Defect dynamics of active nematics and rheology of isotropic gels


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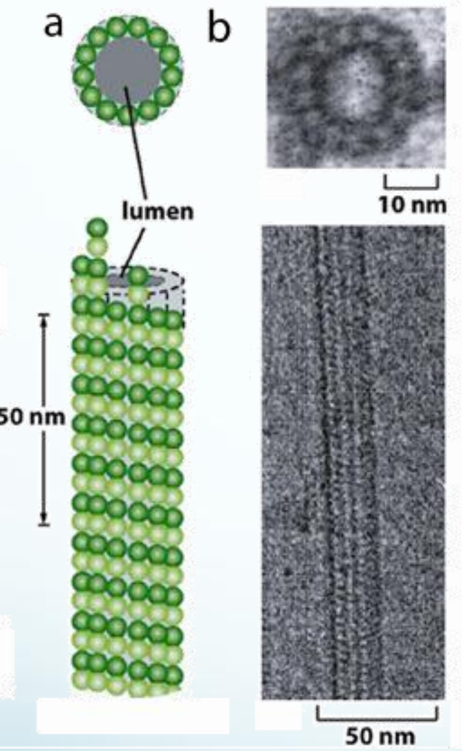
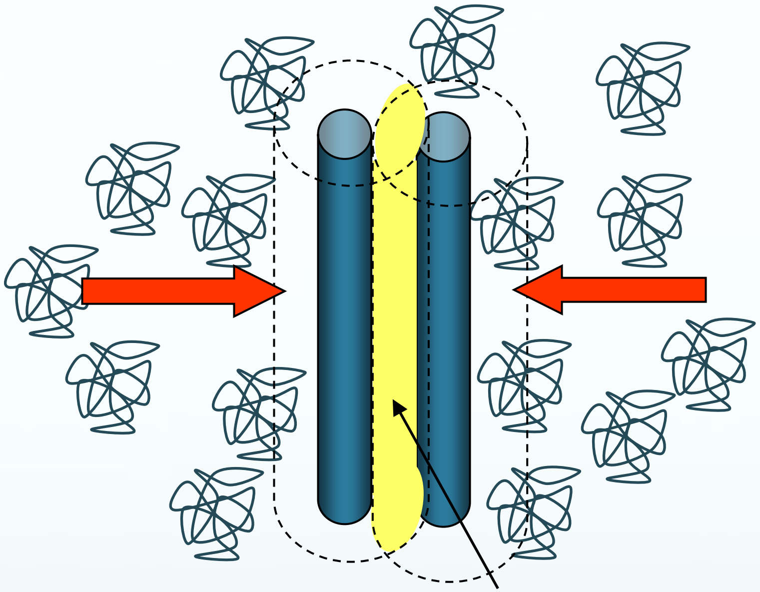
Basic building blocks of active nematics

microtubules



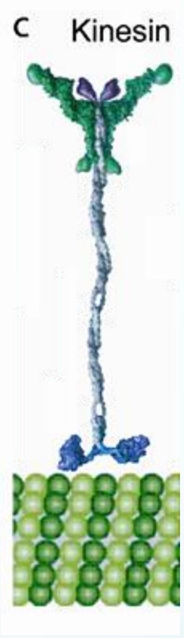
- long rigid filaments
- stabilized with GMPCPP

depletion induced MT bundling



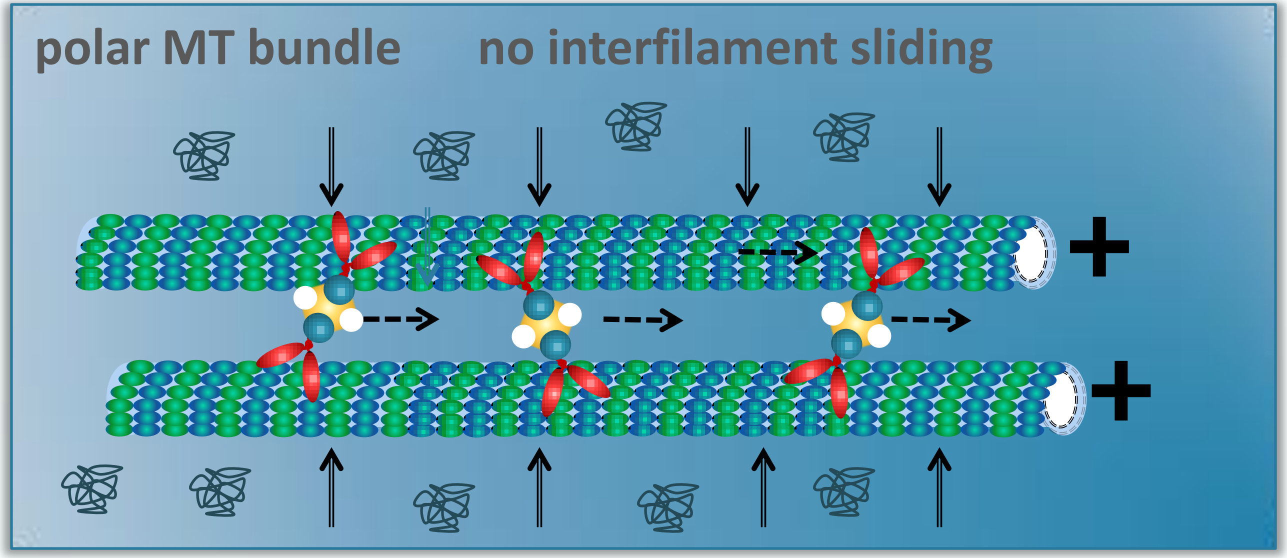
- non-adsorbing polymer (PEG) induced effective attractive interactions which lead to MT bundling

molecular motor kinesin

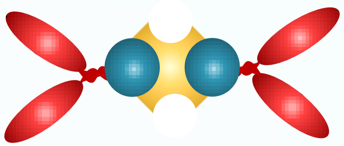


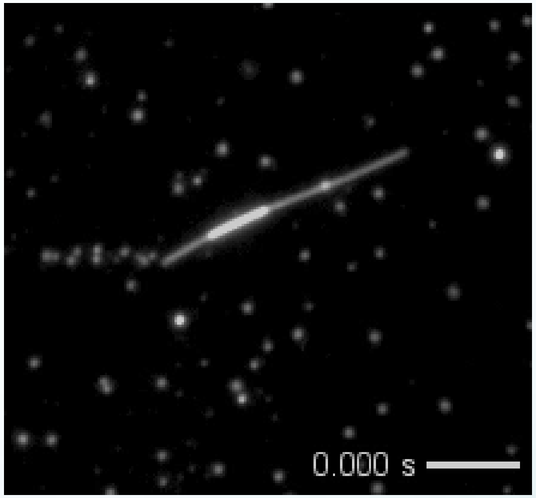
- motors convert energy from ATP hydrolysis into movement along MT backbone

