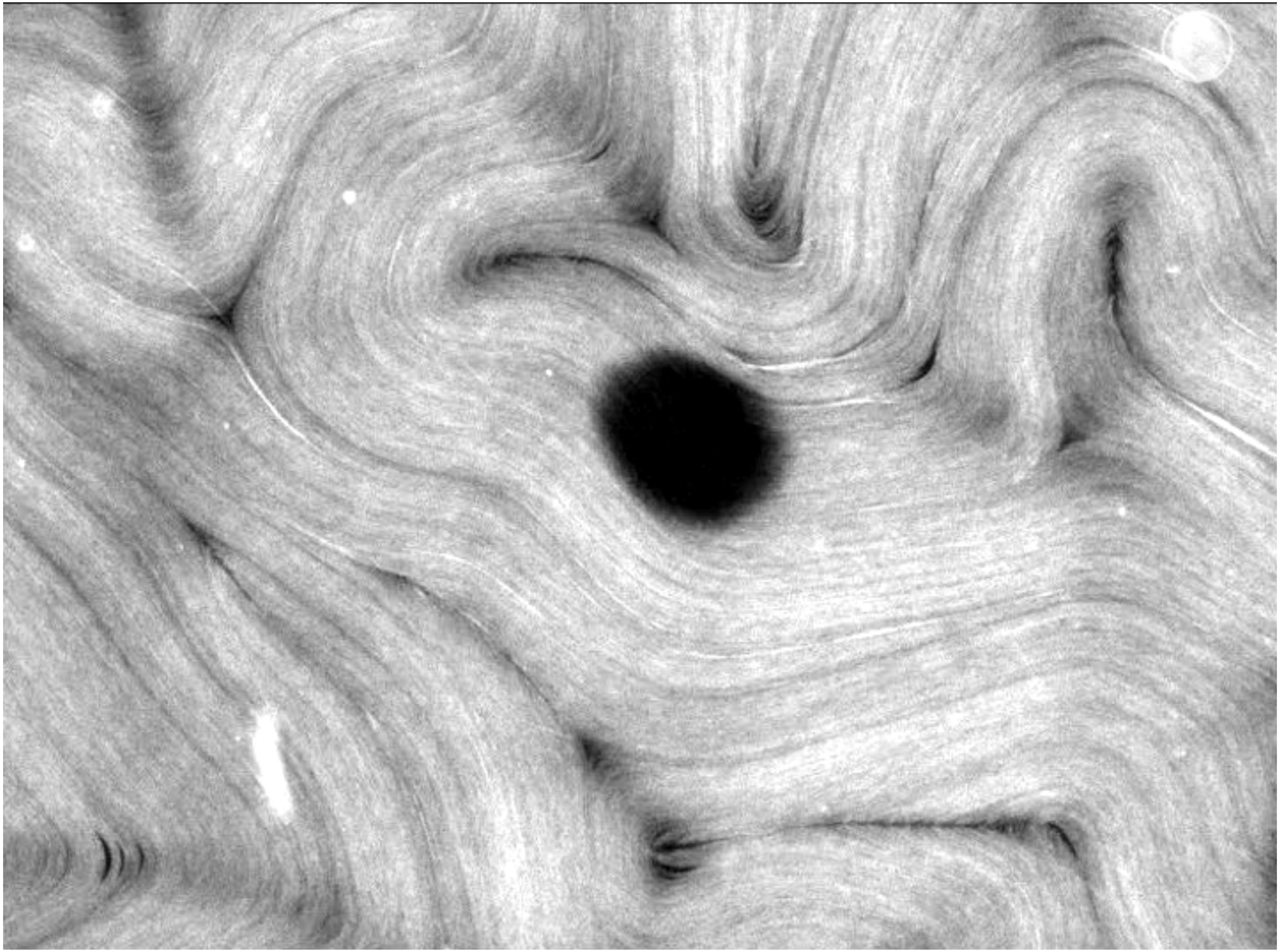




topological defects

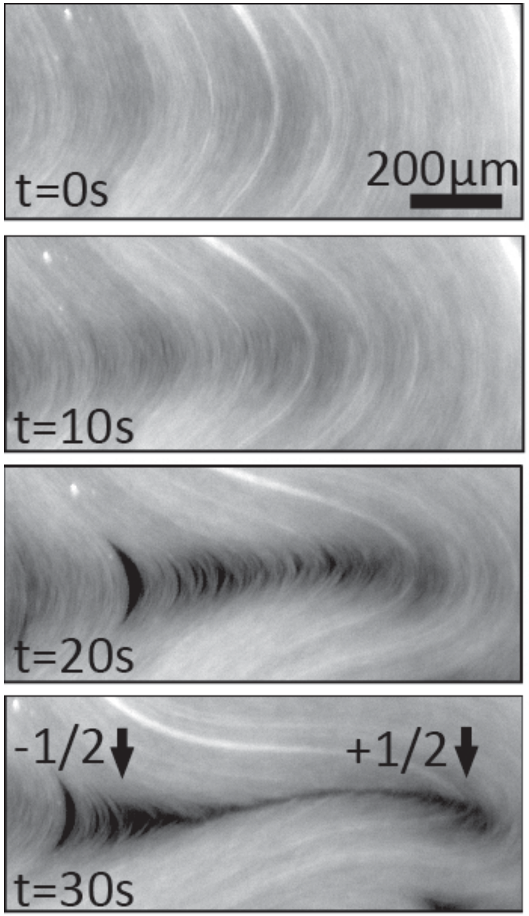


Fluorescence recovery demonstrates extensile stresses

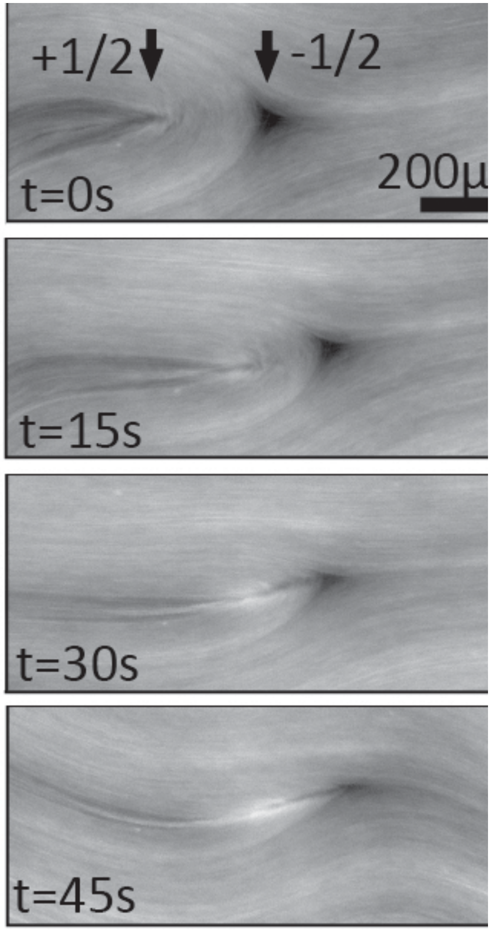


Active nematics – defect dynamics

Bend instability leads to creation of a defect pair

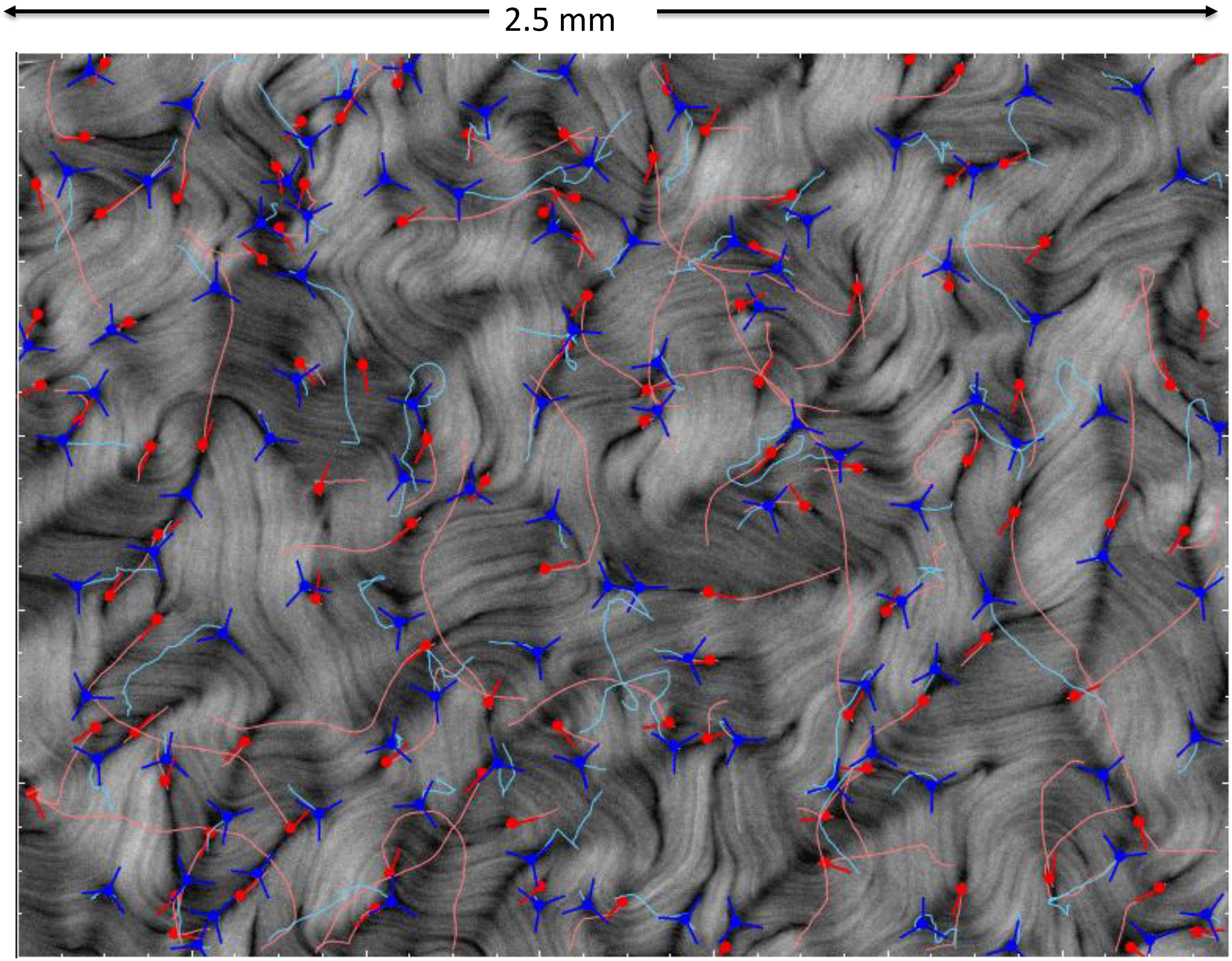


Annihilation of oppositely charged defects

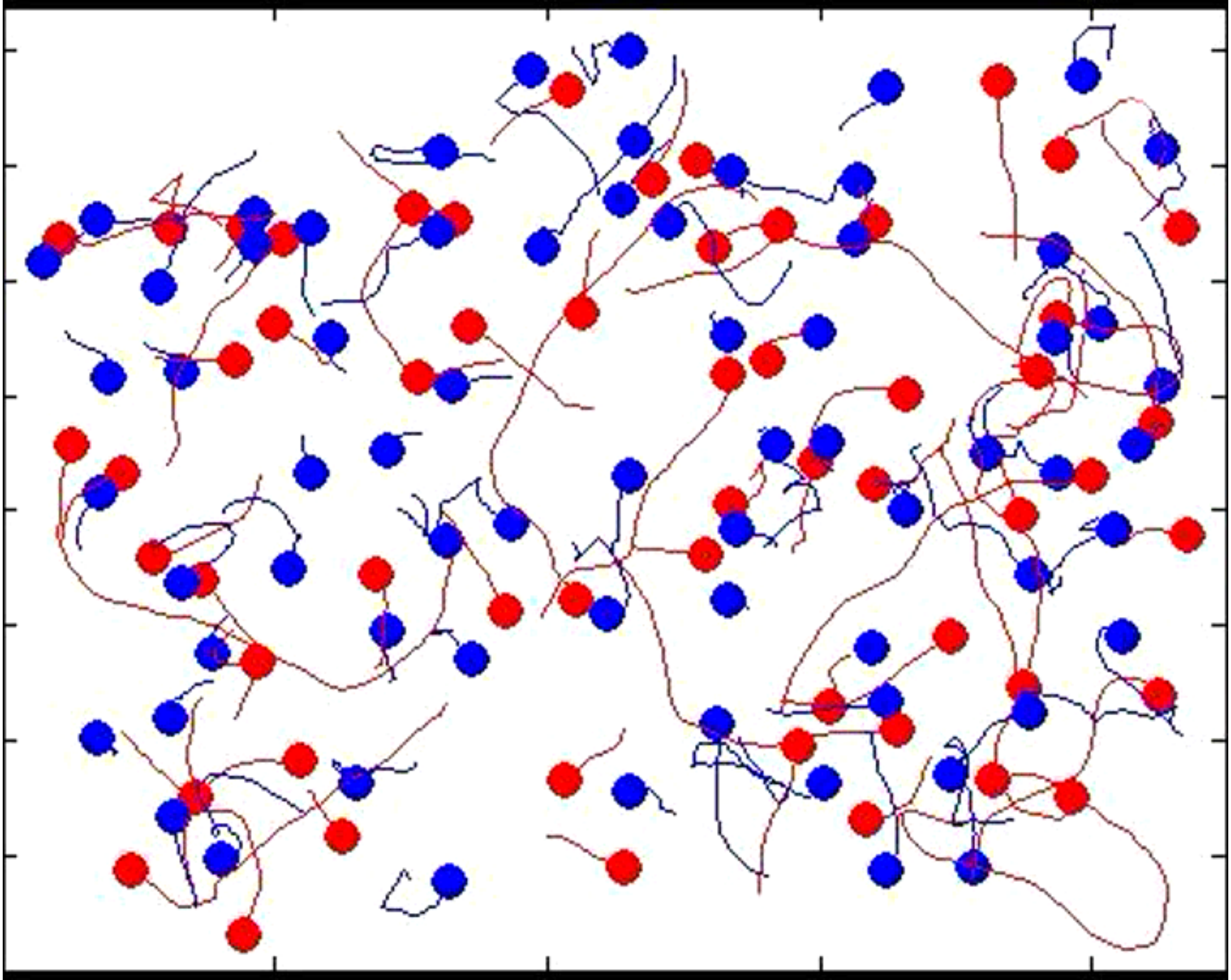


Steady state – defect creation and anihilation rates are balanced

Active nematics do not exist due to inherent bend instability!

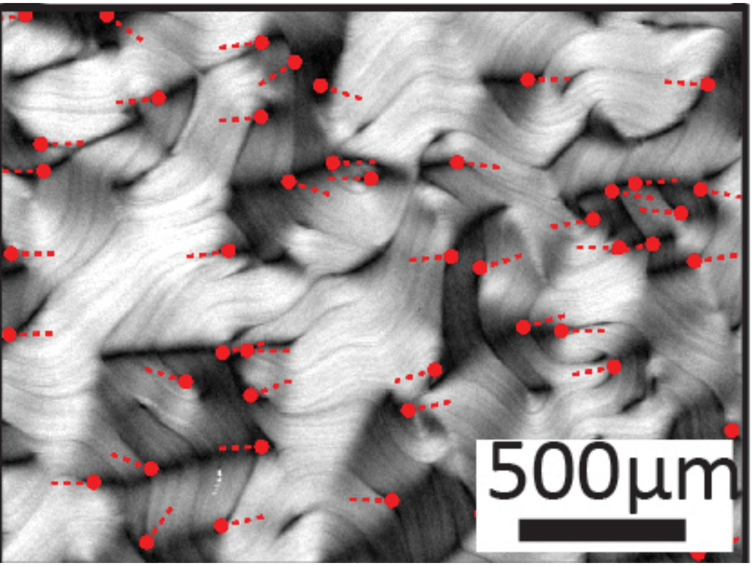


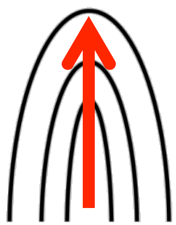
steady-state rate of defect creation and annihilation



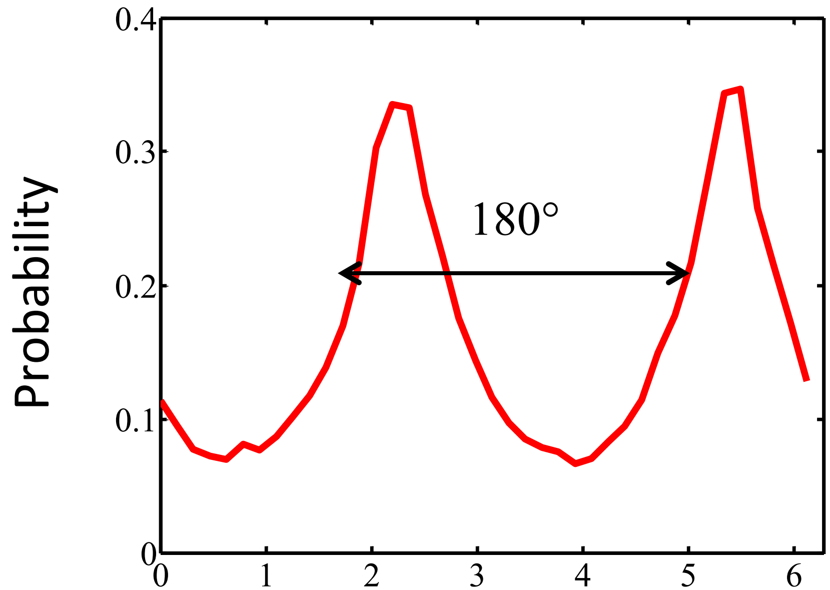
Anisotropic distribution of defect orientation