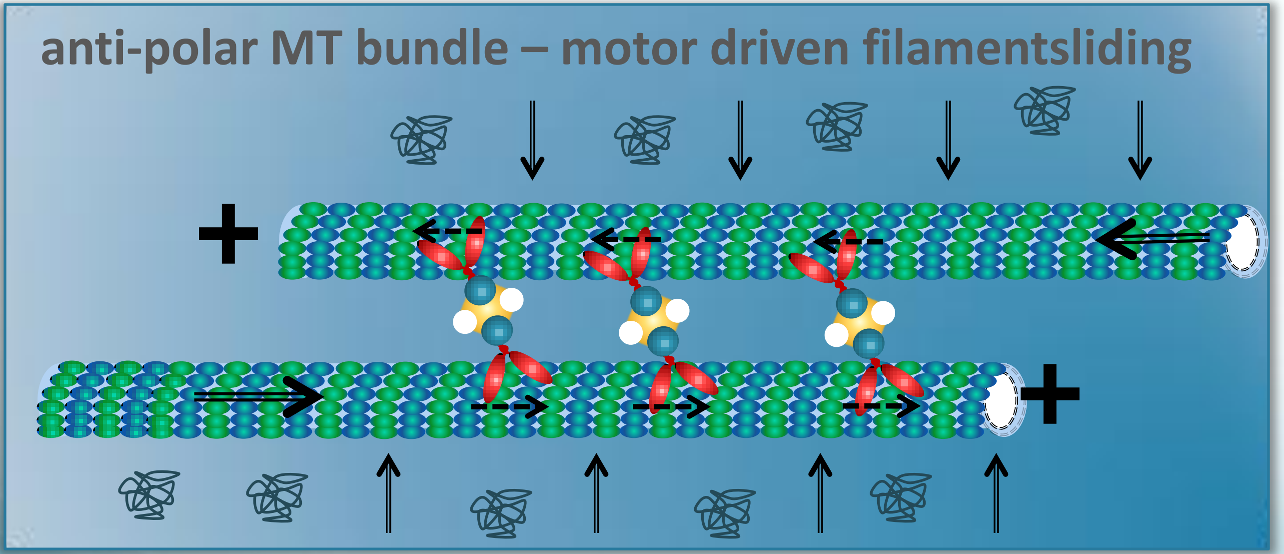
Basic building blocks – extensile MT bundles


polar MT bundle

no interfilament sliding


biotin labeled kinesin are Bound into clusters via Tetrameric streptavidin.

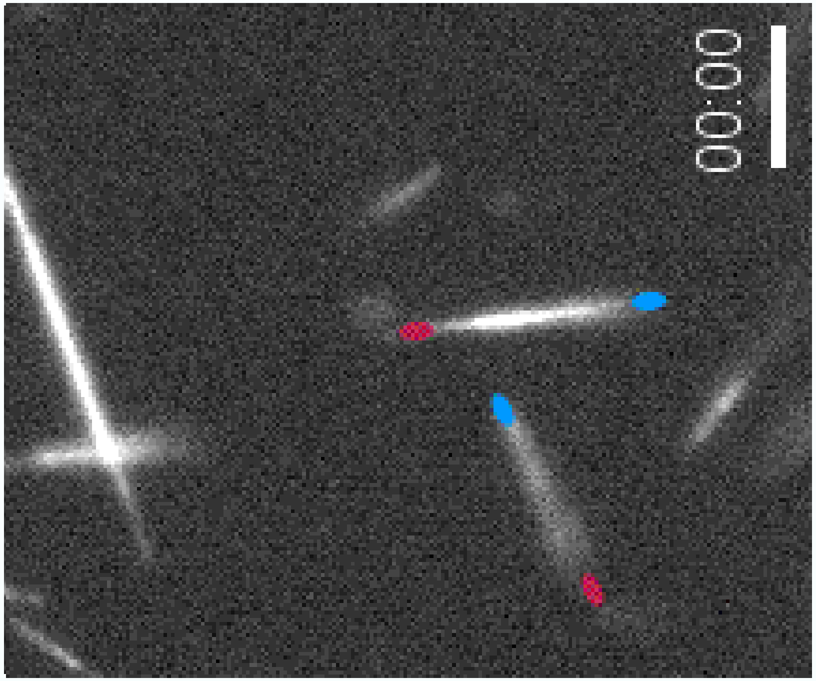



anti-polar MT bundle – motor driven filamentsliding

passive MT bundles – diffusive interfilament sliding

- bundle geometry greatly increases filament sliding efficiency
- MT sliding depends on relative filament polarity !!!