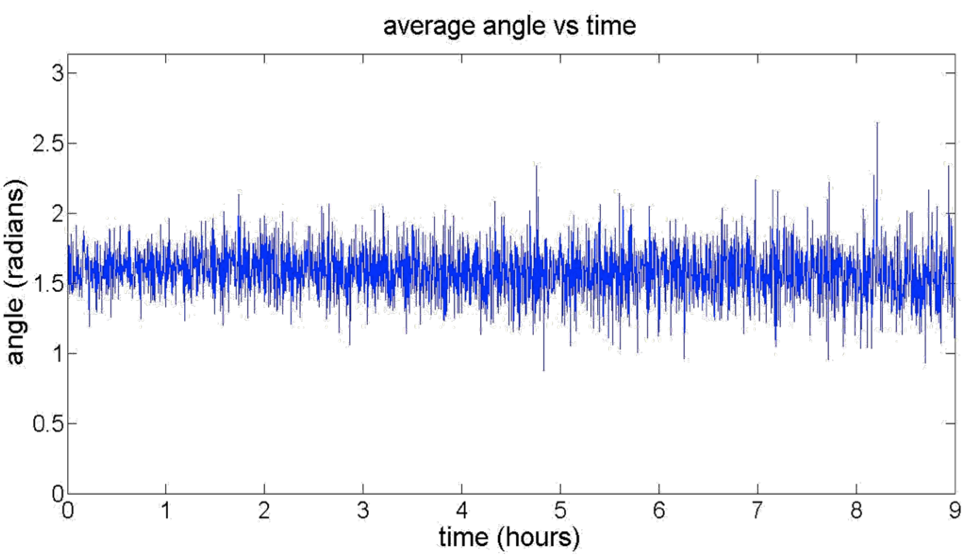
Retardance Image





Orientational probability distribution

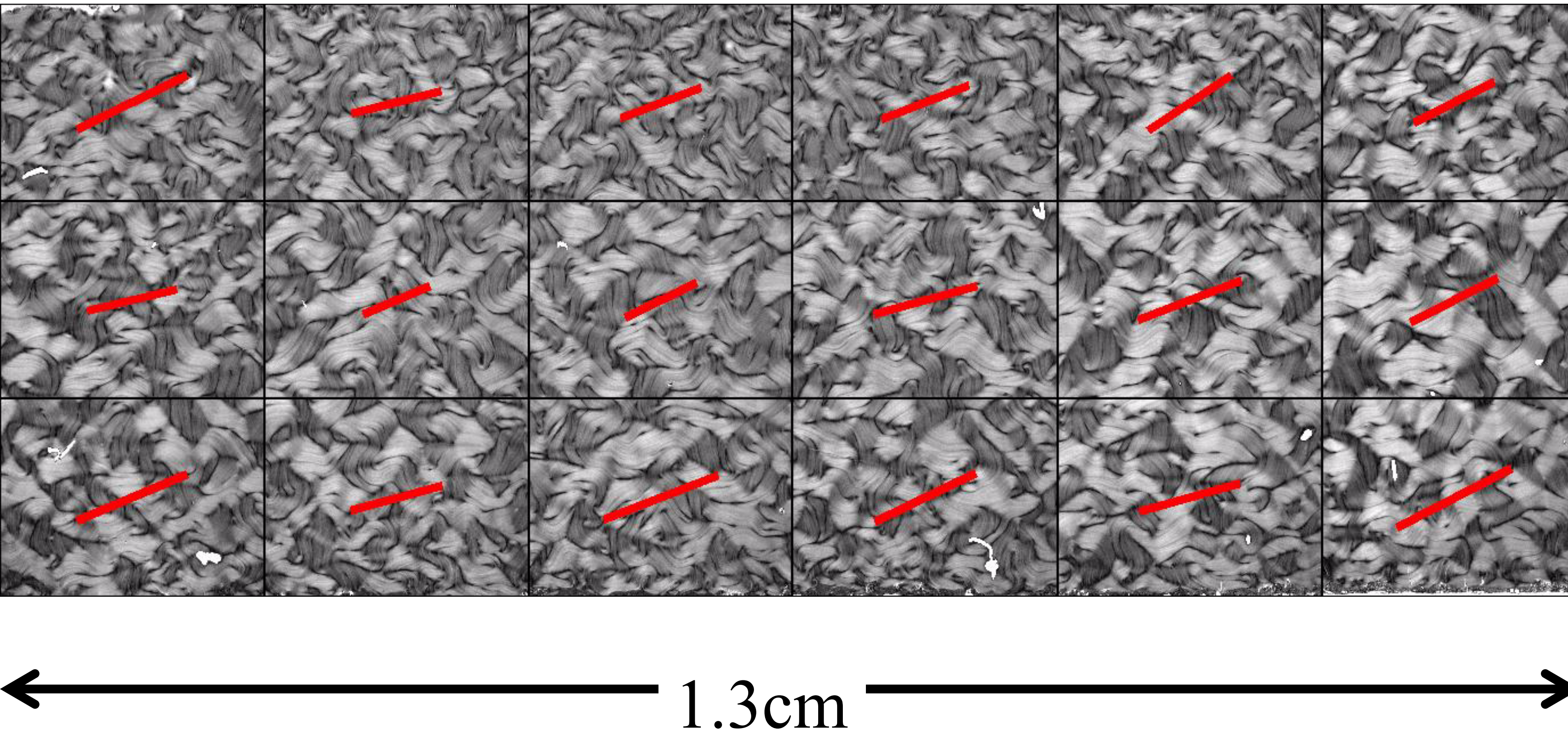




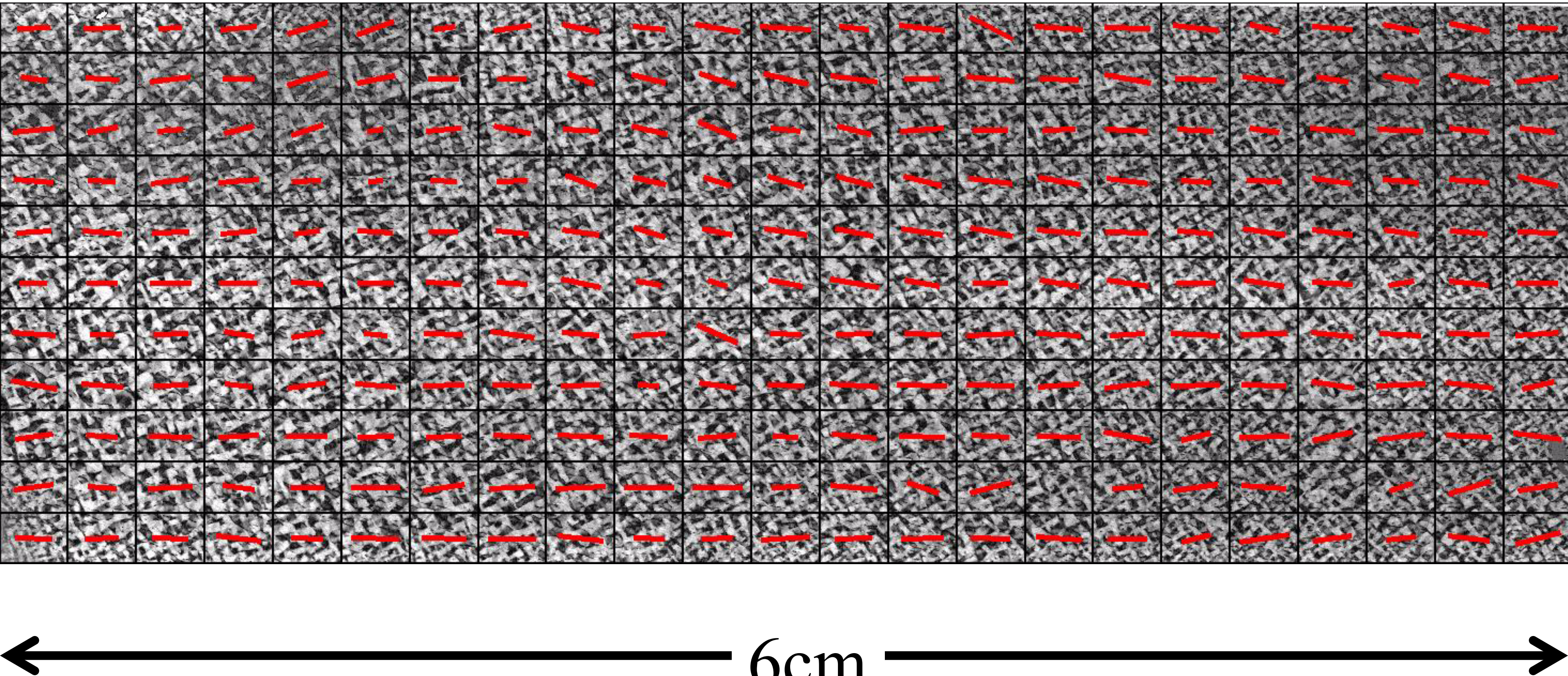
Defects are equality likely to point up or down (nematic symmetry)

Alignment direction persists for hours even though defect lifetime is tens of seconds!

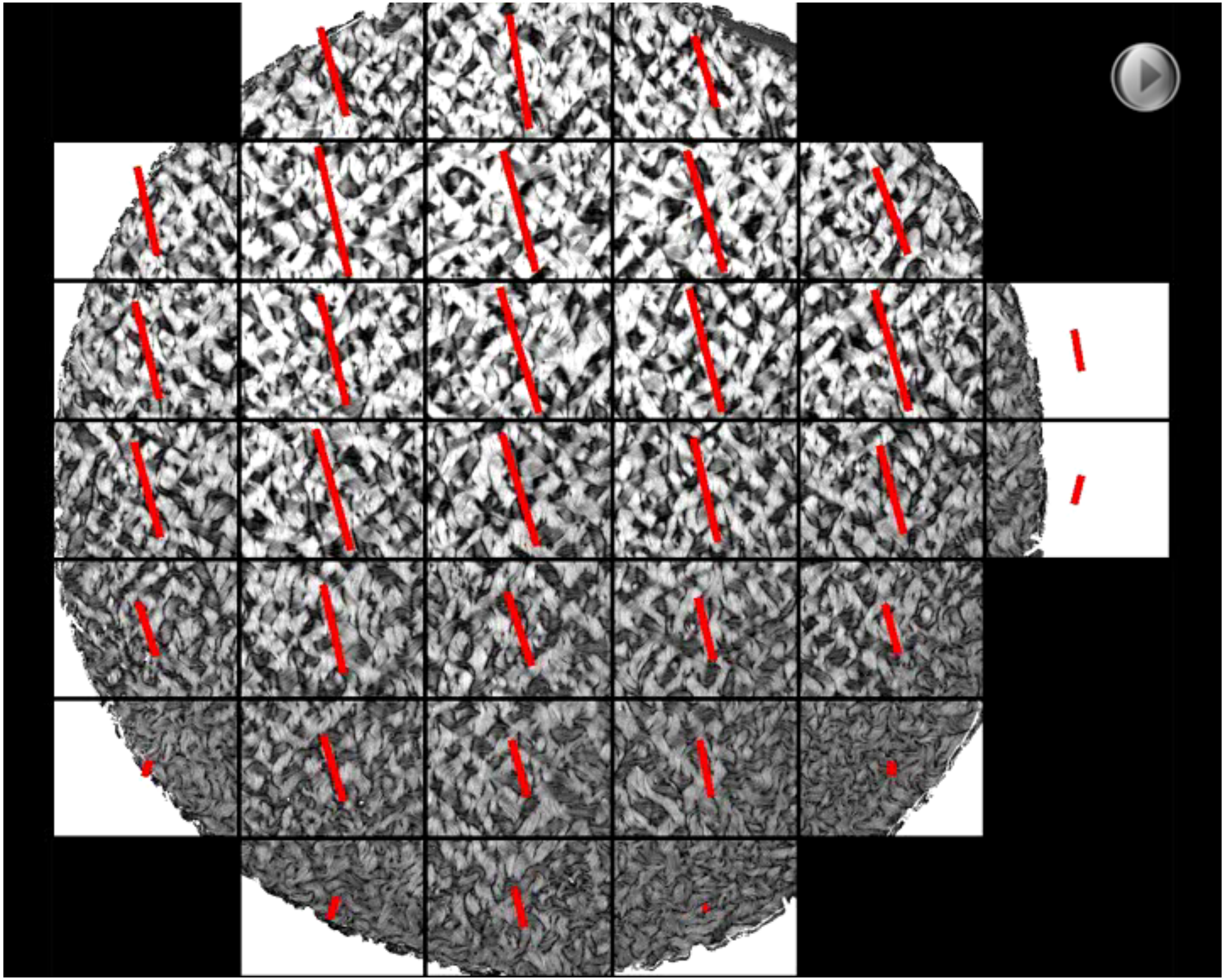
Orientation persists over large distance



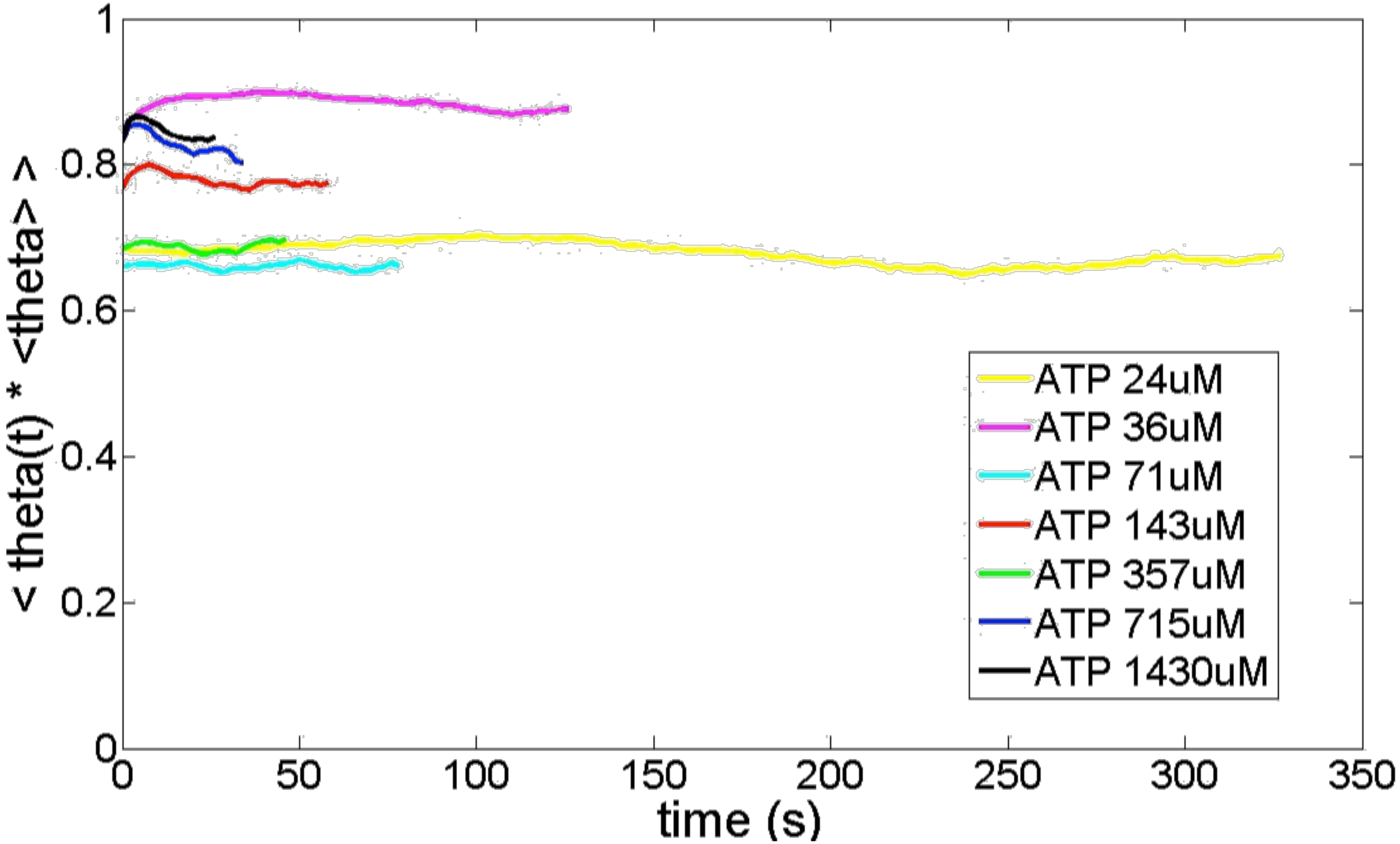
Long range order in active nematics



No anchoring to the walls

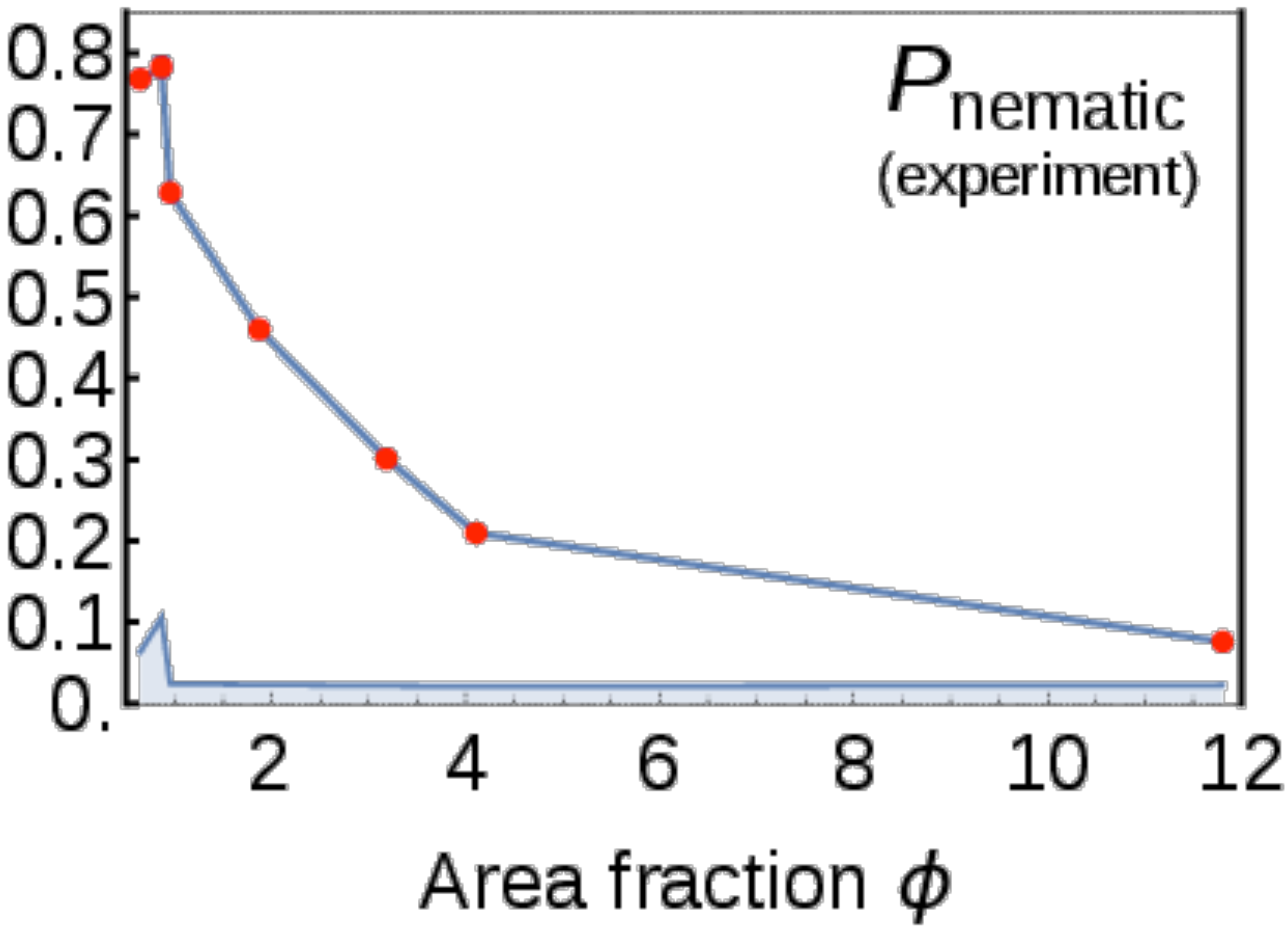


Defect orientation does not depend on the defect age



Defect orientational order parameter

nematic layer thickness controls far-from-equilibrium isotropic-nematic phase transition of defect orientation