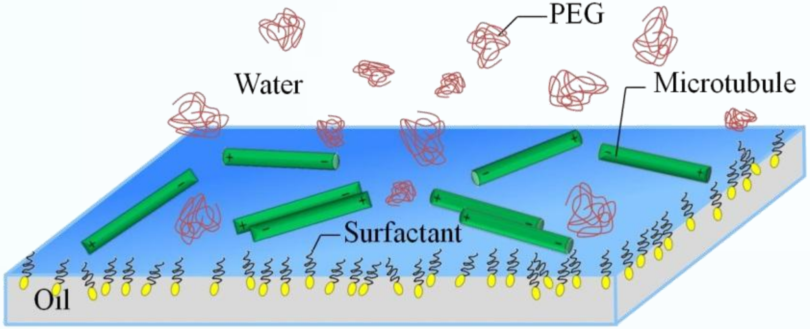
dynamics of isolated extensile MT bundles

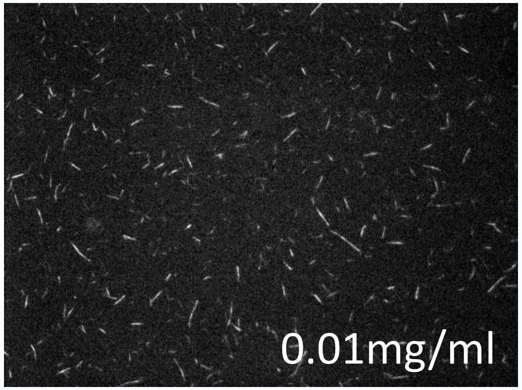


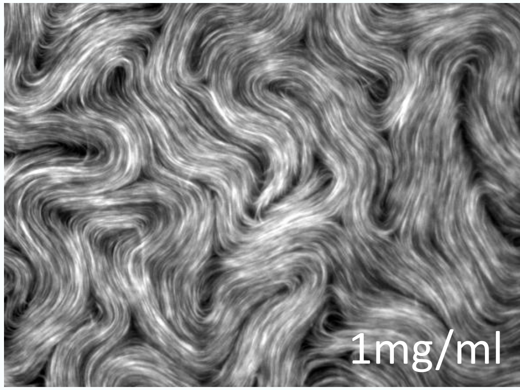
- isolated MT bundles are static indicating polarity sorting
- bundle recombination reinitializes local polarity sorting

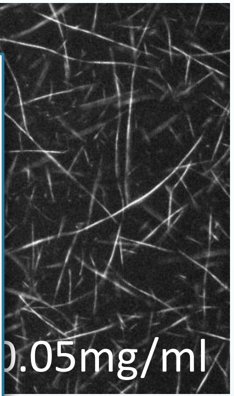
Active Nematic liquid crystals

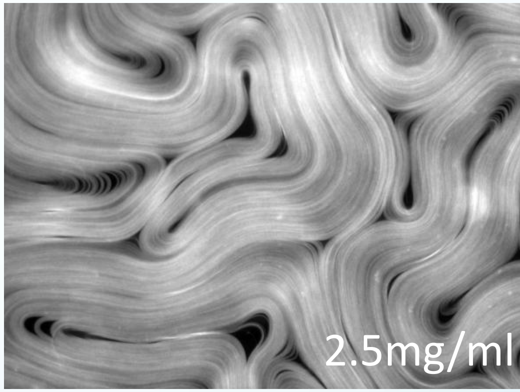
0.01mg/ml

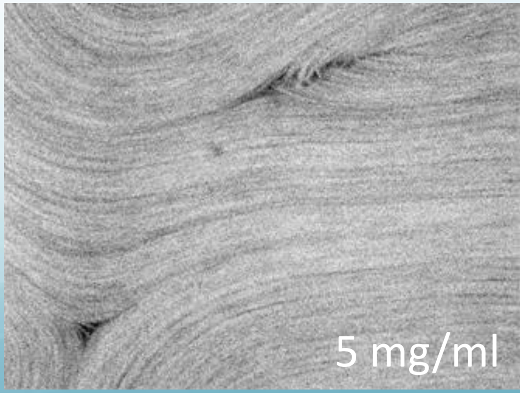




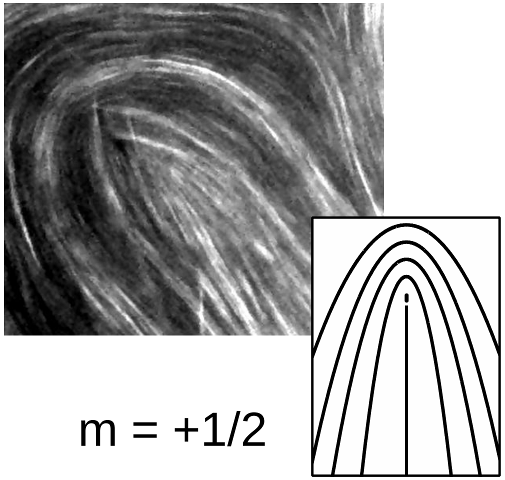




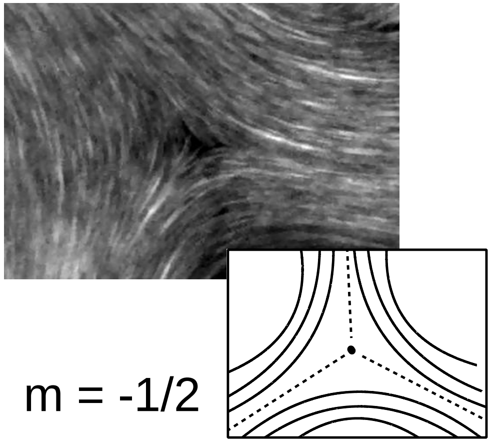




topological defects



m = +1/2



m = -1/2

½ and -½ disclinations indicate nematic order

disclination defects in equilibrium nematics

topological charge Q= +1

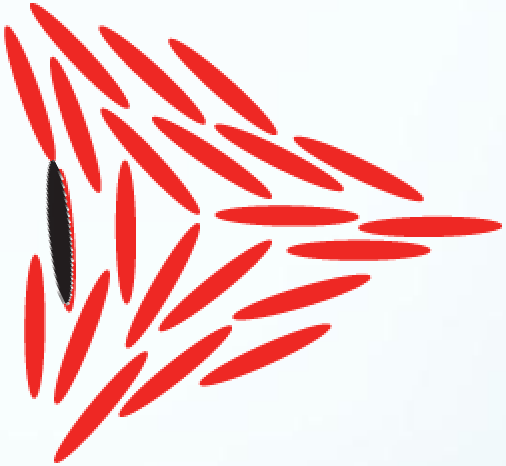
traversing the defect core
requires 360º rotation

topological charge Q= ½

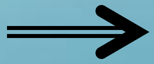
traversing the defect core
requires 180º rotation