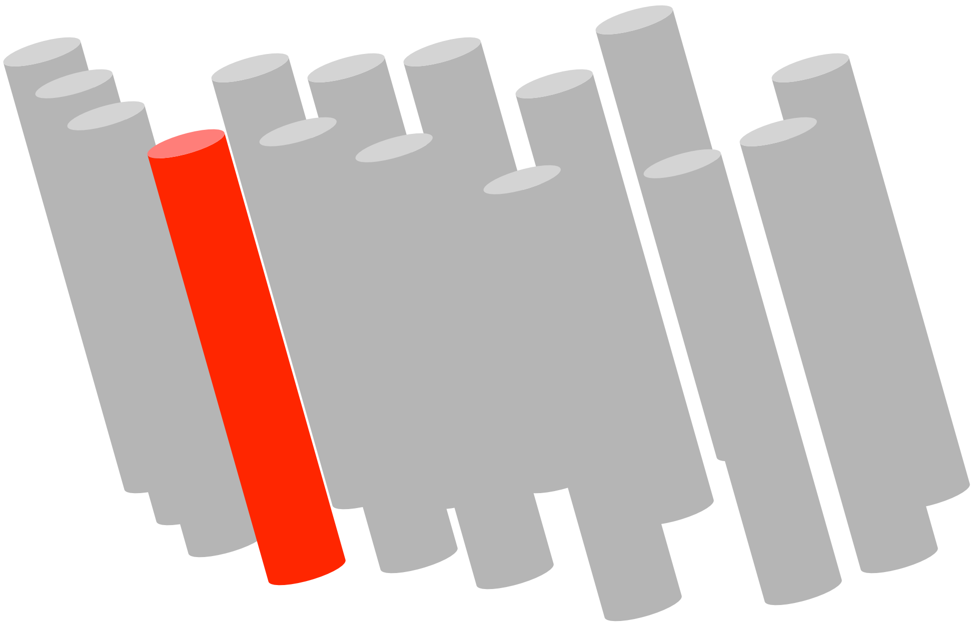
Flows in the Active Nematic

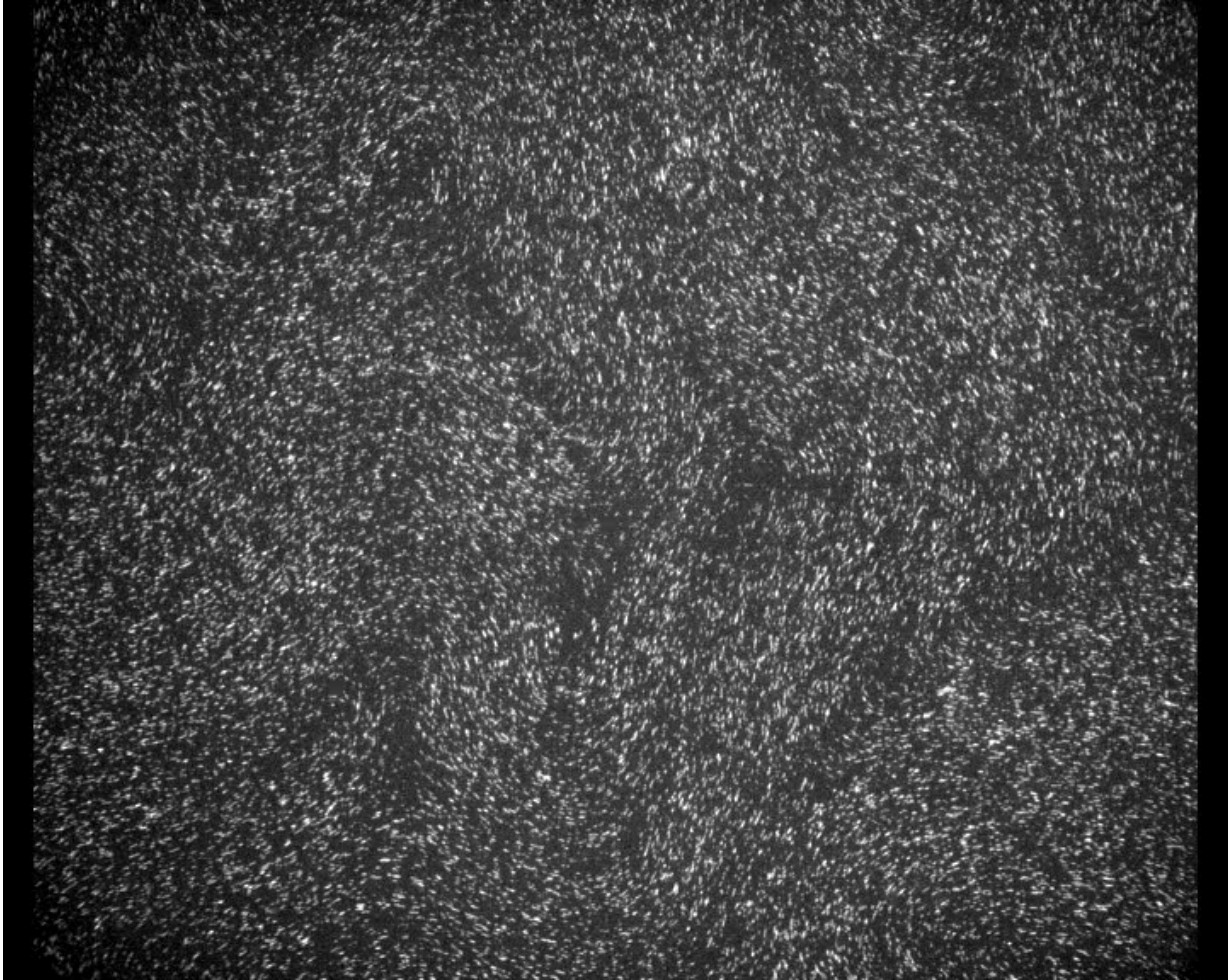
MTs Moving within the Nematic

Fluid above the nematic

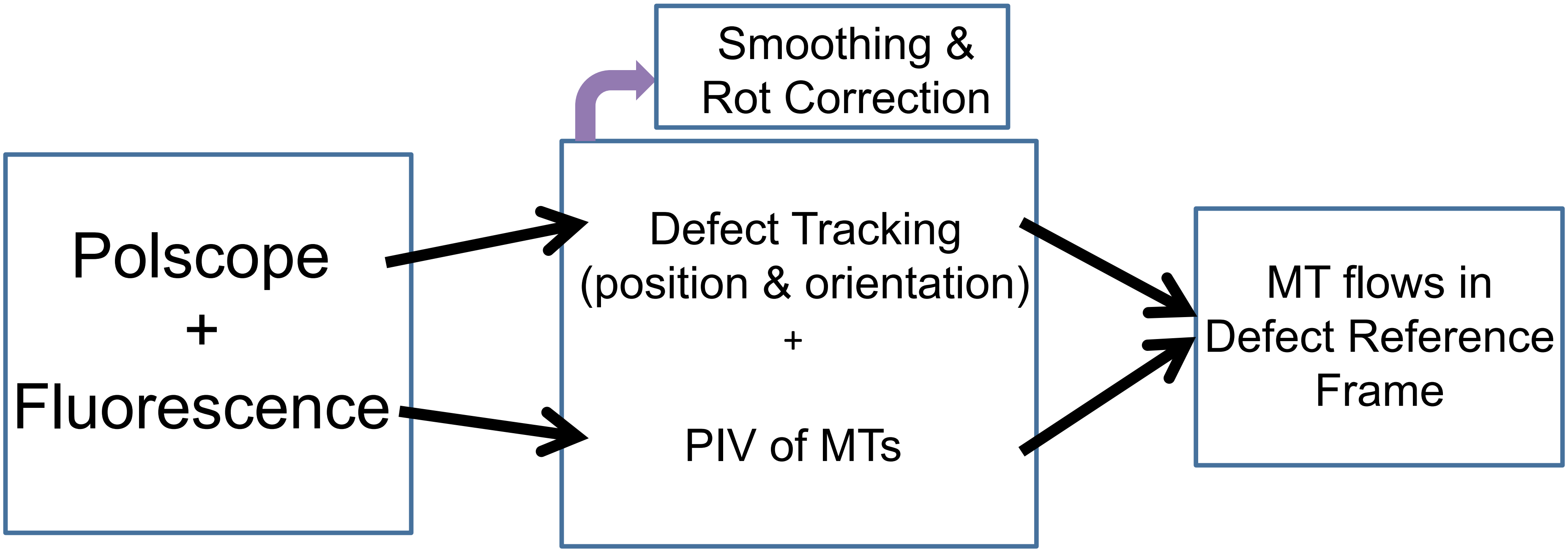
Approach

- Label 1 out of 10,000 MT filaments
- Track how single MTs move in the nematic

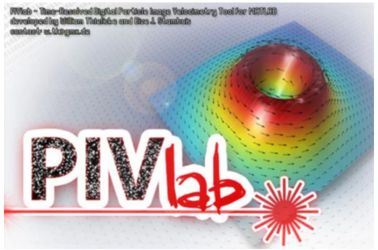


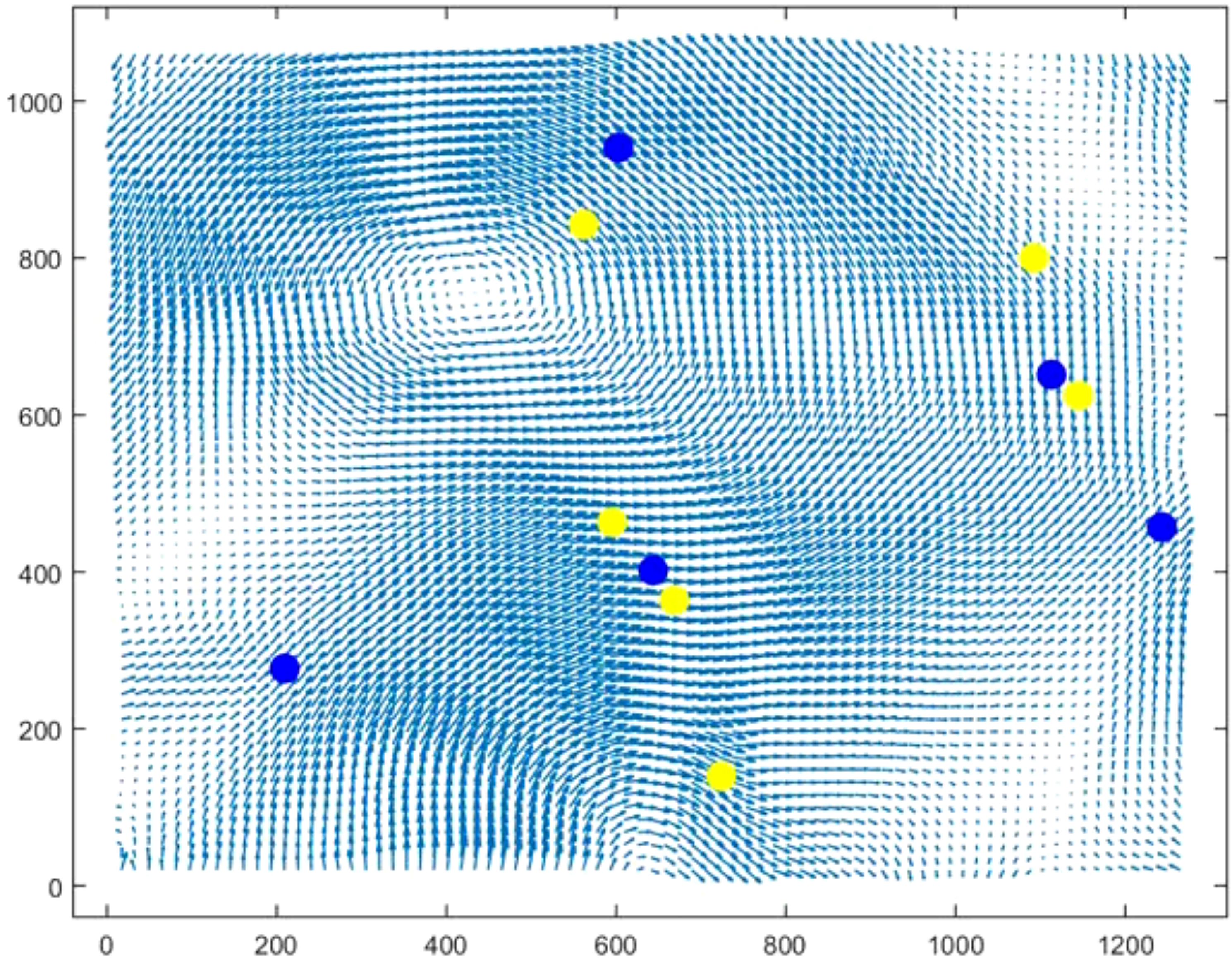


Processing Method



PIV = Particle Image Velocimetry (shows flows)

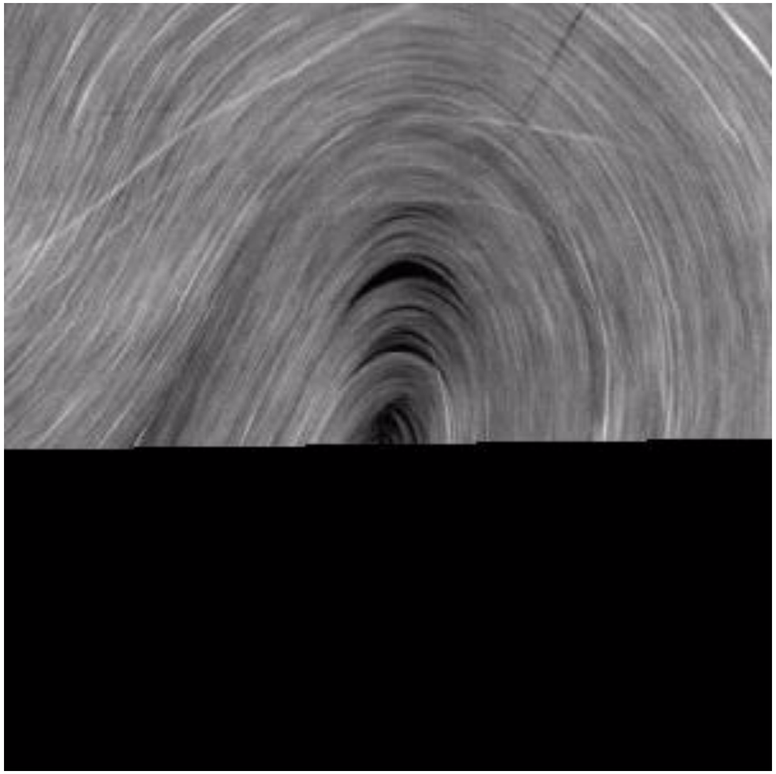




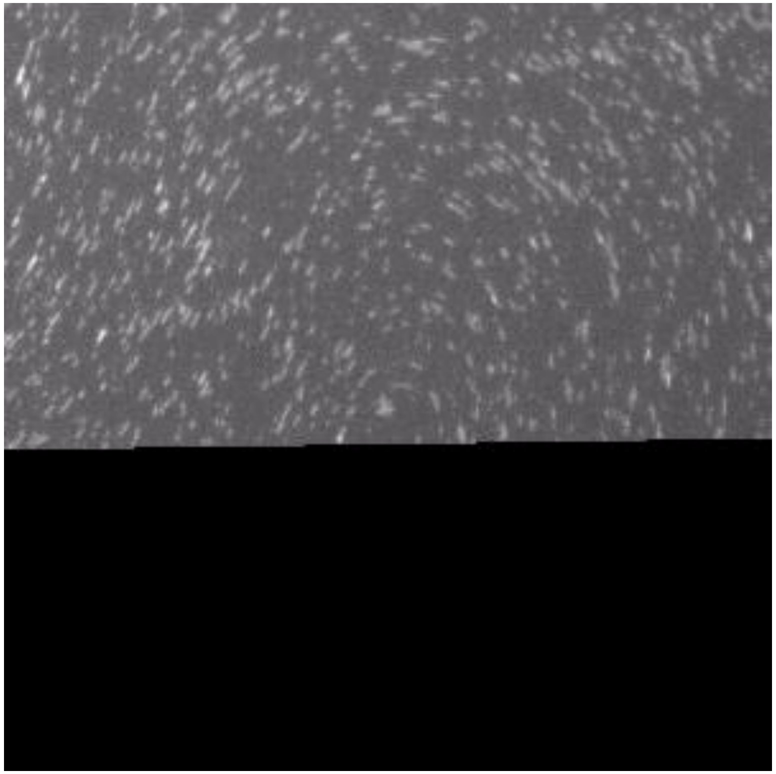
+1/2

-1/2

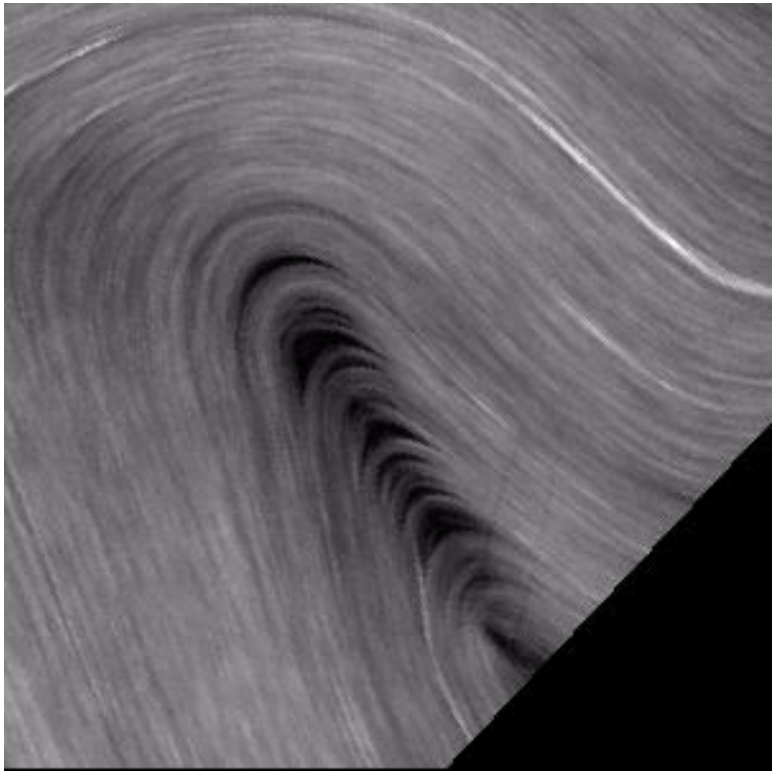
In the +1/2 Defect Reference Frame



Retardance Map



Fluorescence Image



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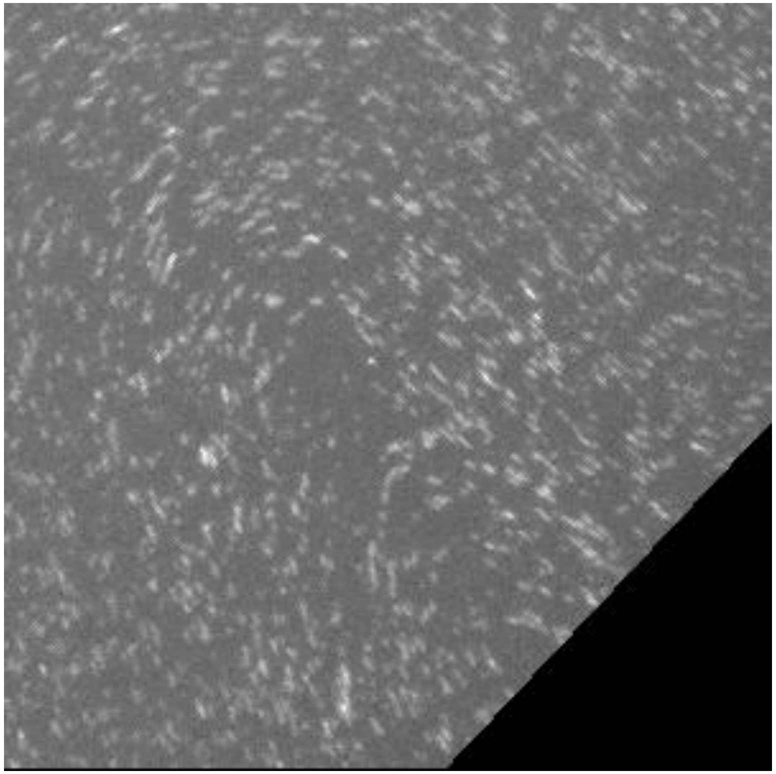
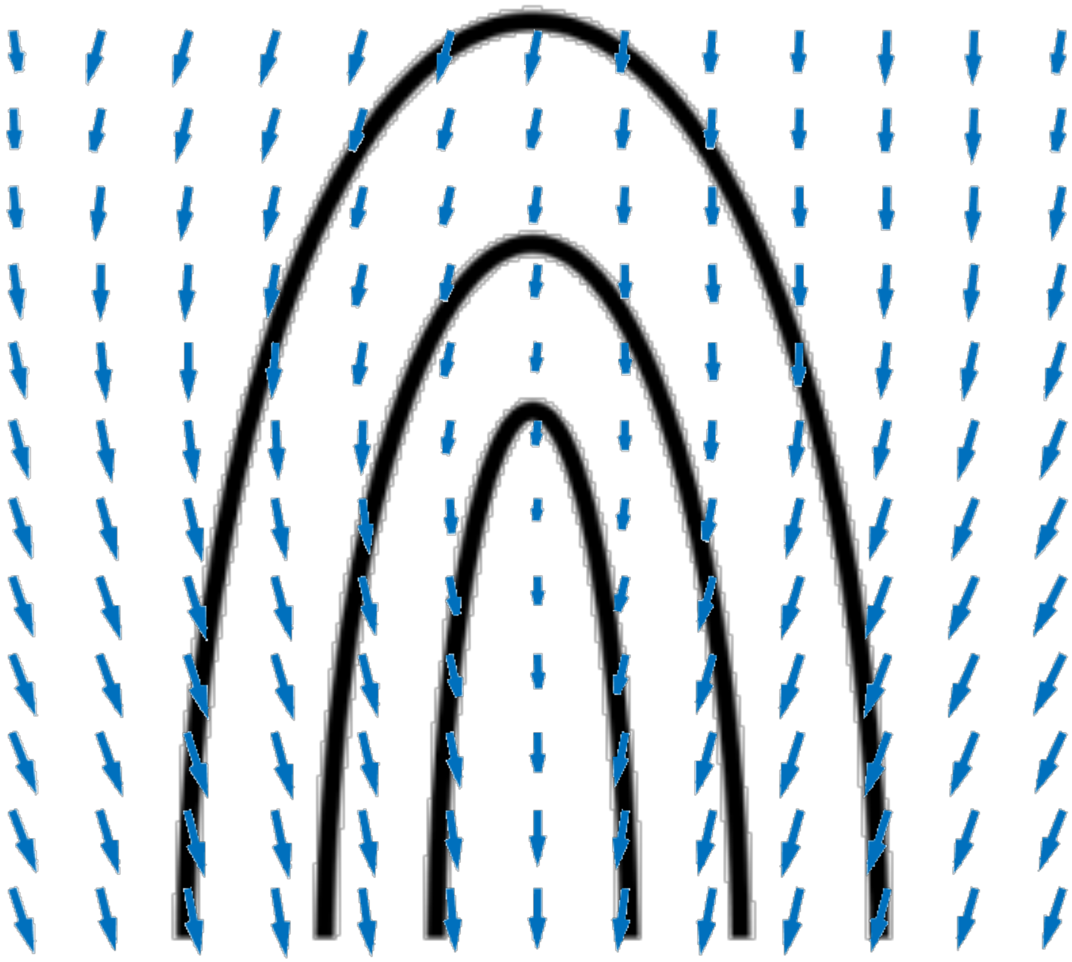
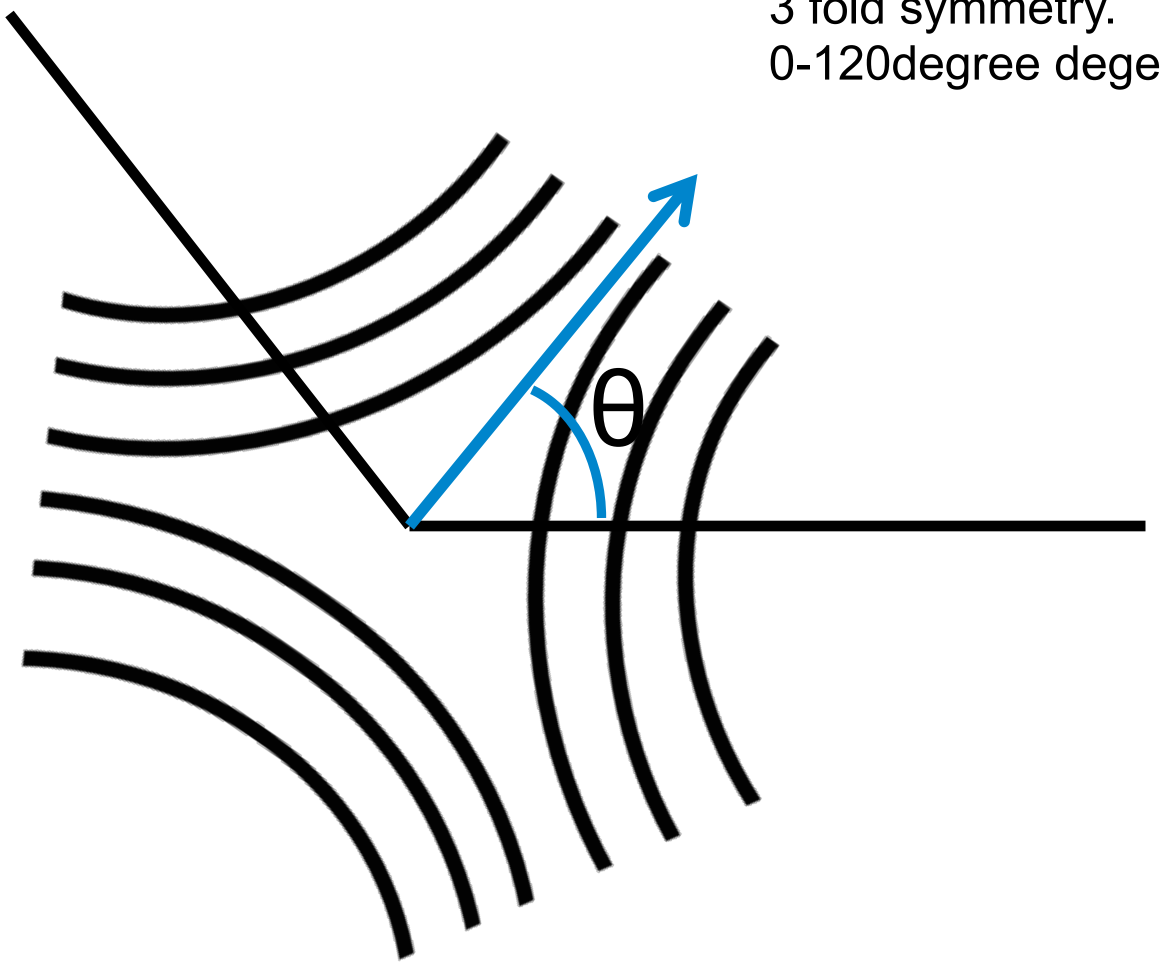


Fluorescence Image

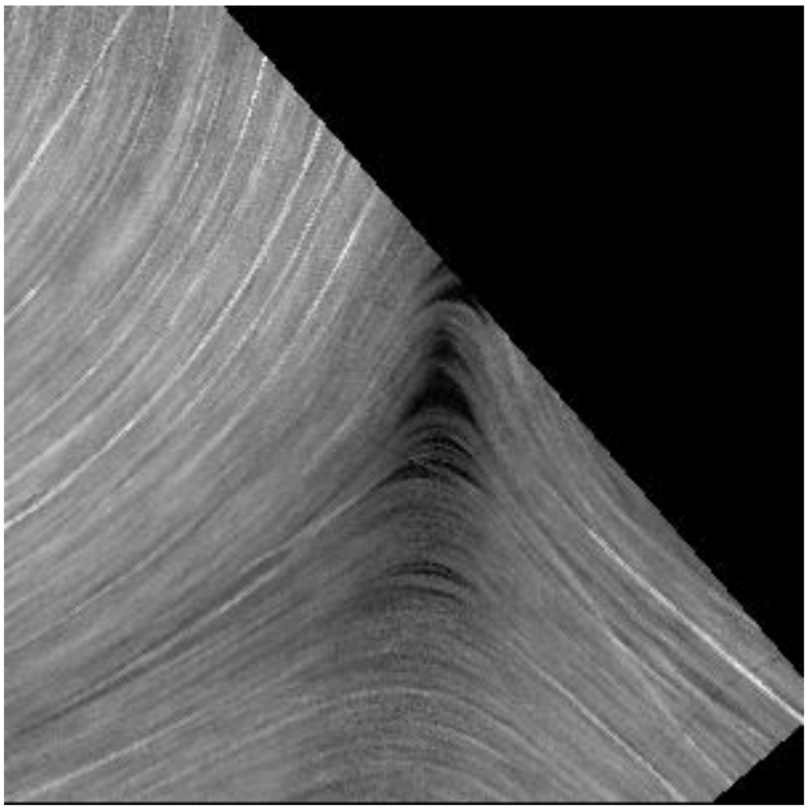
+1/2 Flow Field



In Defect Reference Frame



3 fold symmetry.
0-120degree degeneracy.



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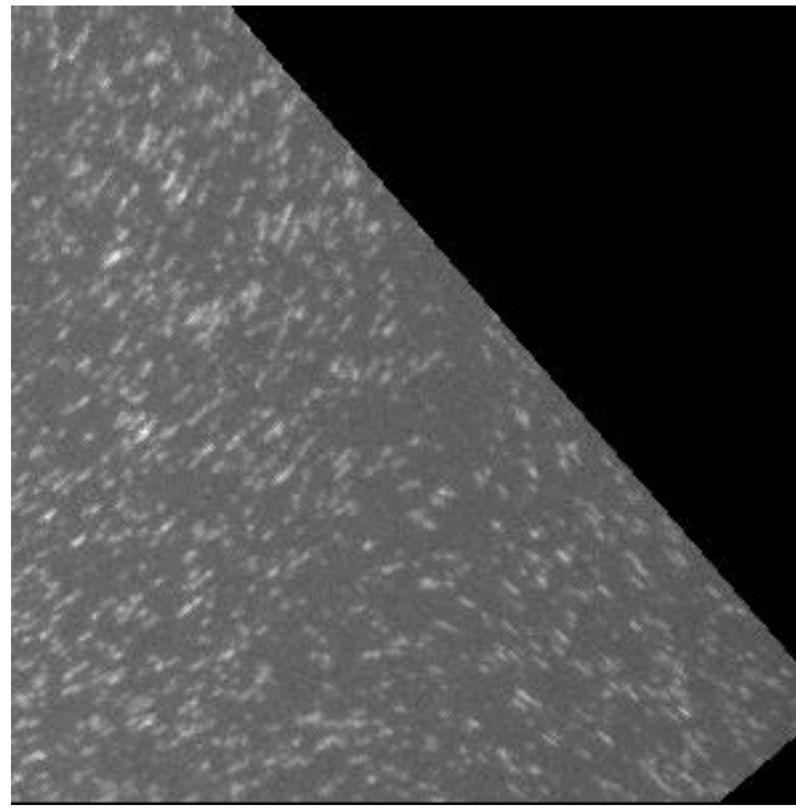
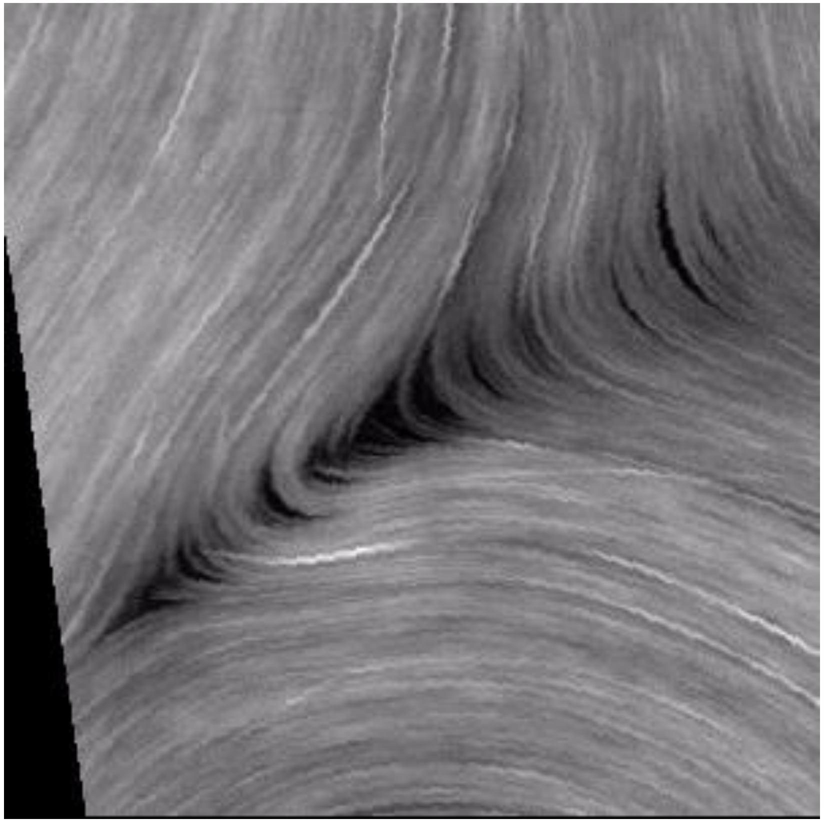


Fluorescence Image



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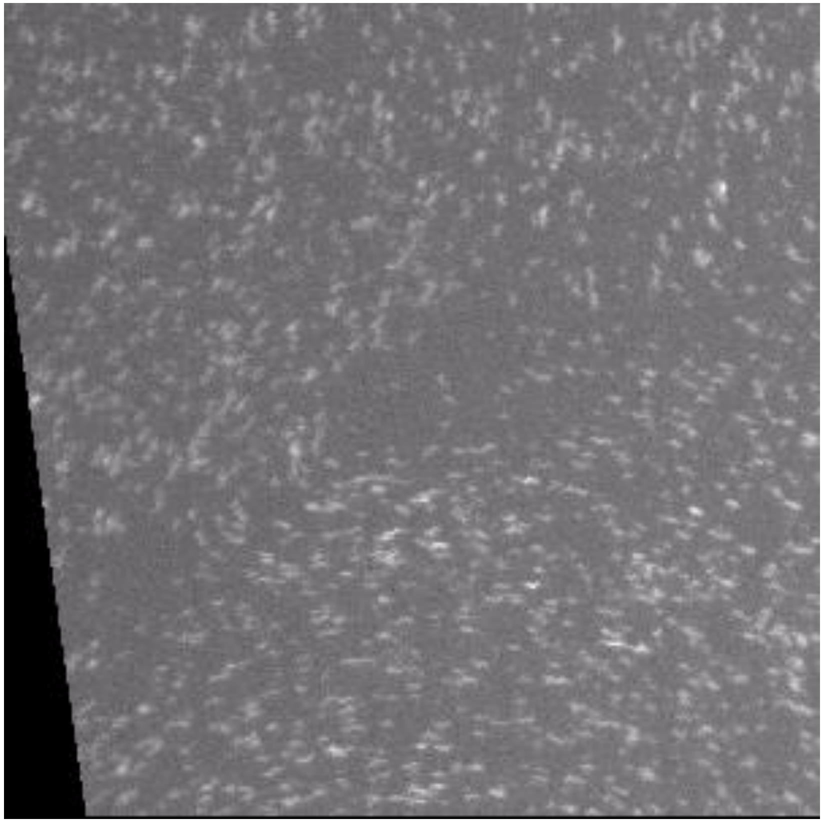
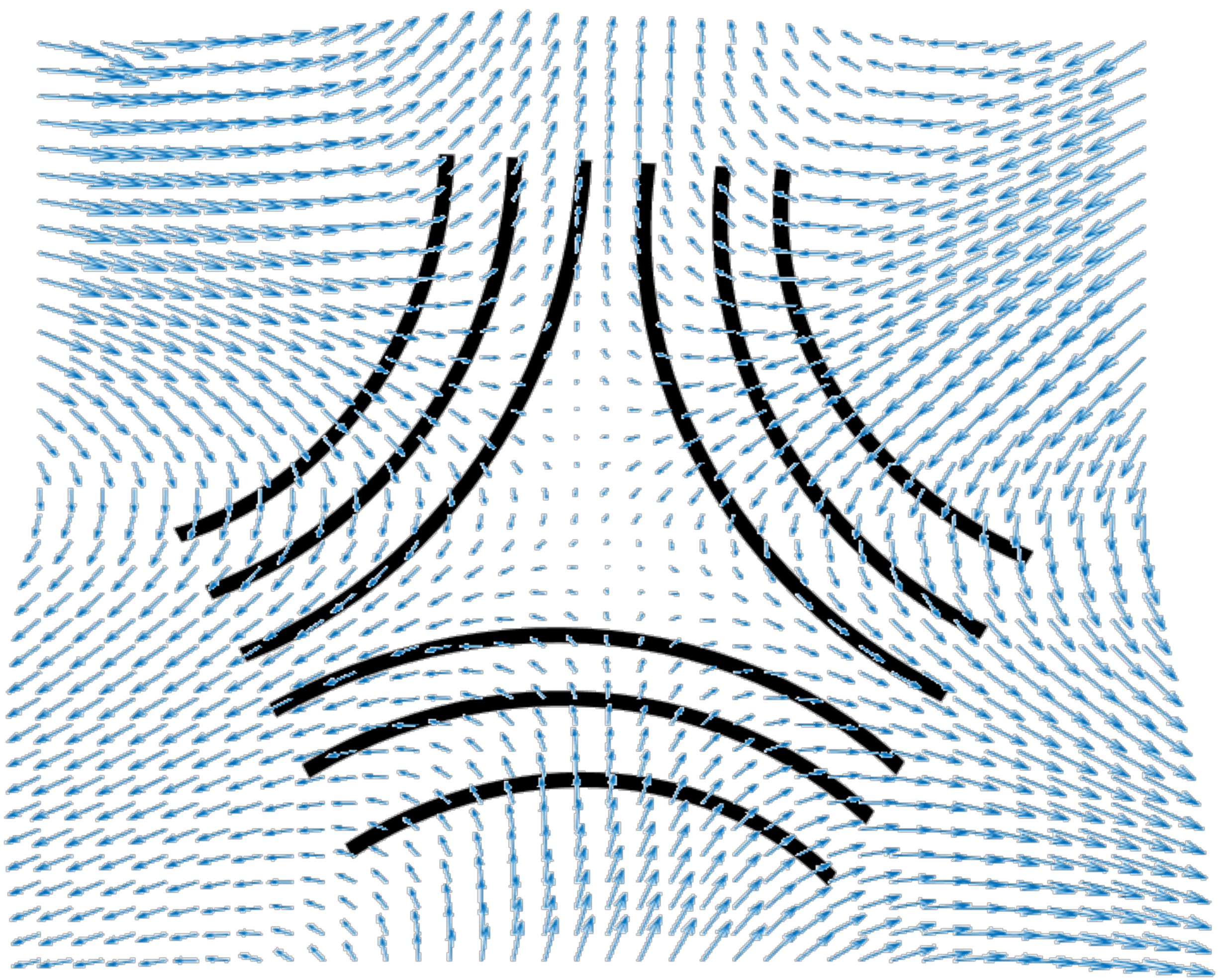
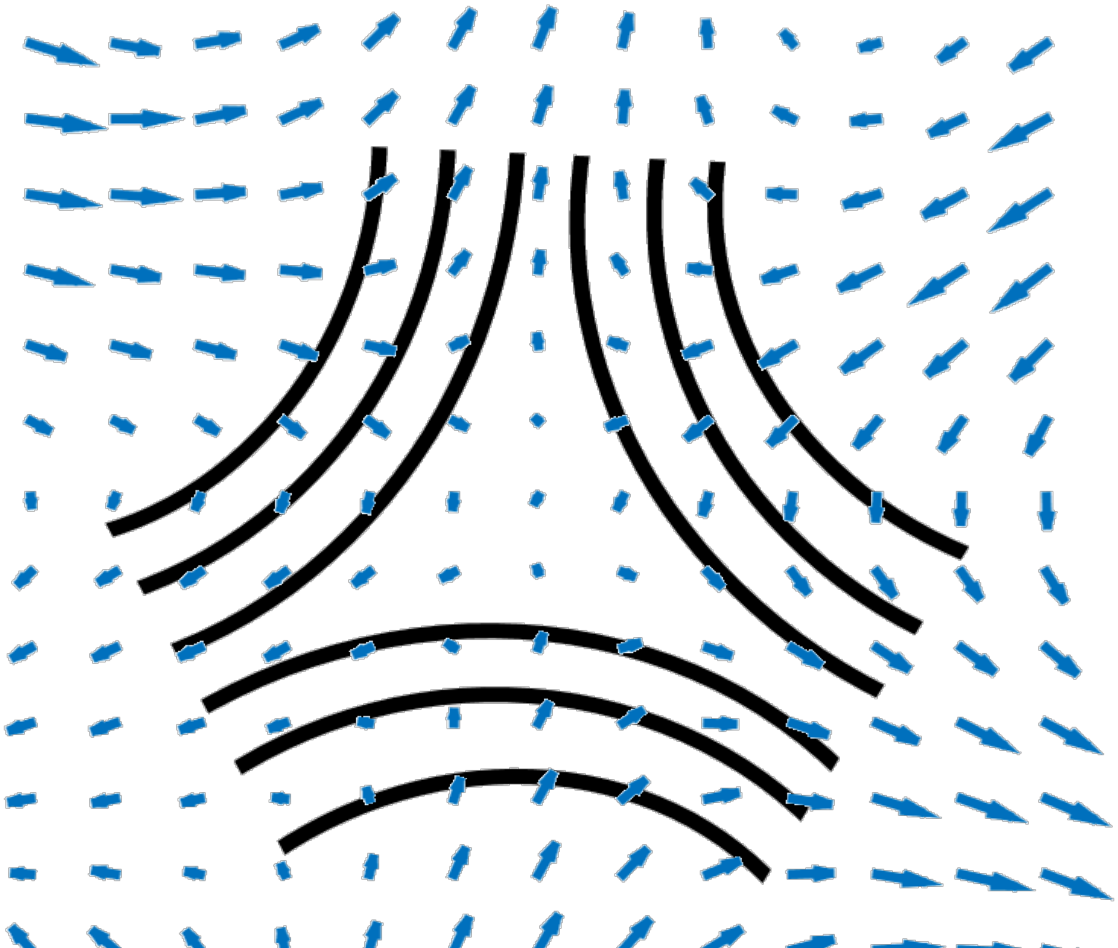


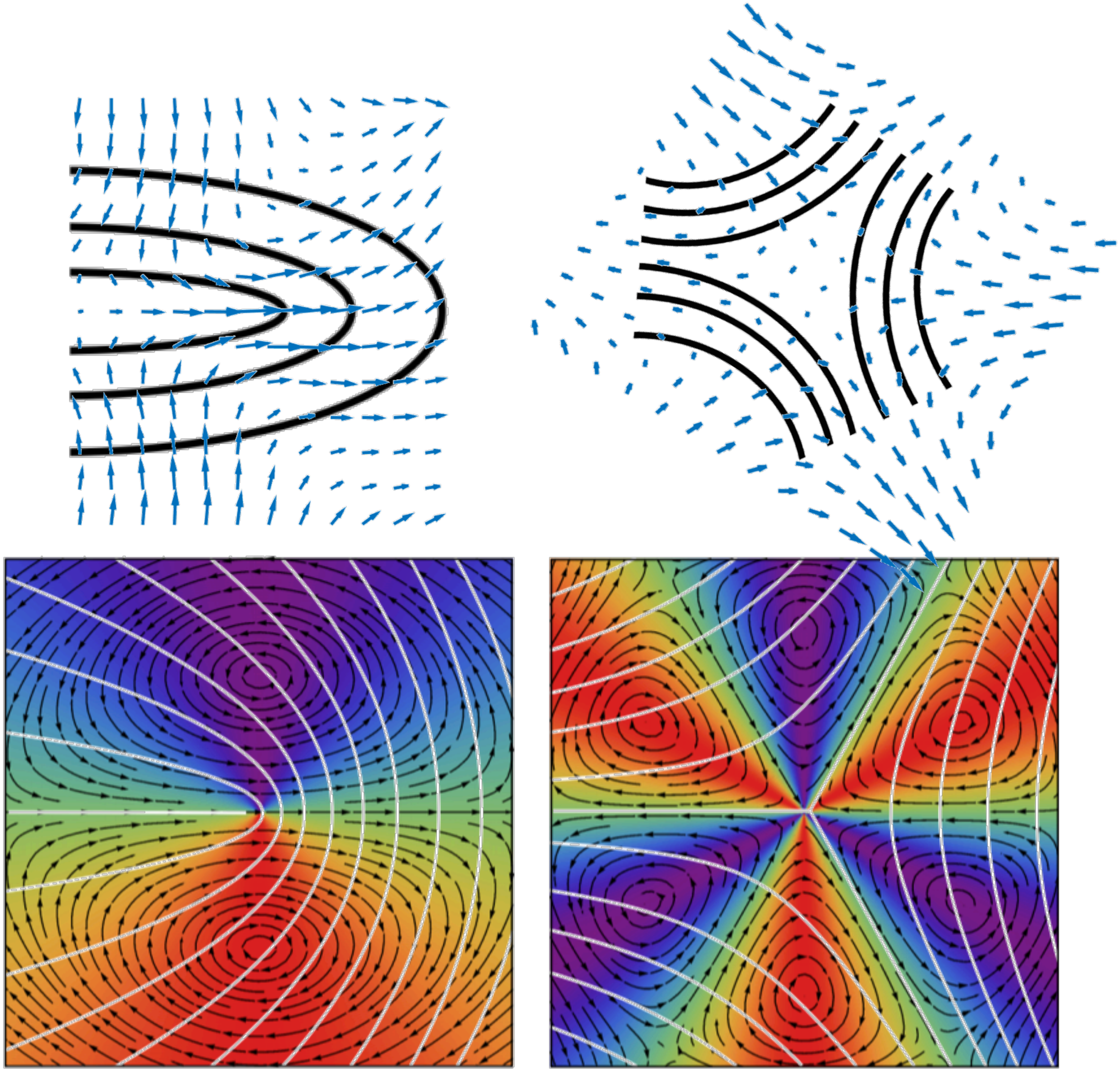
Fluorescence Image

-1/2 Flow Field



-1/2 Flow Field

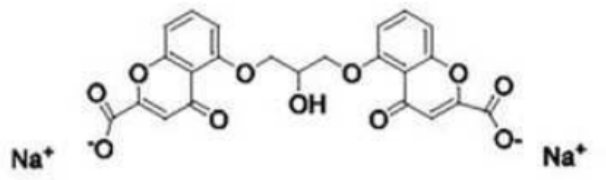




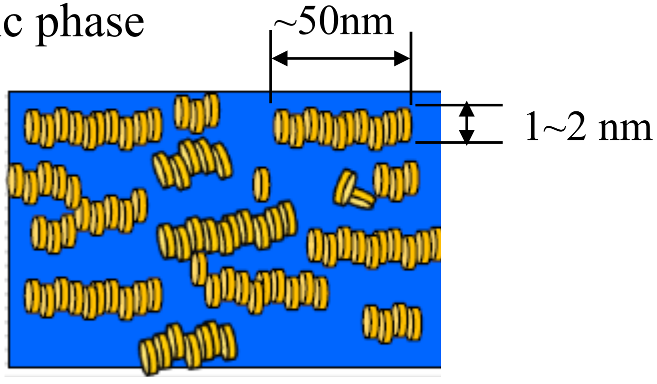
Luca Giomi – arXiv:1409.1555v1

Living liquid crystals = chromonic liquid crystals + swimming bacteria

Chromonic liquid crystal:
Disodium Cromoglycate (DSCG)

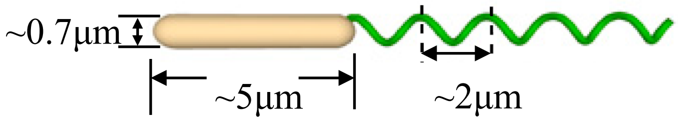


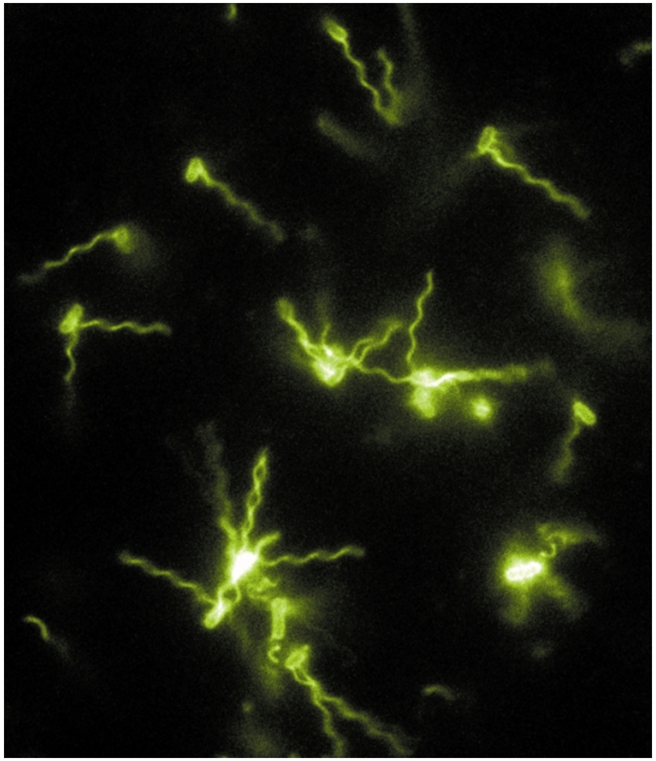
Nematic phase



$\hat{\mathbf{n}}$: director

Bacillus subtilis





Planar cell, high bacteria concentration

P

A

$v_{initial}$ ↓↑

n ↕

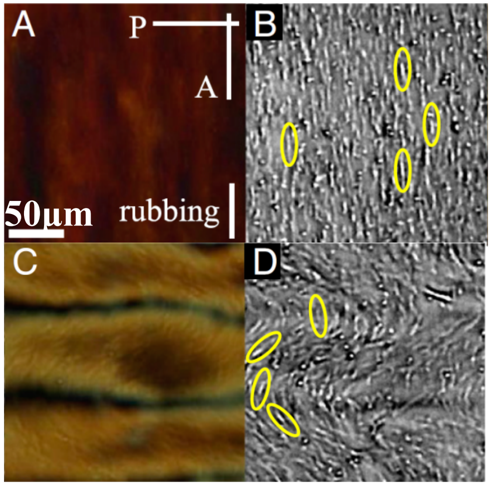
Play speed: 100x

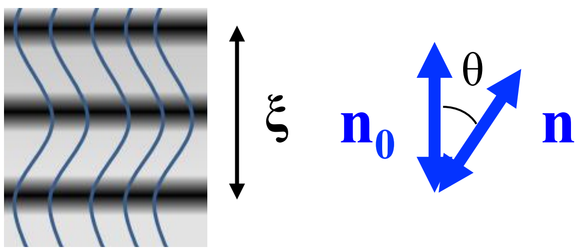
PNAS 111, 1265–1270 (2014)