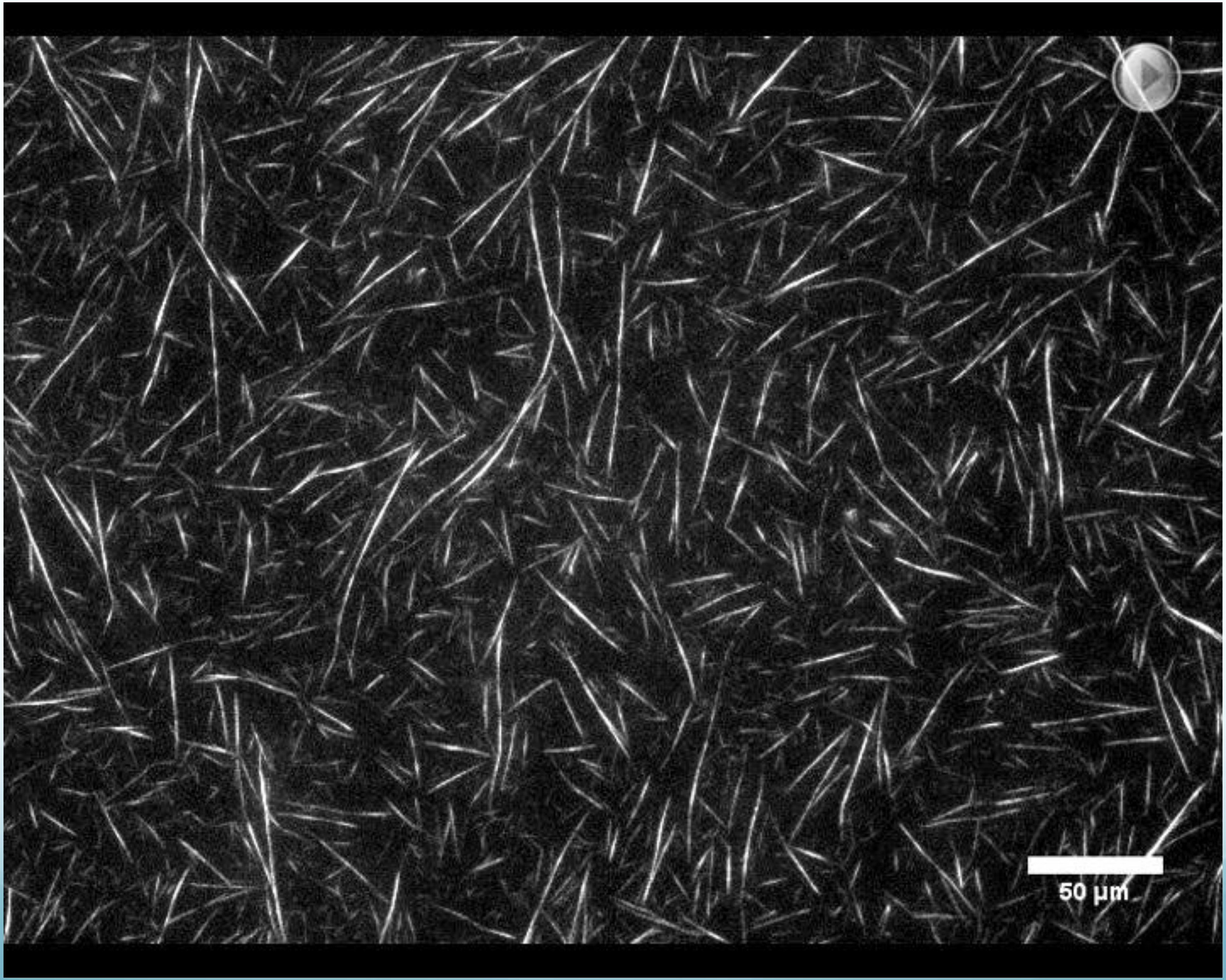
Q = +½

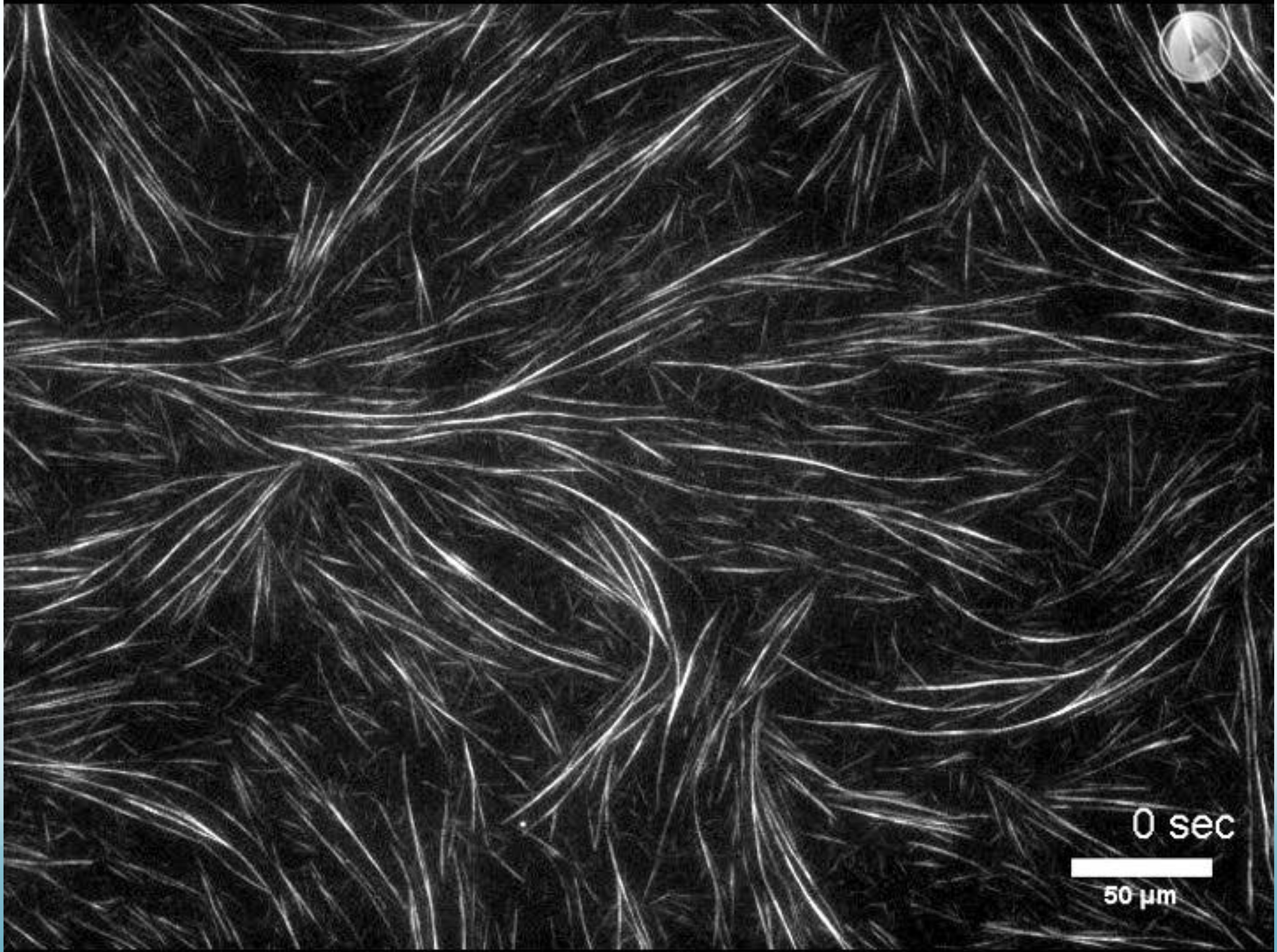
Q = -½



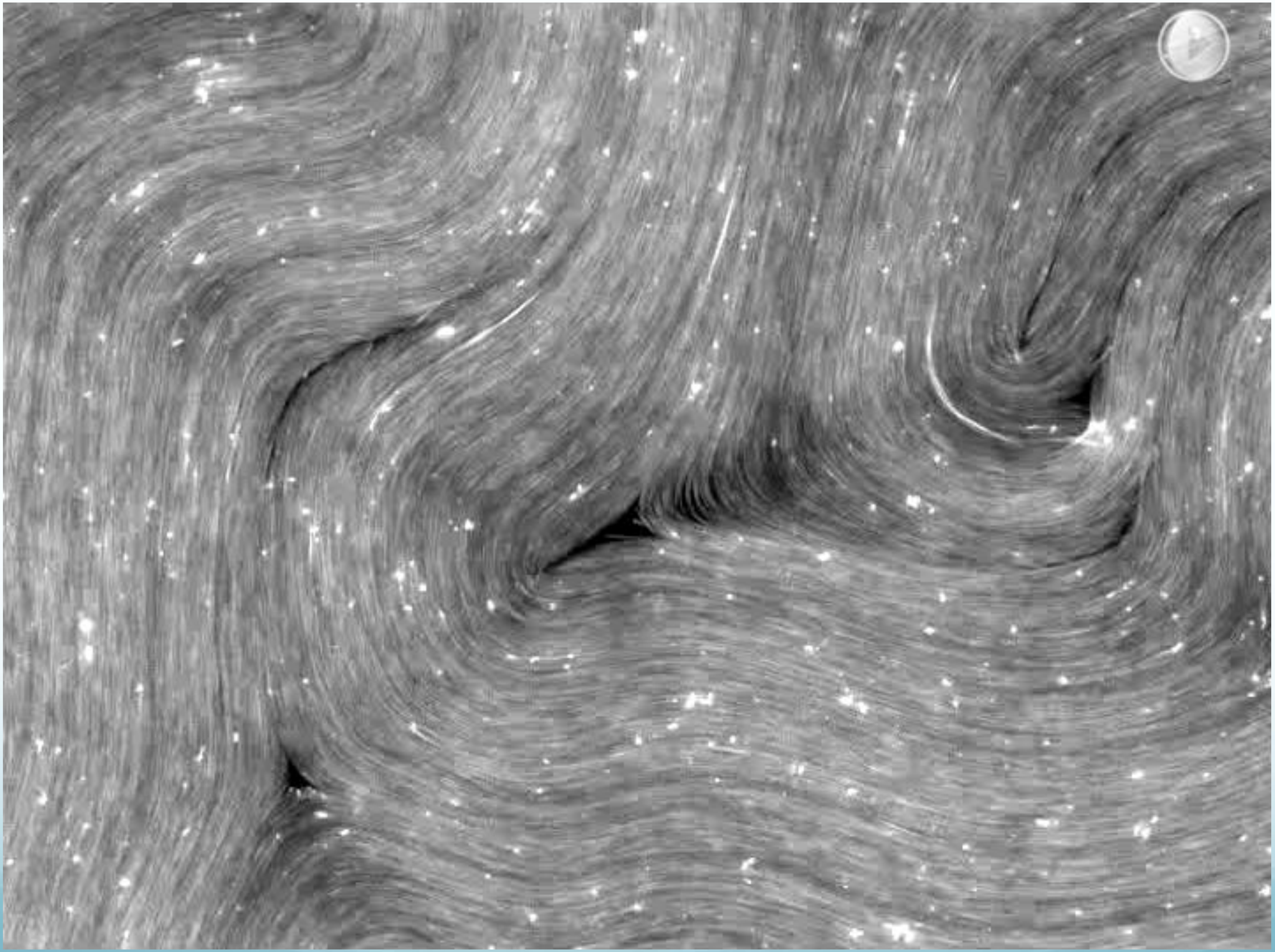
- +½ and -½ defects can annihilate to create defect free nematic
- thermal fluctuations are not strong enough to drive spontaneous unbinding of defect pair
- ½ defect only form in a system with nematic symmetry (arrowless bar)



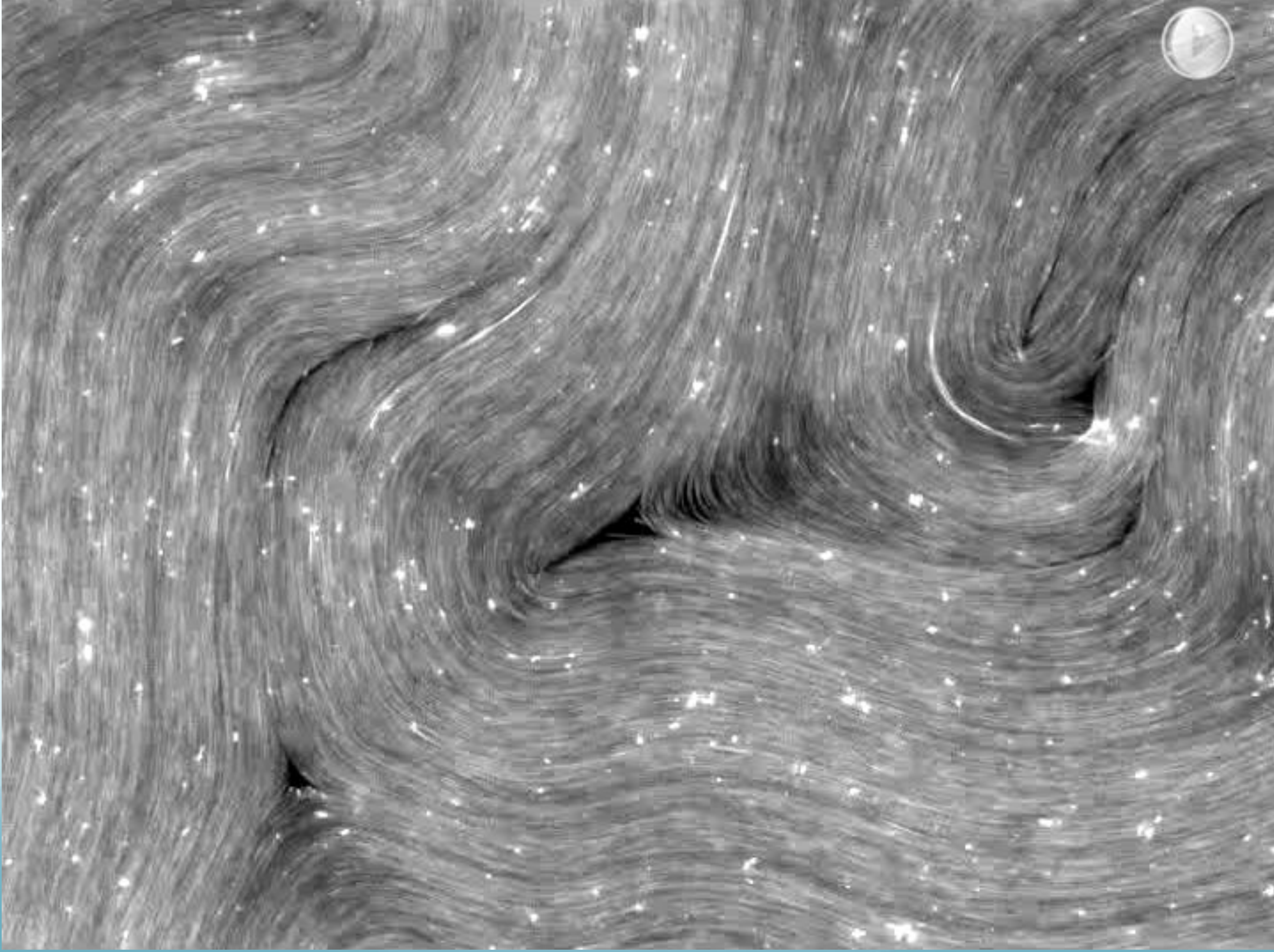

50 µm

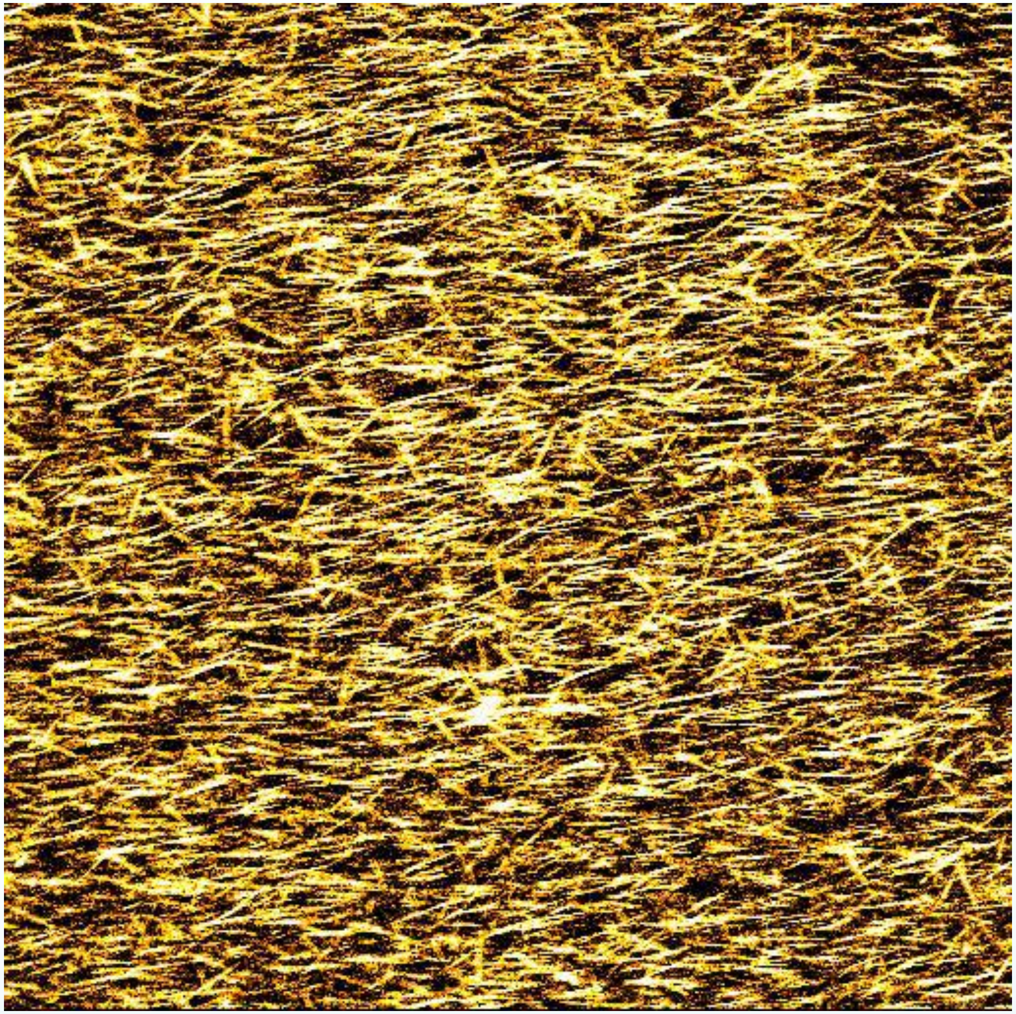

0 sec
50 µm

- equilibrium liquid crystals – static defects
- active liquid crystals – spontaneous motility

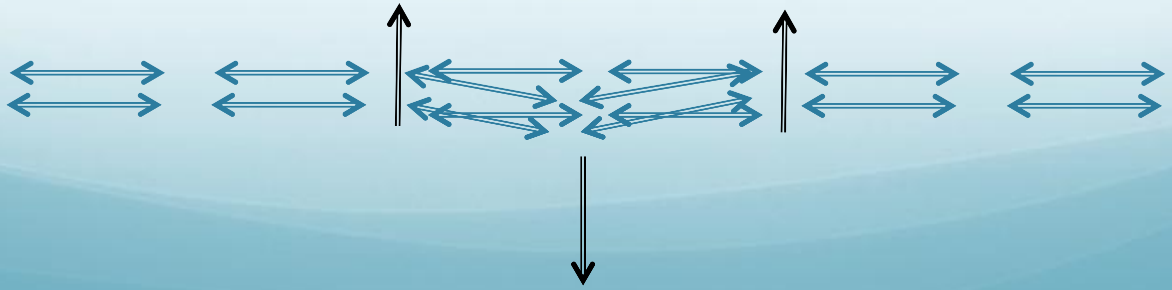


Active liquid crystals exhibit streaming flows !