Origin of modulation

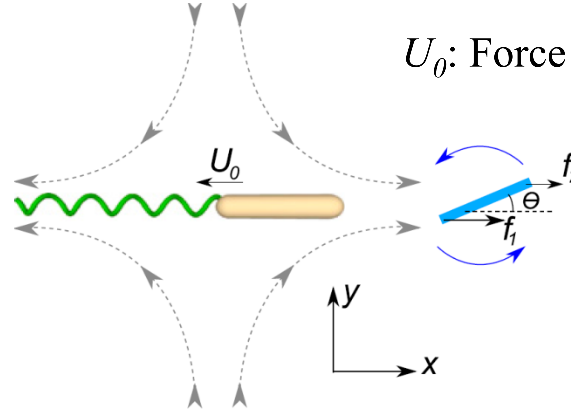
inactive

active



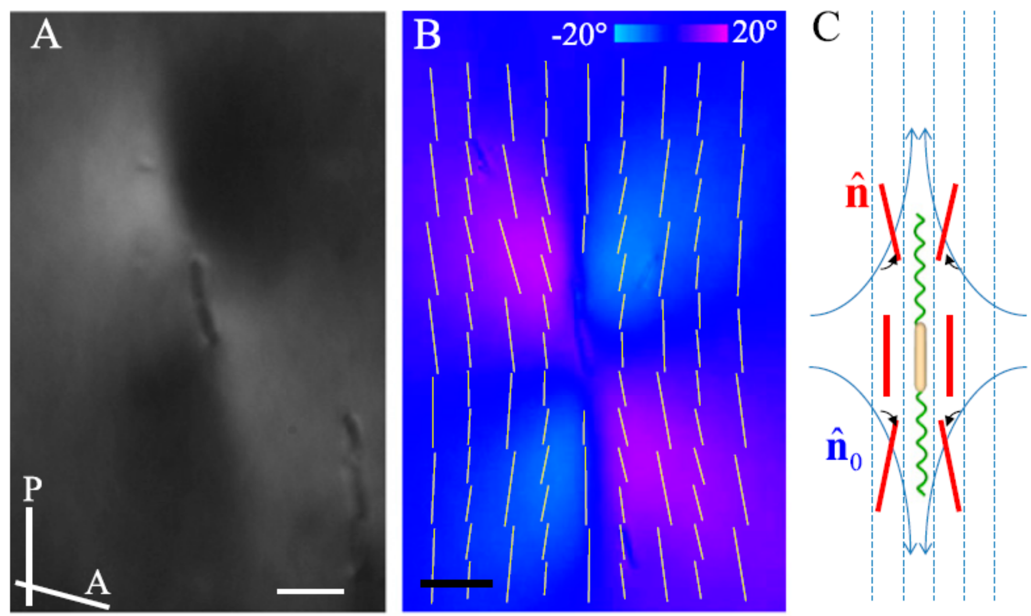


Bacterial flow → shear stress→ director distortion



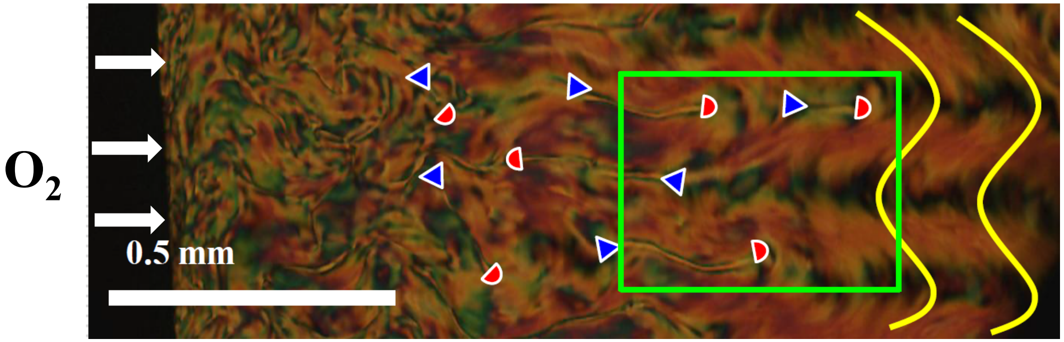
U_0: Force dipole ~1pN μm

Director distortion by a double-headed bacterium



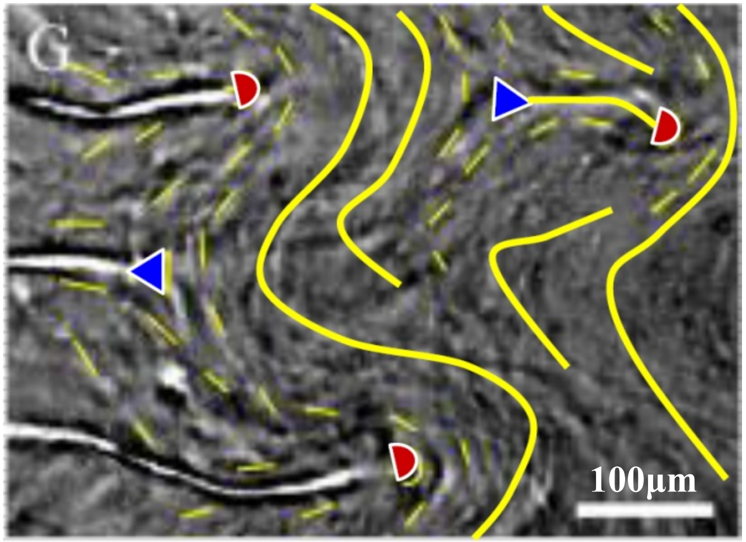
Simha and Ramaswamy, PRL (2002)

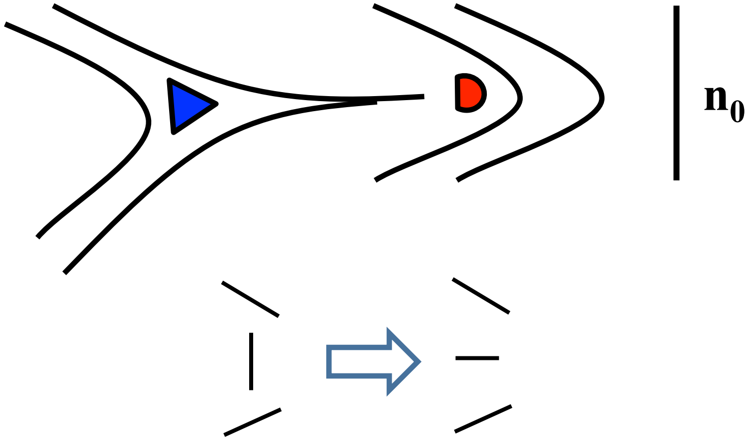
Walls replaced by disclination pairs



Nucleation of disclination pairs

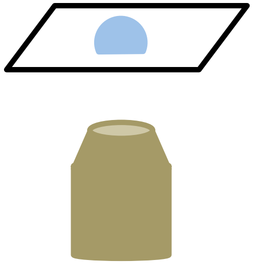
Director within the pair realigned by 90˚ w.r.t. the original director

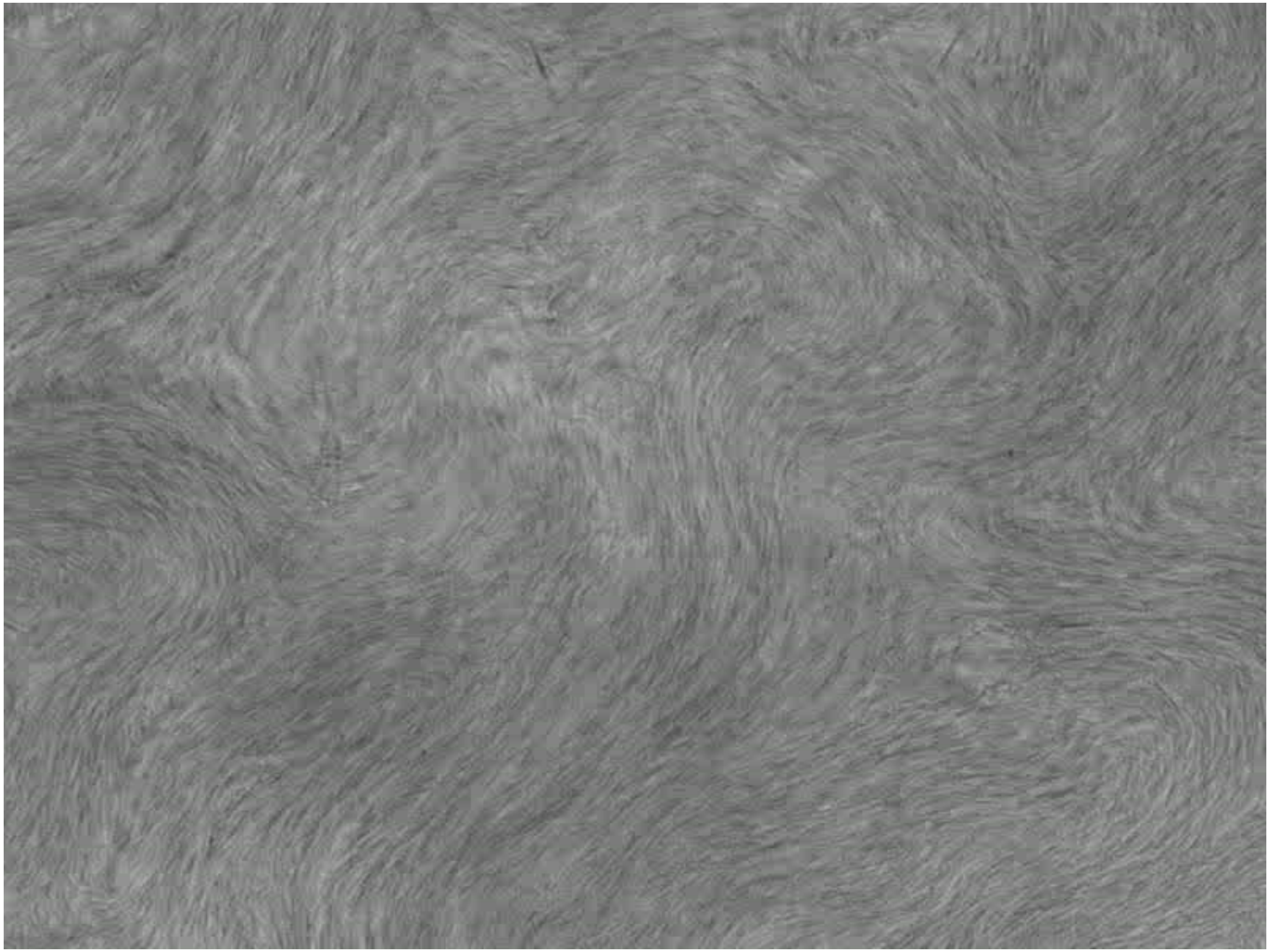




Collective motion in a sessile drop: creating and annihilation of topological defects

Topological turbulence of ± disclinations at low Reynolds number.
Bacteria concentration ≈ 1/10 concentration as compare to in water





Outline

1. **building blocks of microtubule based active matter**

2. **planar active nematic**

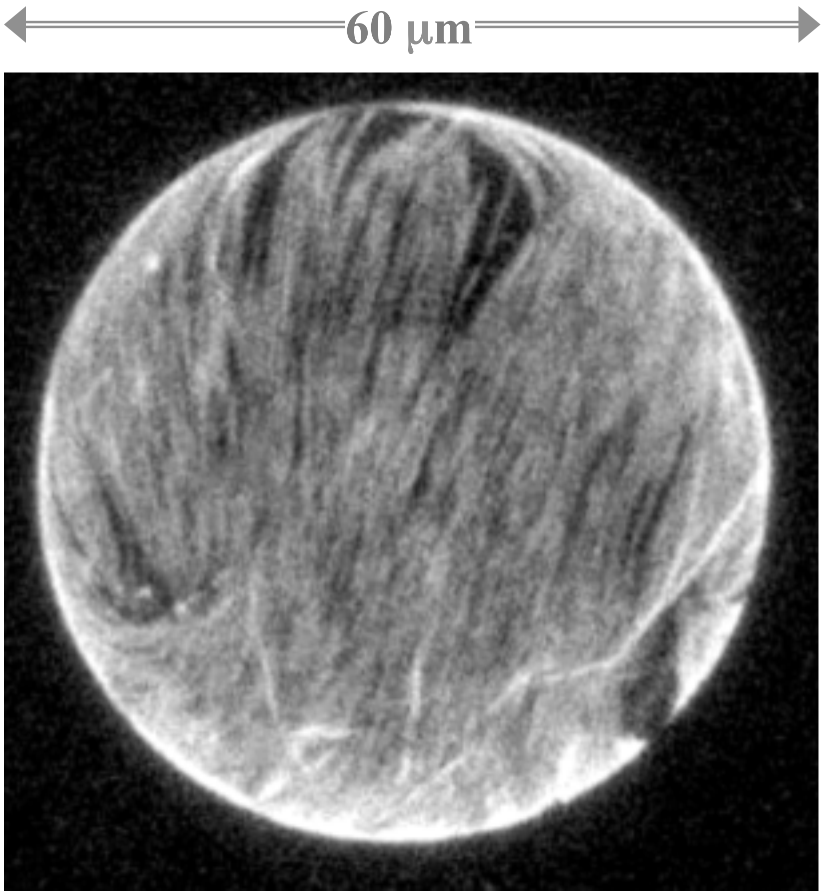
   dynamical flowing state characterized by spontaneous defect generation and annihilation

   bend instability locally destroys nematic order generating defects

   on larger scales anisotropic defect interactions recover long-range nematic order

3. **Confined active nematics**

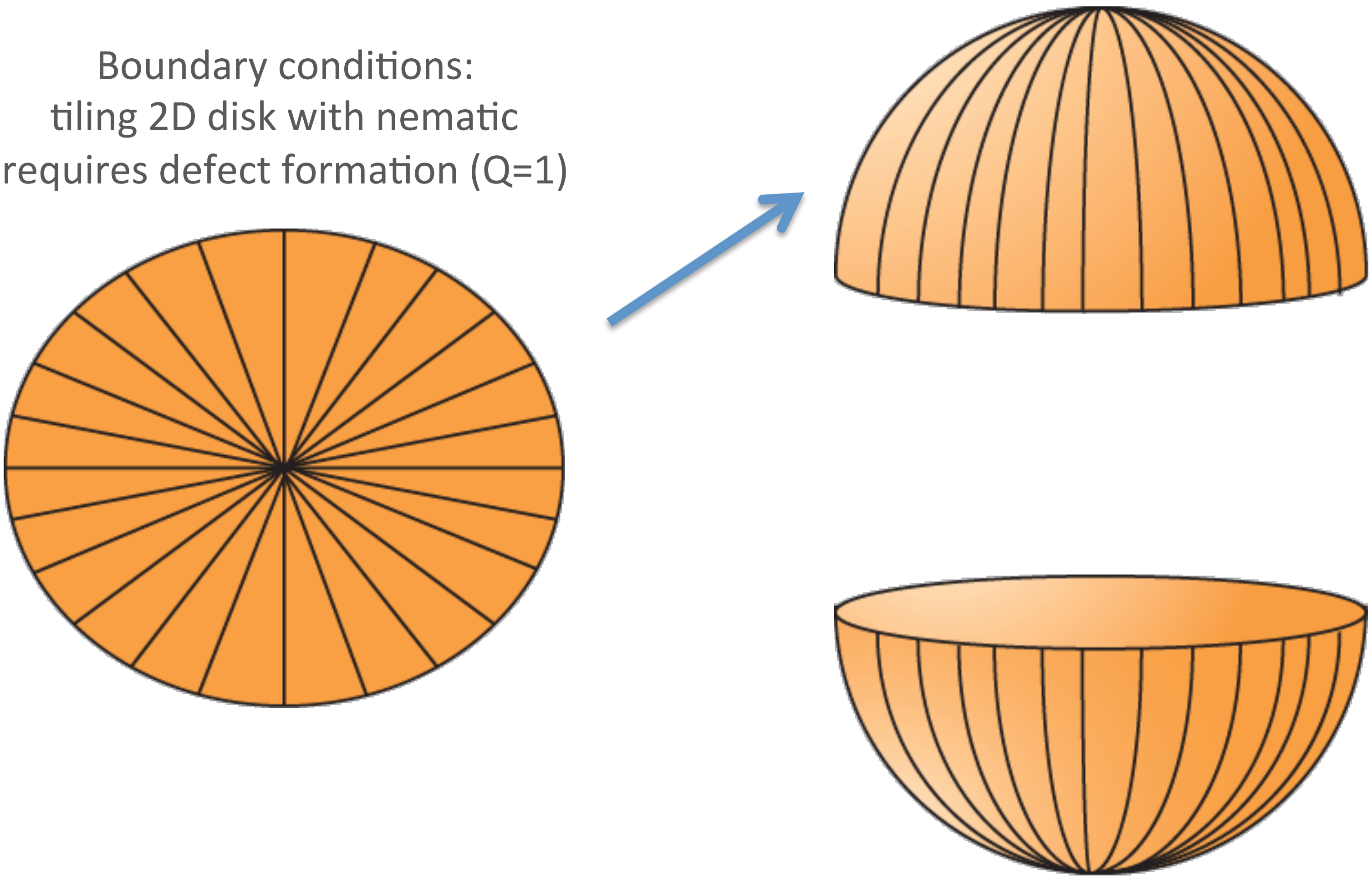
Active isotropic gels confined in vesicles



Microtubule bundles form a thin cortex comprised of aligned microtubules

Mathematics: "You can't comb a hairy ball"

Boundary conditions:
tiling 2D disk with nematic
requires defect formation (Q=1)

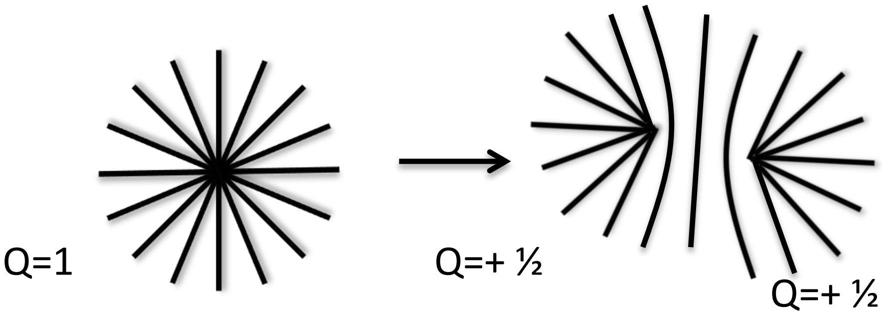


tiling a sphere with generate defects whose total topological charge Q=2

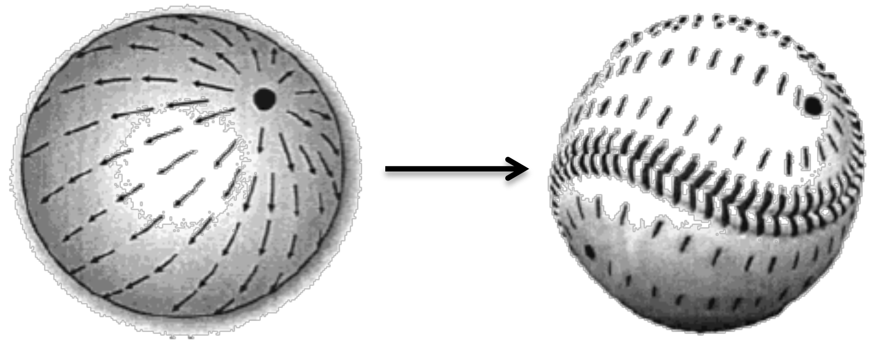
Equilibrium spherical nematics minimize elastic energy

Theoretical predictions

Q=1 defect can split into two Q=+½ defects
reducing the overall energy

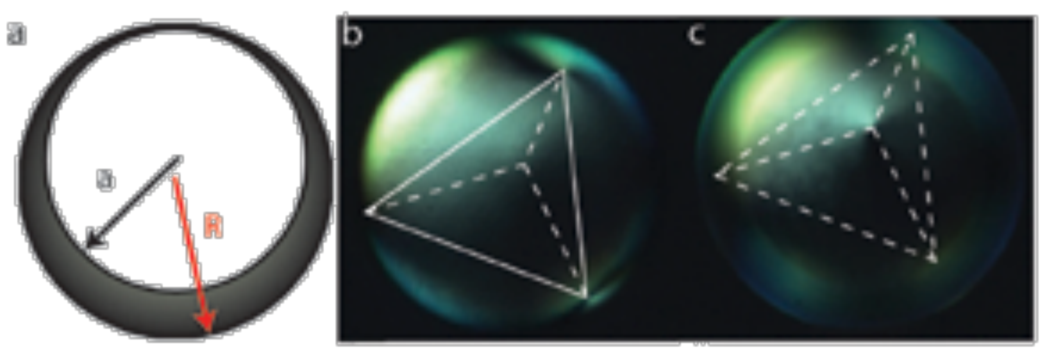


equilibrium nematic on a sphere:
four +½ defects located
at four corners of a tetrahedra