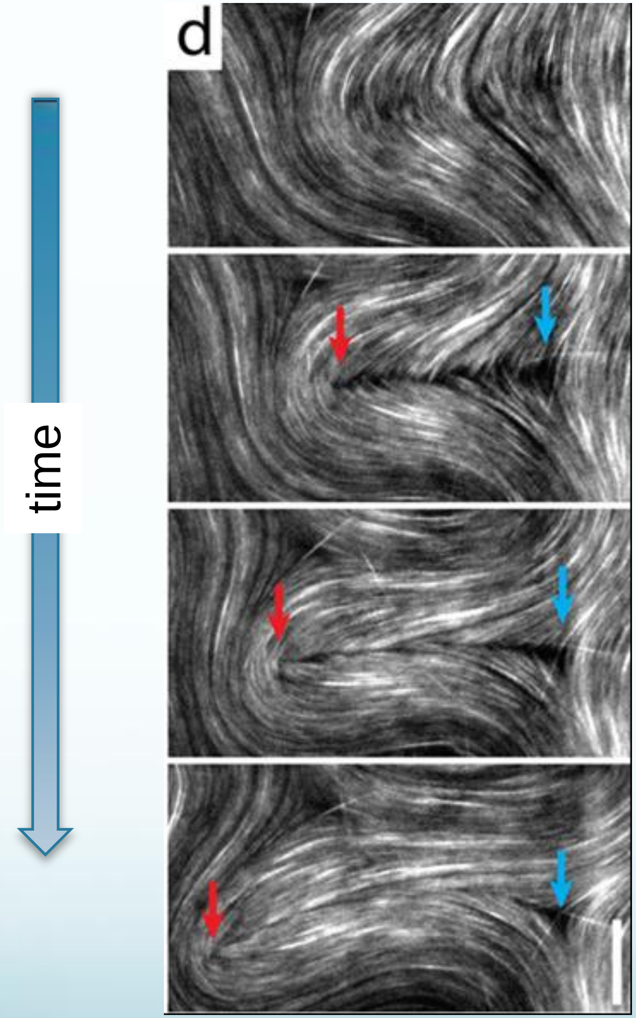




aligned extensile filaments are unstable against bend fluctuations



MT active nematics: bucking instability leads to defect creation and anihilation