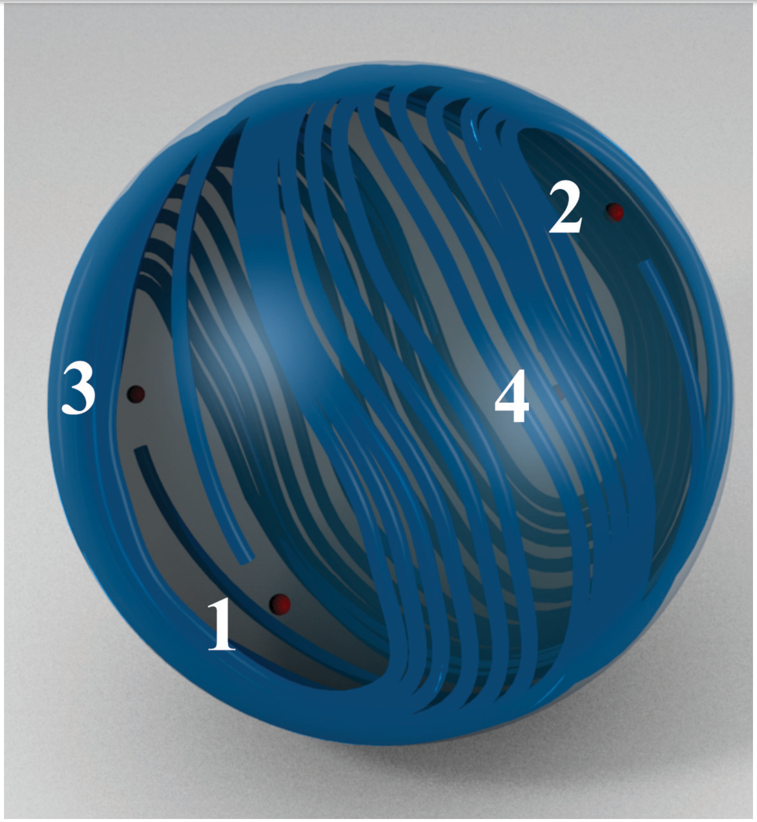


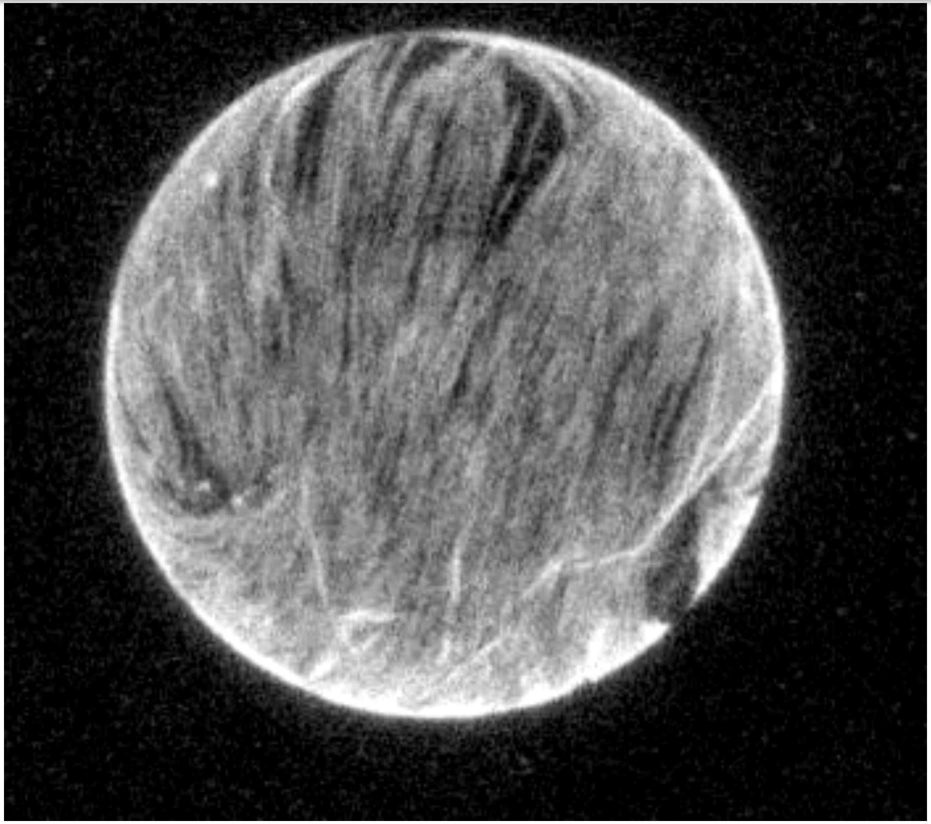
Experiments

liquid crystals in a double emulsion droplets



Spherical active nematics





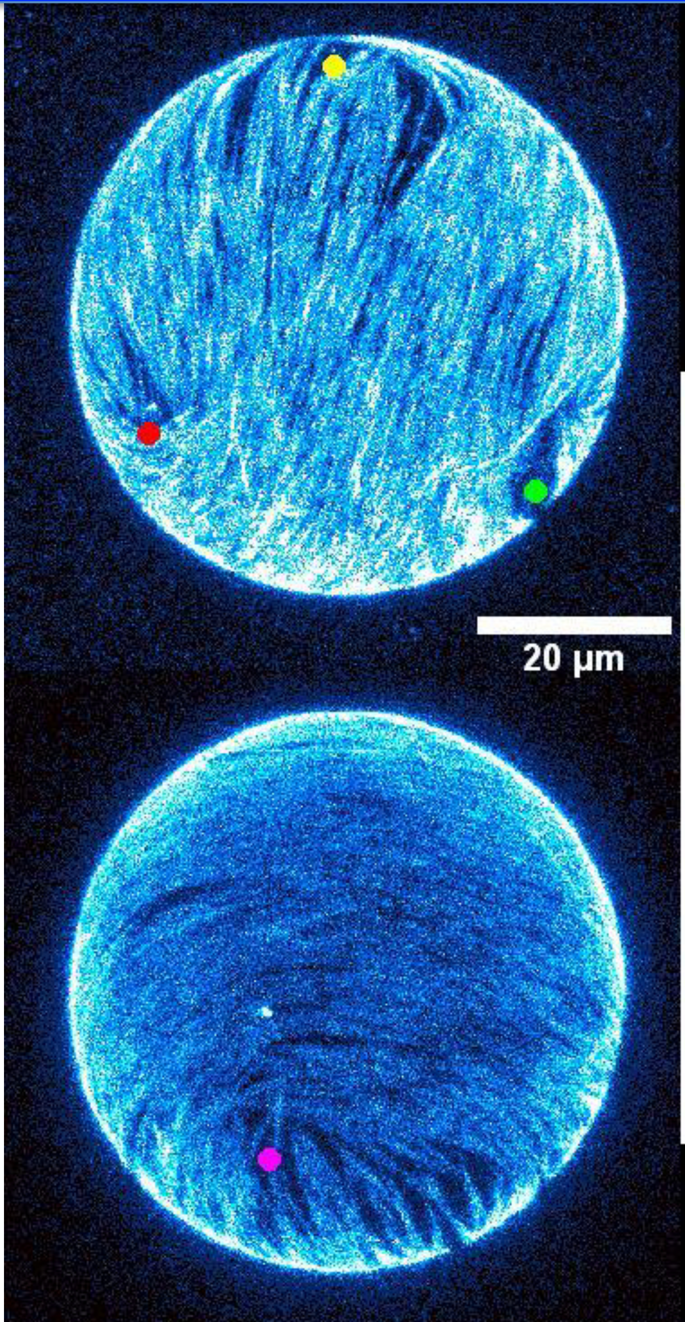
Defects acquire motility and move with preferred speed and direction!

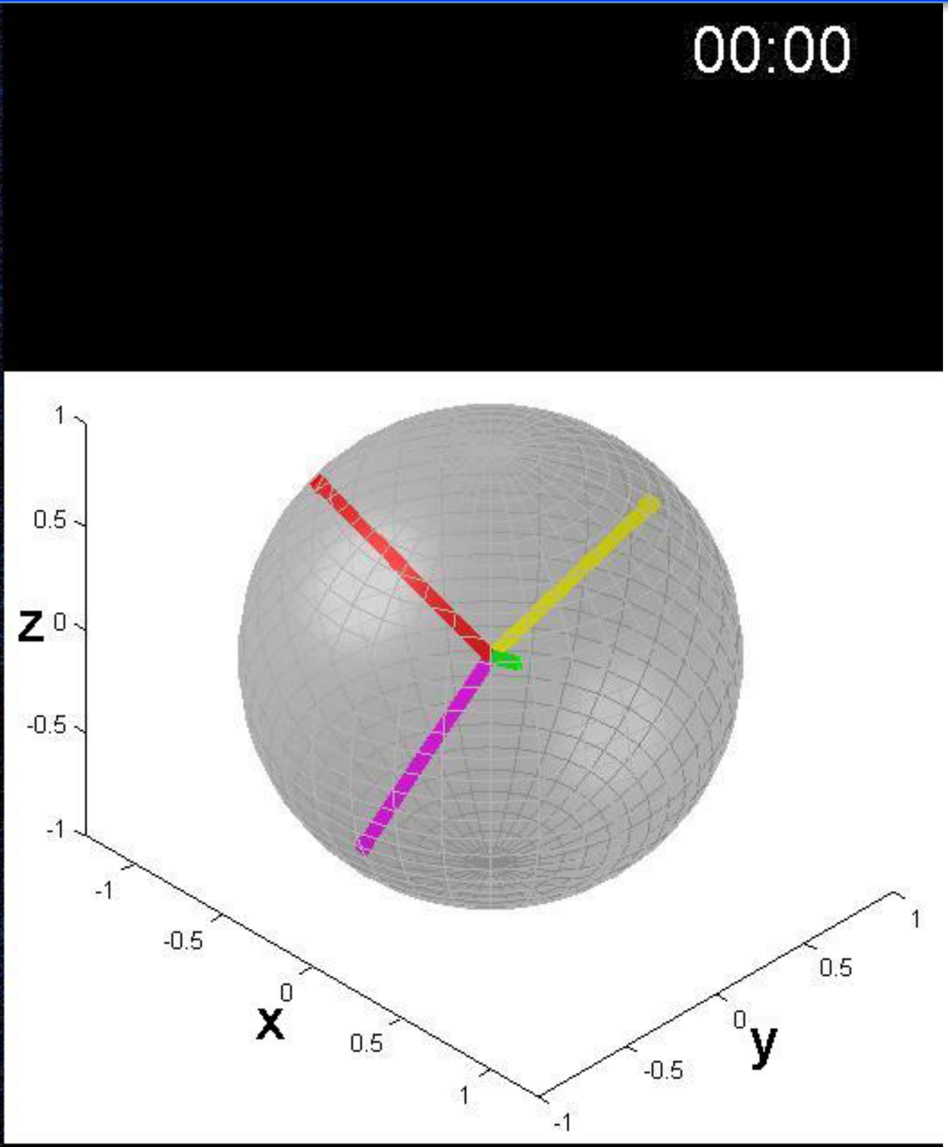
Defects cannot simultaneously minimize elastic distortions and follow their preferred dynamics.

Tracking defect dynamics

Top view

Botttom view

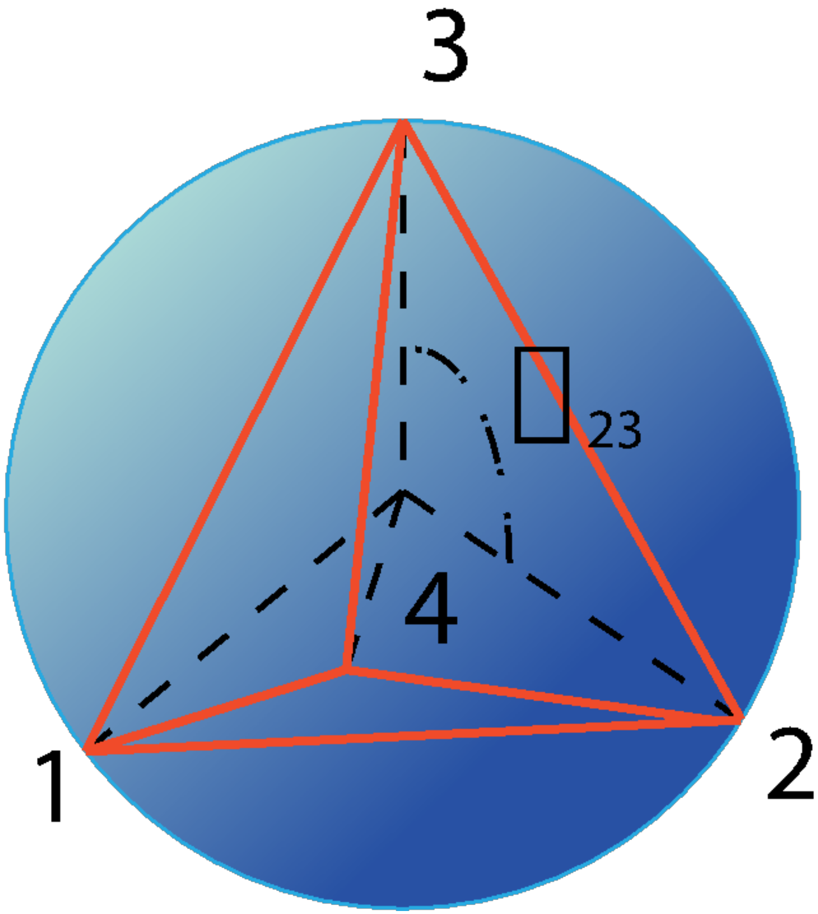




Tracking defect dynamics

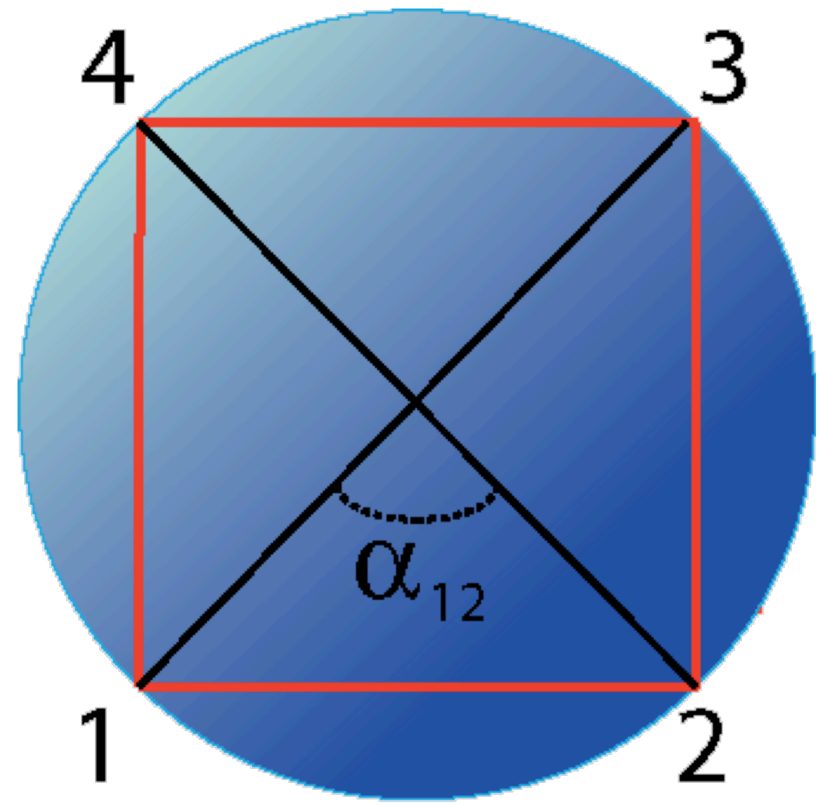
tetrahedral defect configuration

$\alpha_{12}=\alpha_{13}=\alpha_{14}=\alpha_{23}=\alpha_{24}=\alpha_{34}=109^o$

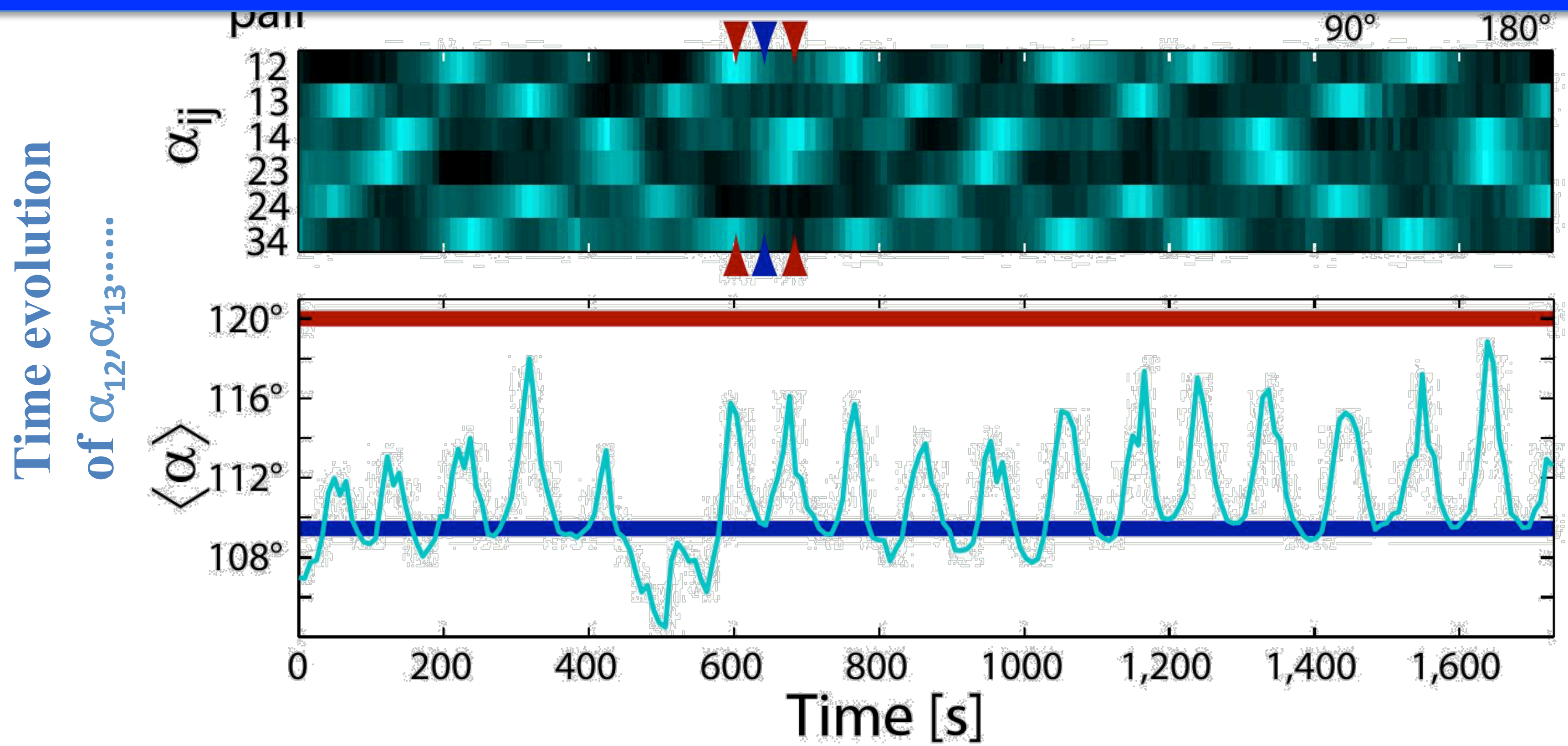


planar defect configuration

$\alpha_{12}=\alpha_{23}=\alpha_{34}=\alpha_{41}=90^o$
$\alpha_{24}=\alpha_{13}=180^o$

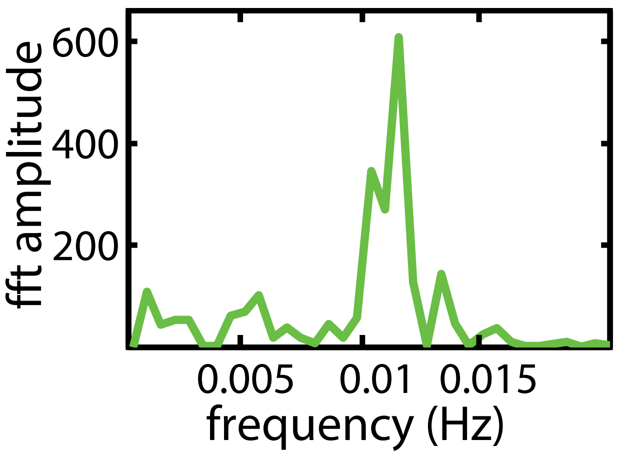


Spherical active nematic in a oscillator

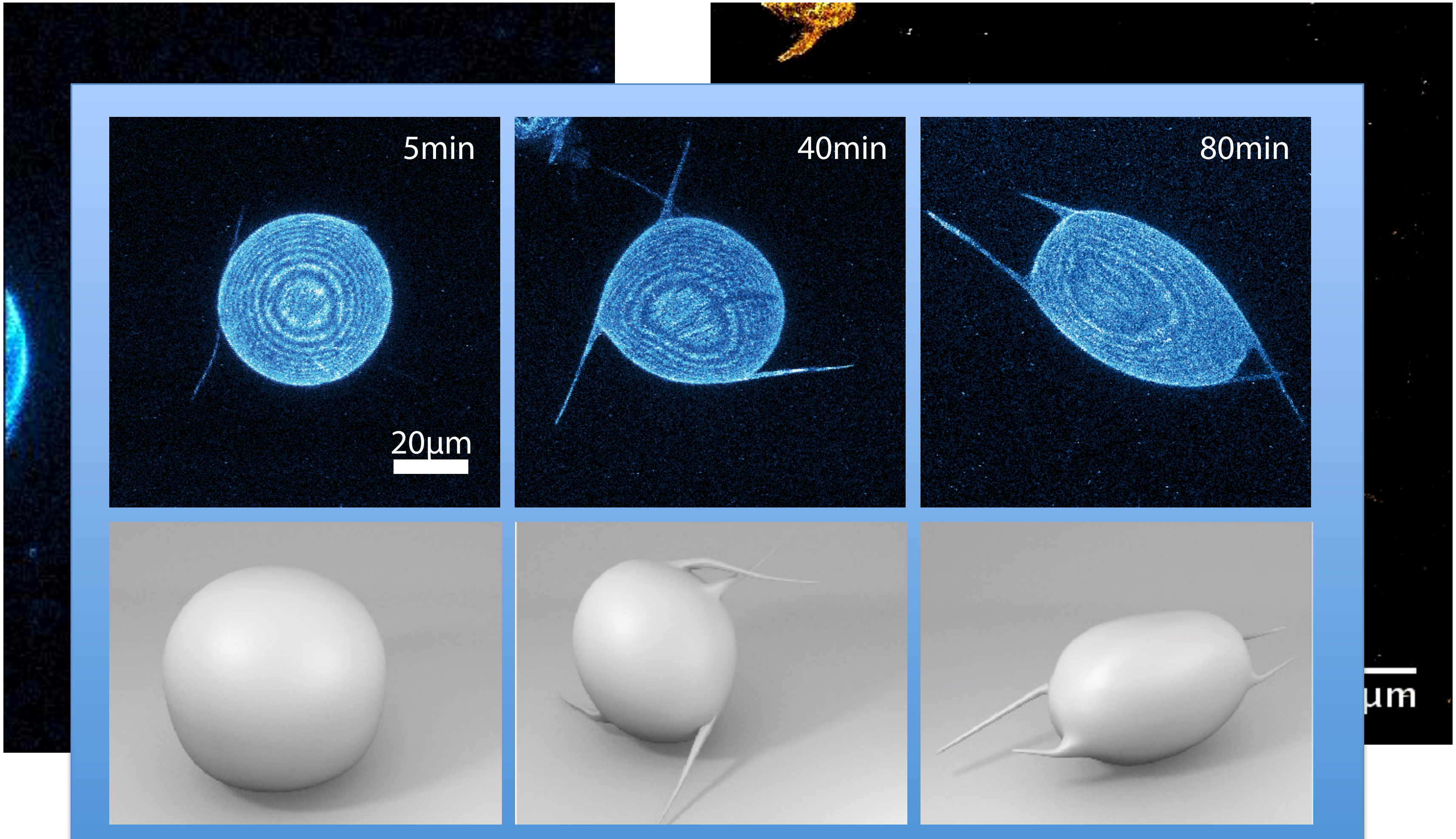


Defects oscillate between tetrahedral and planar configurations

synthetic "clock" with tunable frequency



Active nematic cortex drives vesicle shape changes



Vesicles deformation is tightly coupled to dynamics of underlying nematic defects

Protrusion are determined by topology

Outline

1. microscopic building blocks of microtubule based active matter

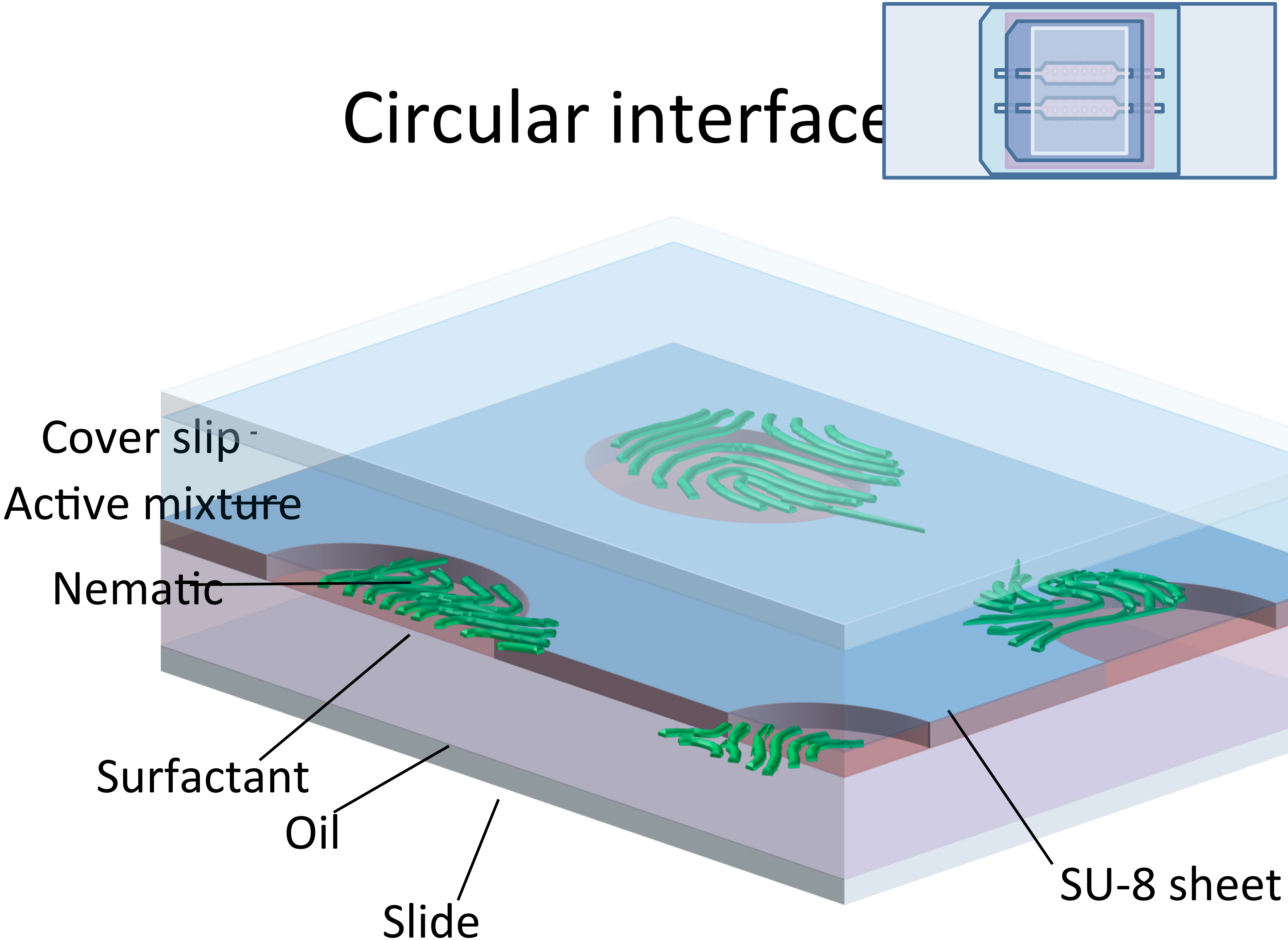
2. dynamics of isotropic active gels

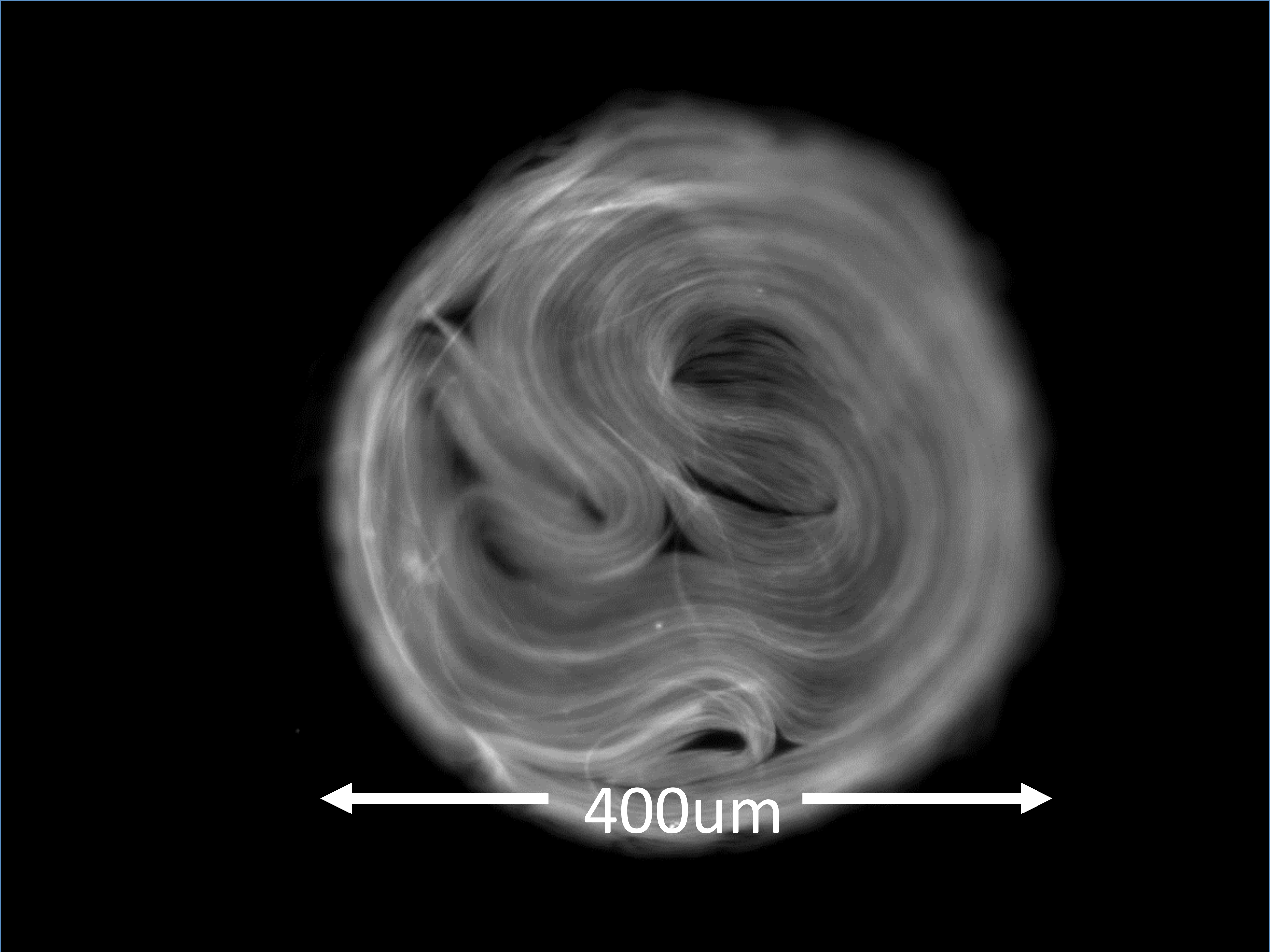
3. active nematic on a sphere

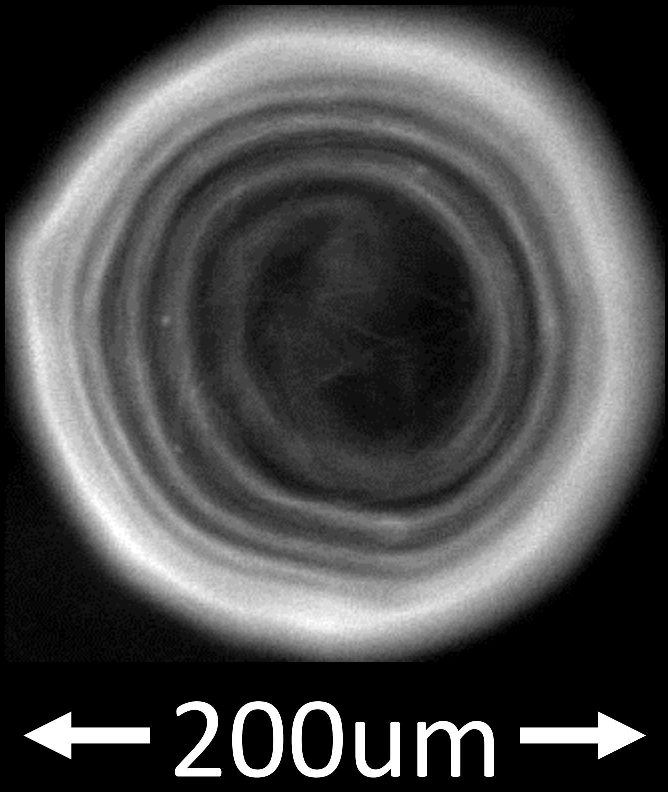
   - topology determines defect number
   - motile defects exhibit deterministic oscillatory dynamics
   - indefinite defect lifetime

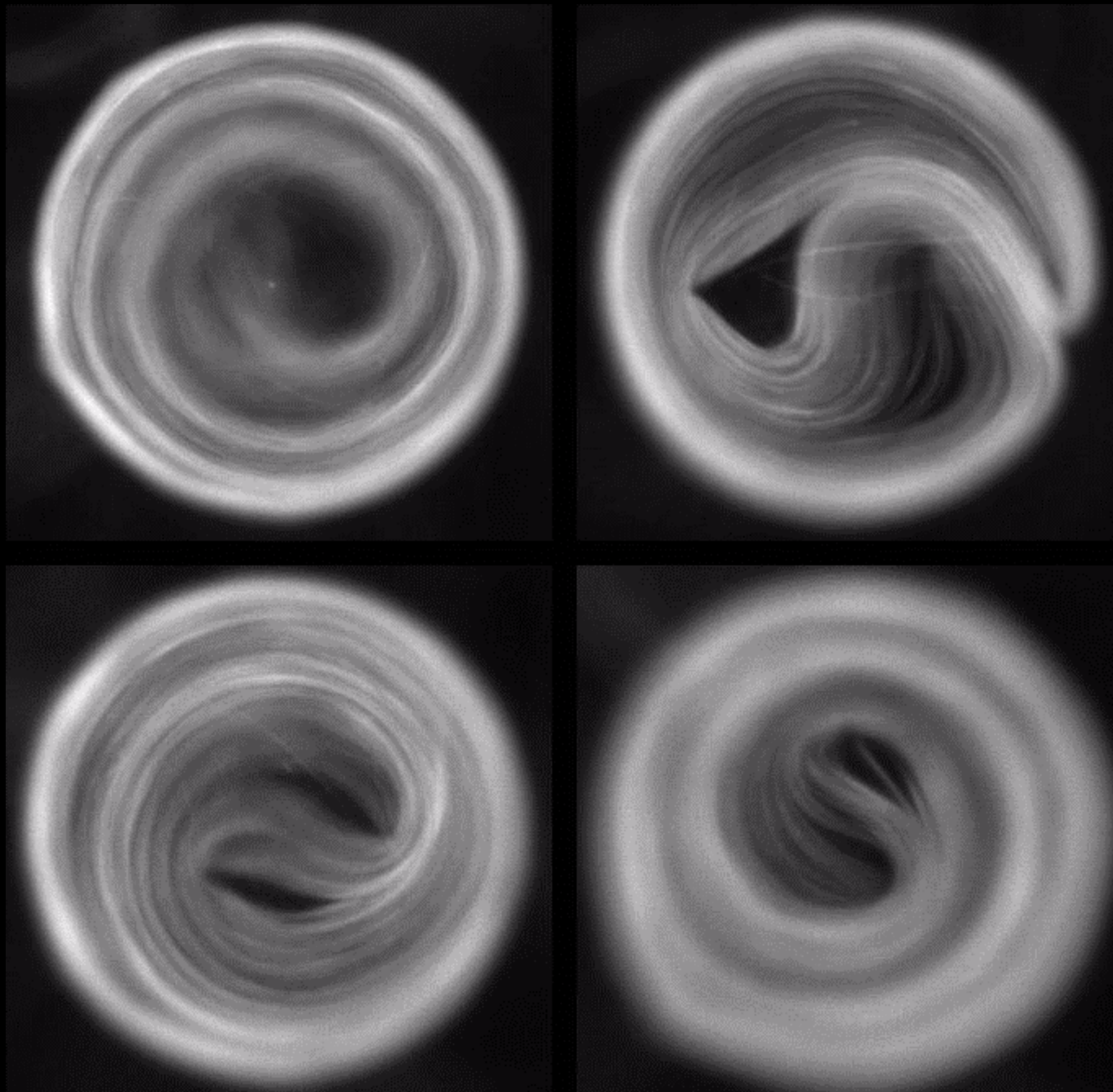
4. 2D circular active nematic

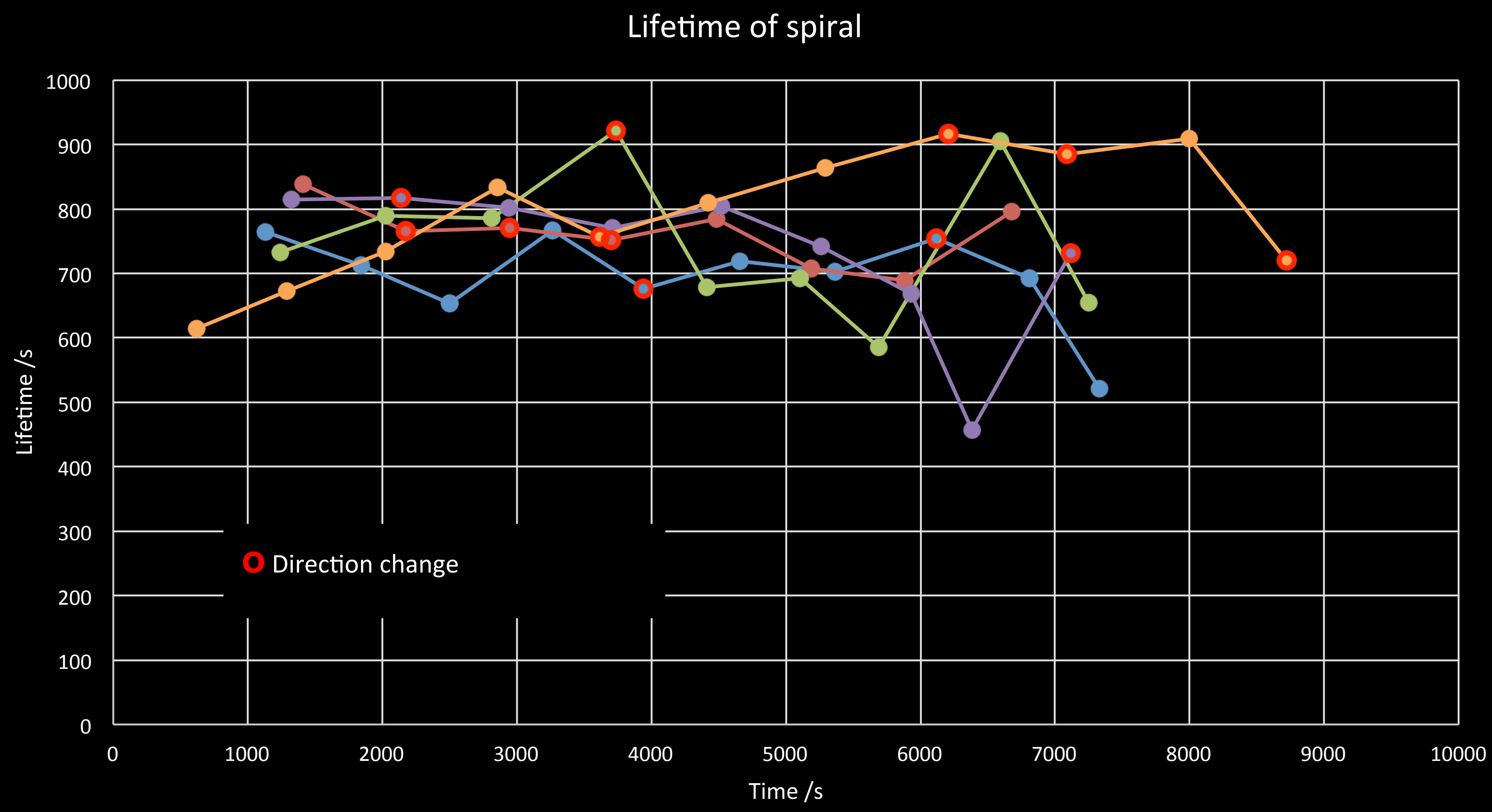
Circular interface




400um

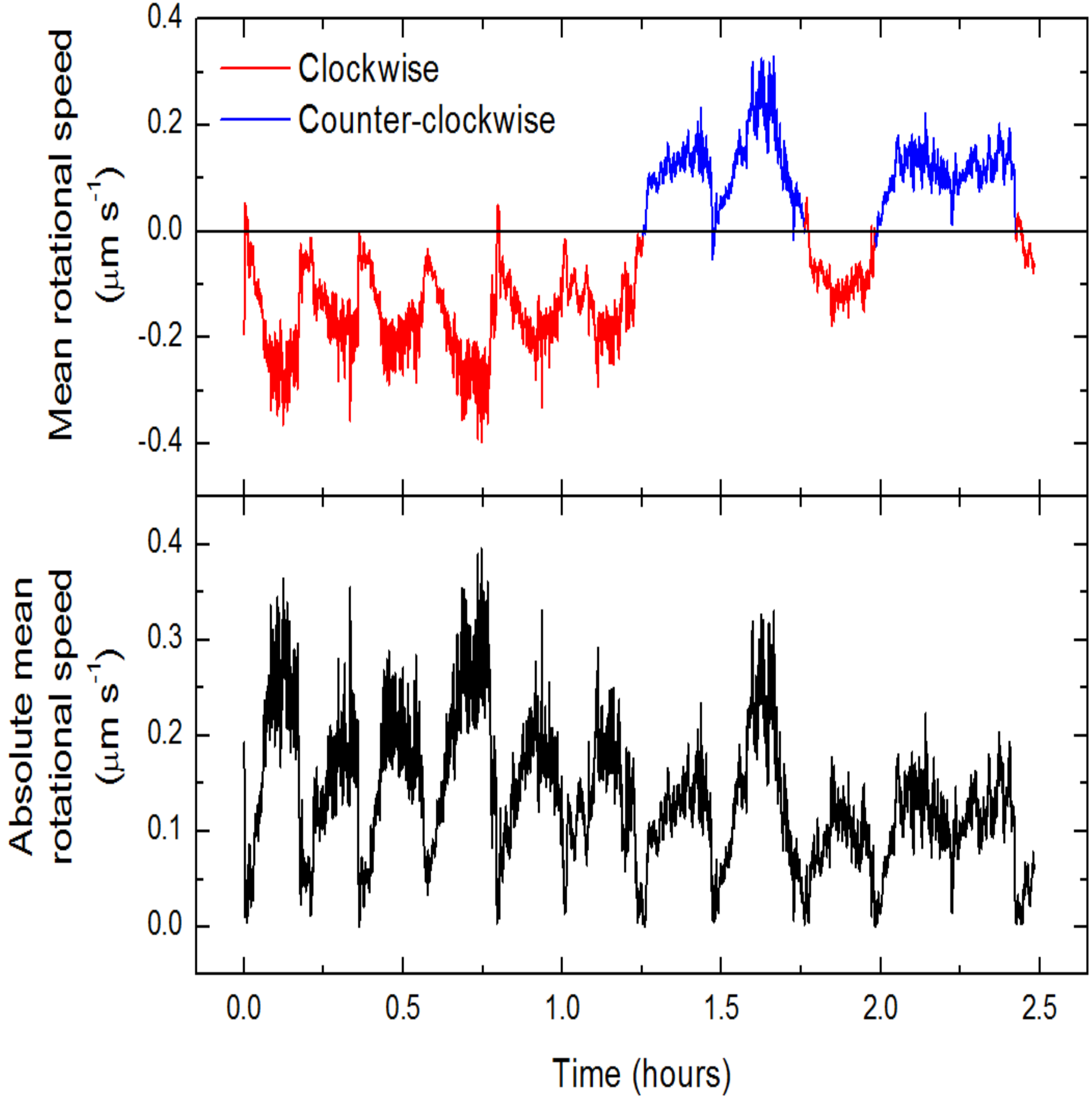

200um





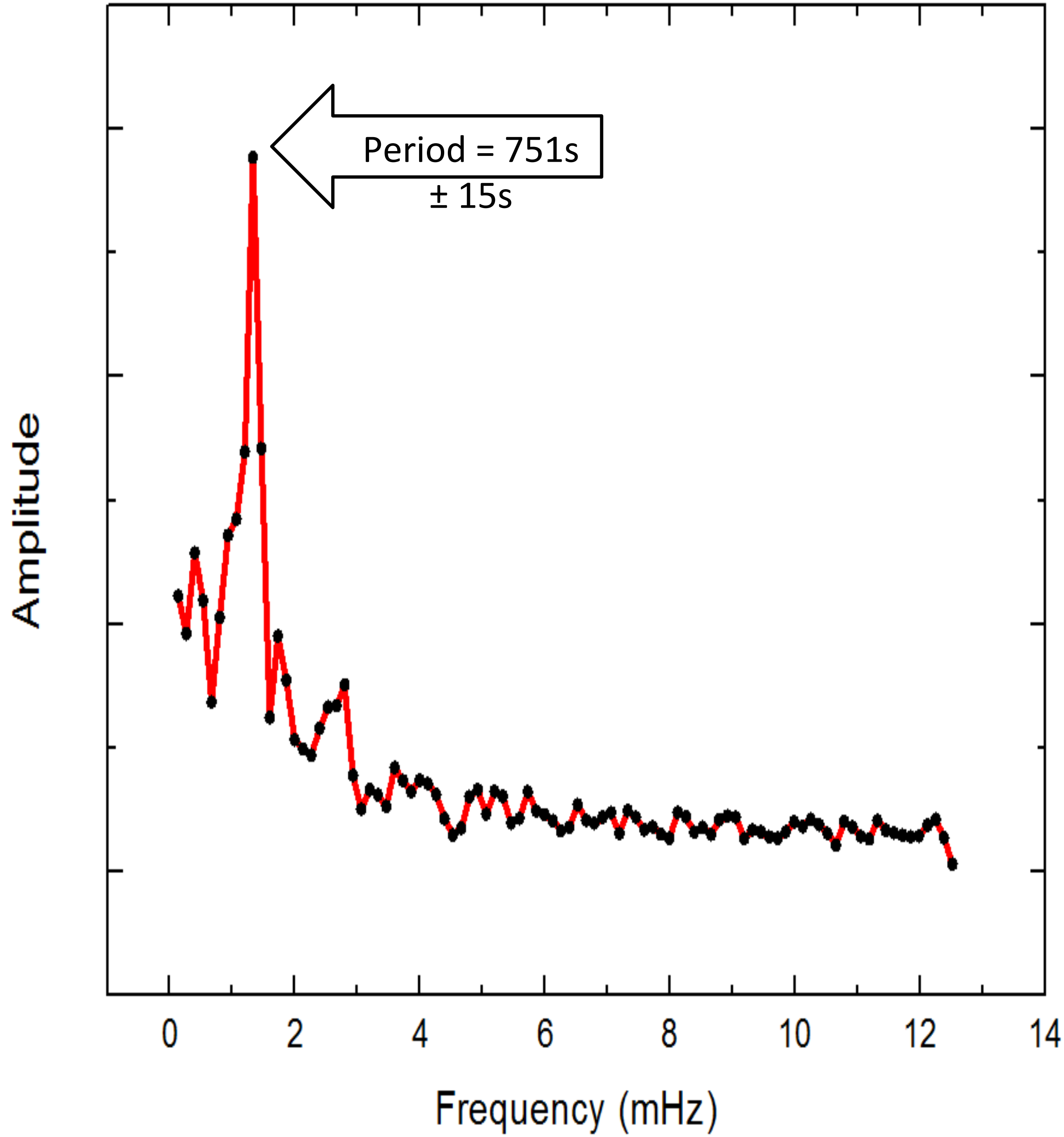
Lifetime of spiral
Lifetime /s
Time /s
1000
900
800
700
600
500
400
300
200
100
0
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Direction change

Periodic motion



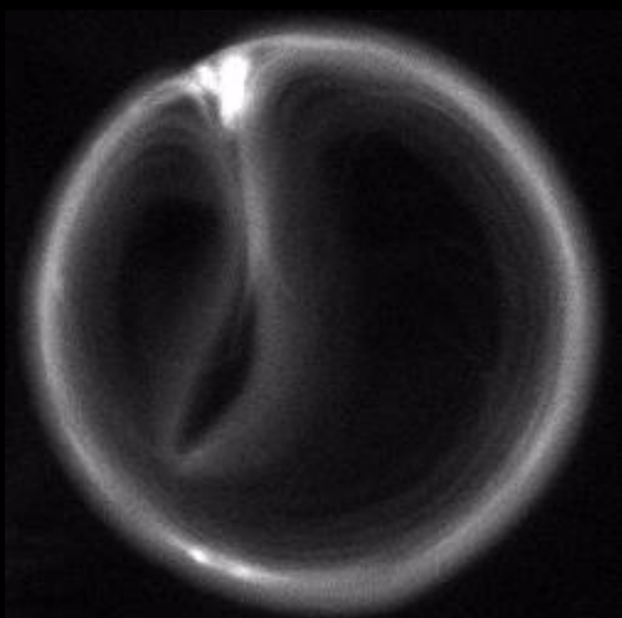
Periodic motion

Average FFT of velocity data from 5 circles.

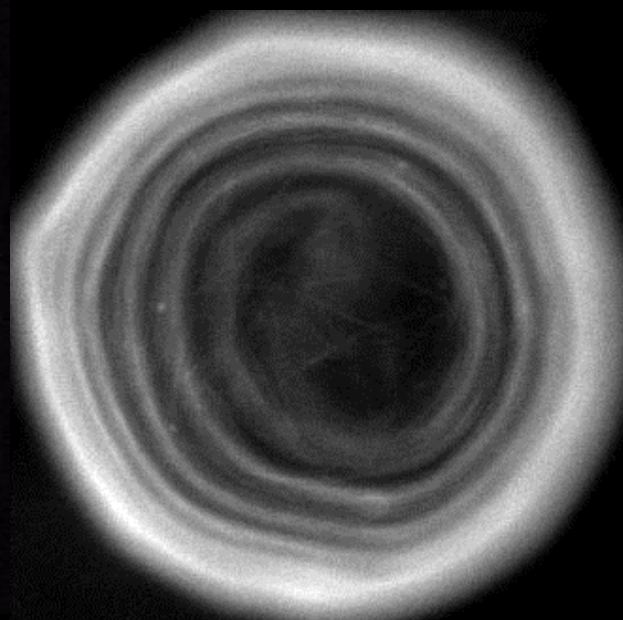


Confinement diameter

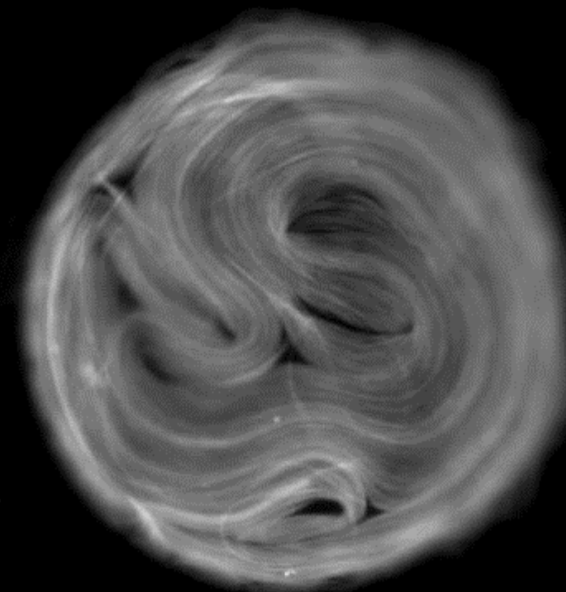
Not to scale



150 µm
~ 184 s



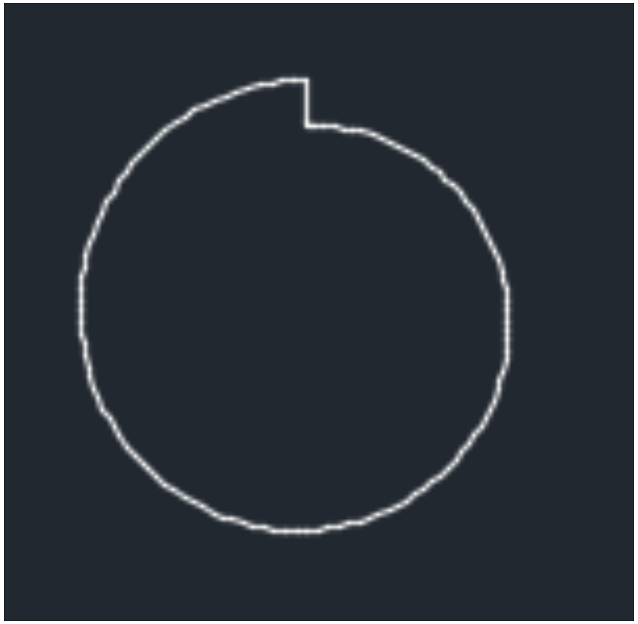
200 µm
751 s

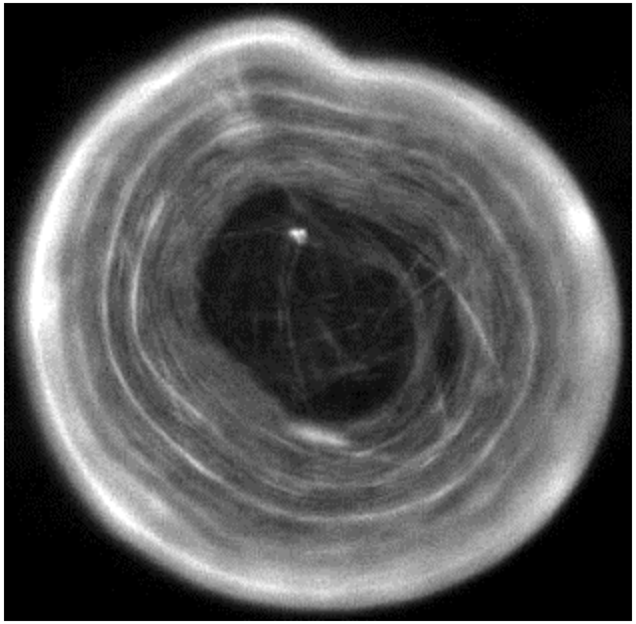


400 µm
?

25x real time

Directed motion



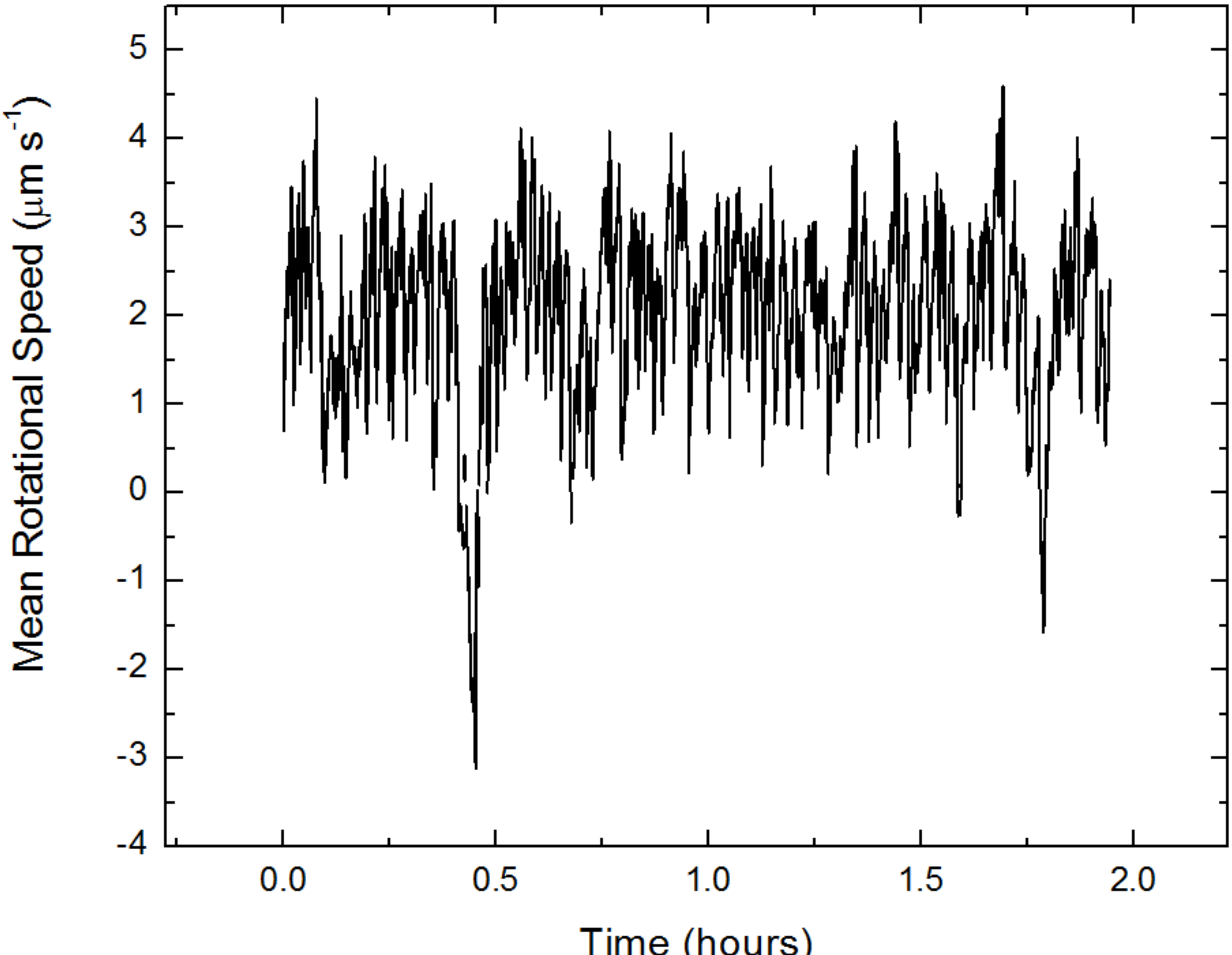


Fast!

Usually same direction

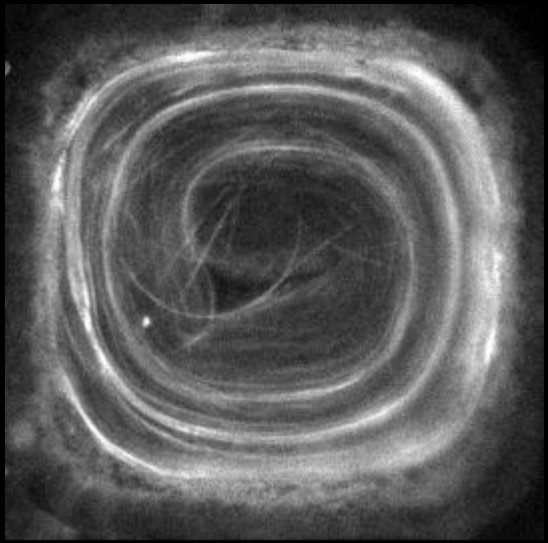
Many defects from notch

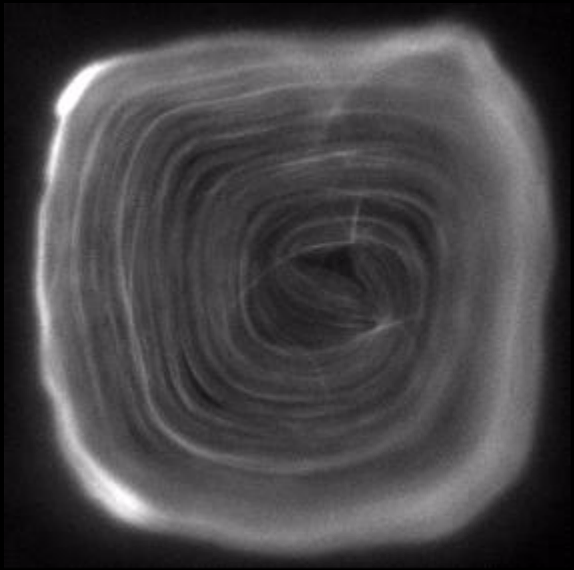
Lasts for about 10 hrs.
Activity continues, but defect nucleation not controlled.
Therefore also lose direction control.



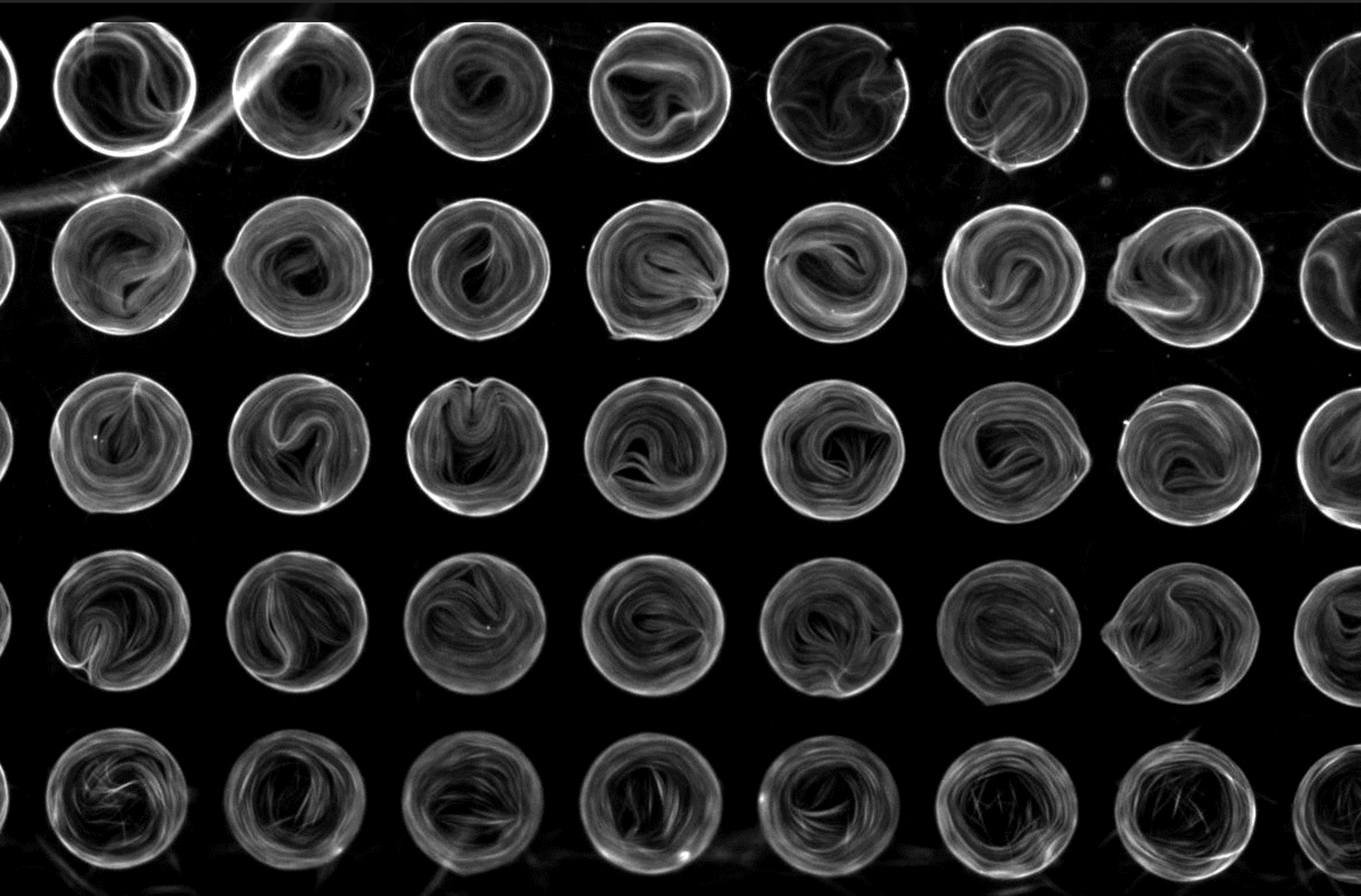
Mean Rotational Speed (μm s-1)
5
4
3
2
1
0
-1
-2
-3
-4
0.0
0.5
1.0
1.5
2.0
Time (hours)

Square (sort of)

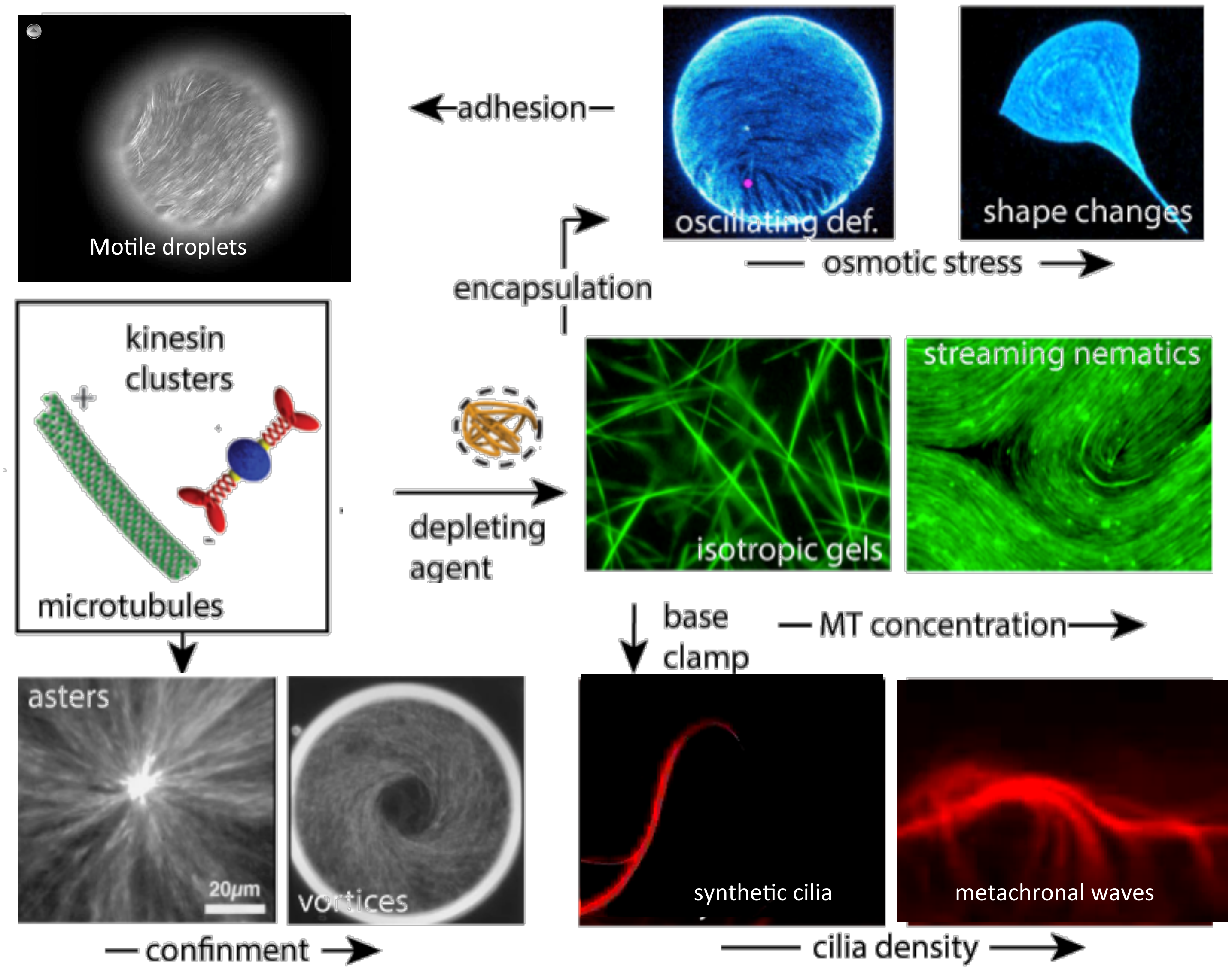




Next steps: synchronization?



Conclusions



Leibler, Surrey, Needelec, 1998

- Complex far-from-equilibrium dynamics from simple building blocks