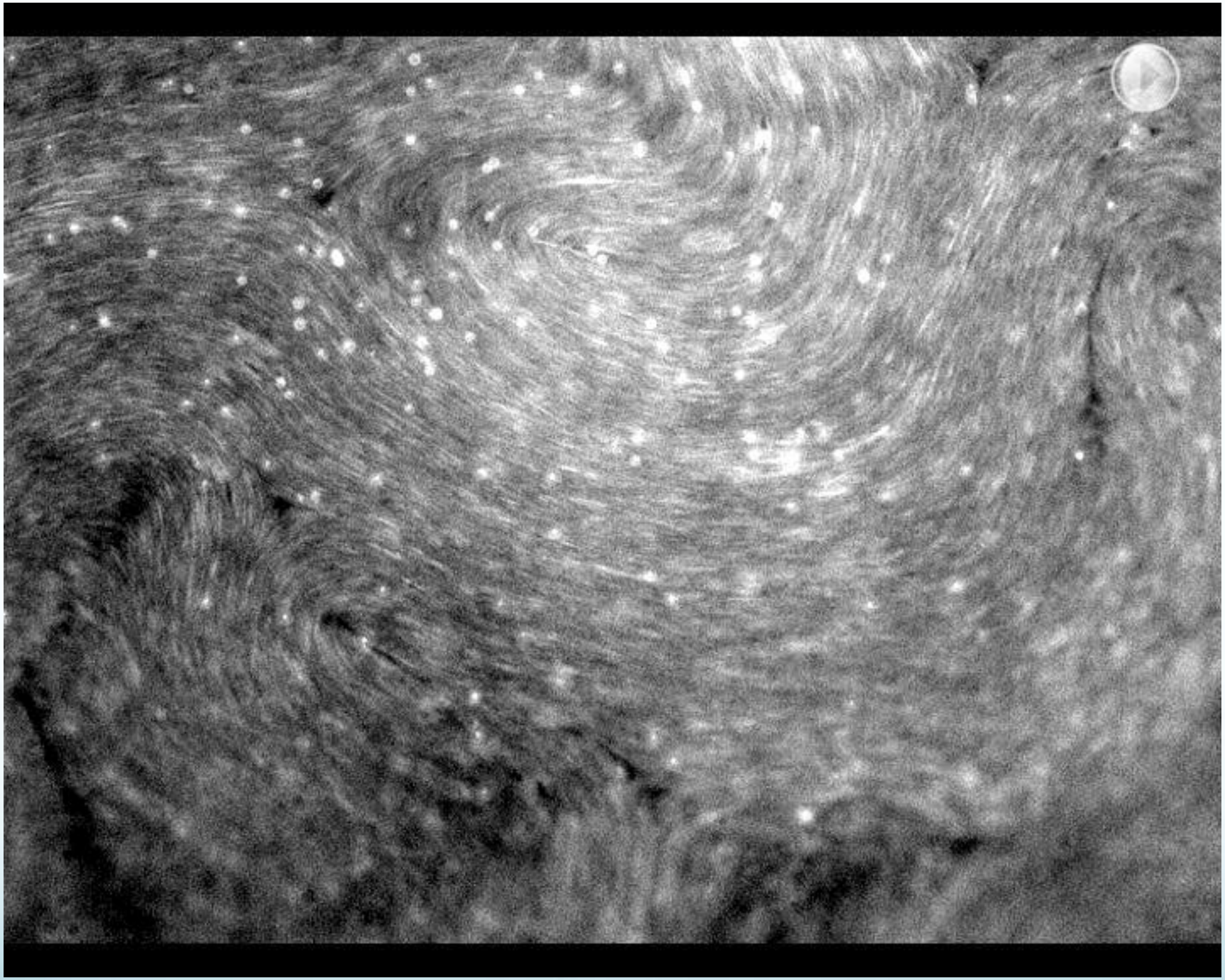
bend instability leads to buckling

fracture of the director field leads to unbinding of a defect pair

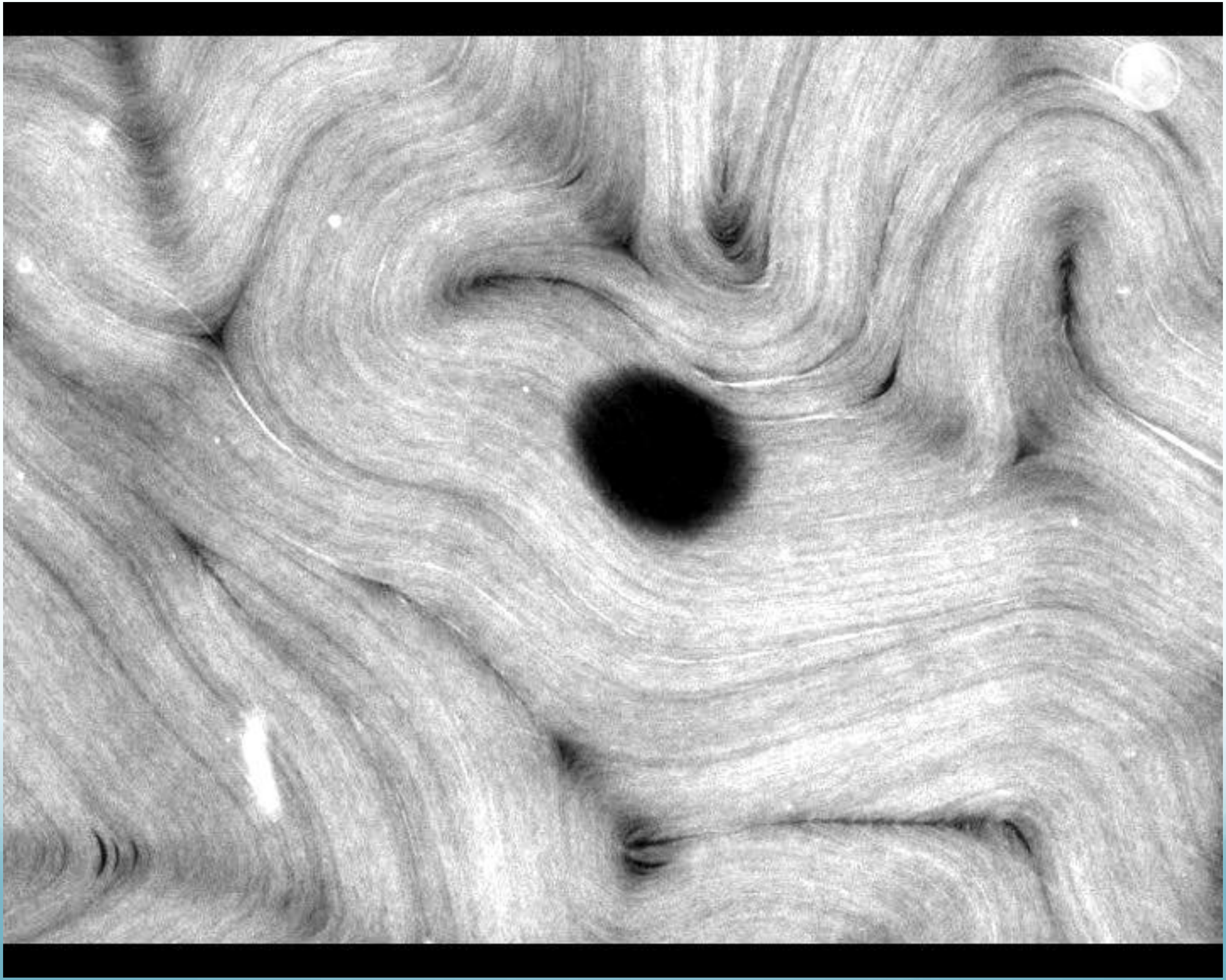
asymmetric +½ defect is motile

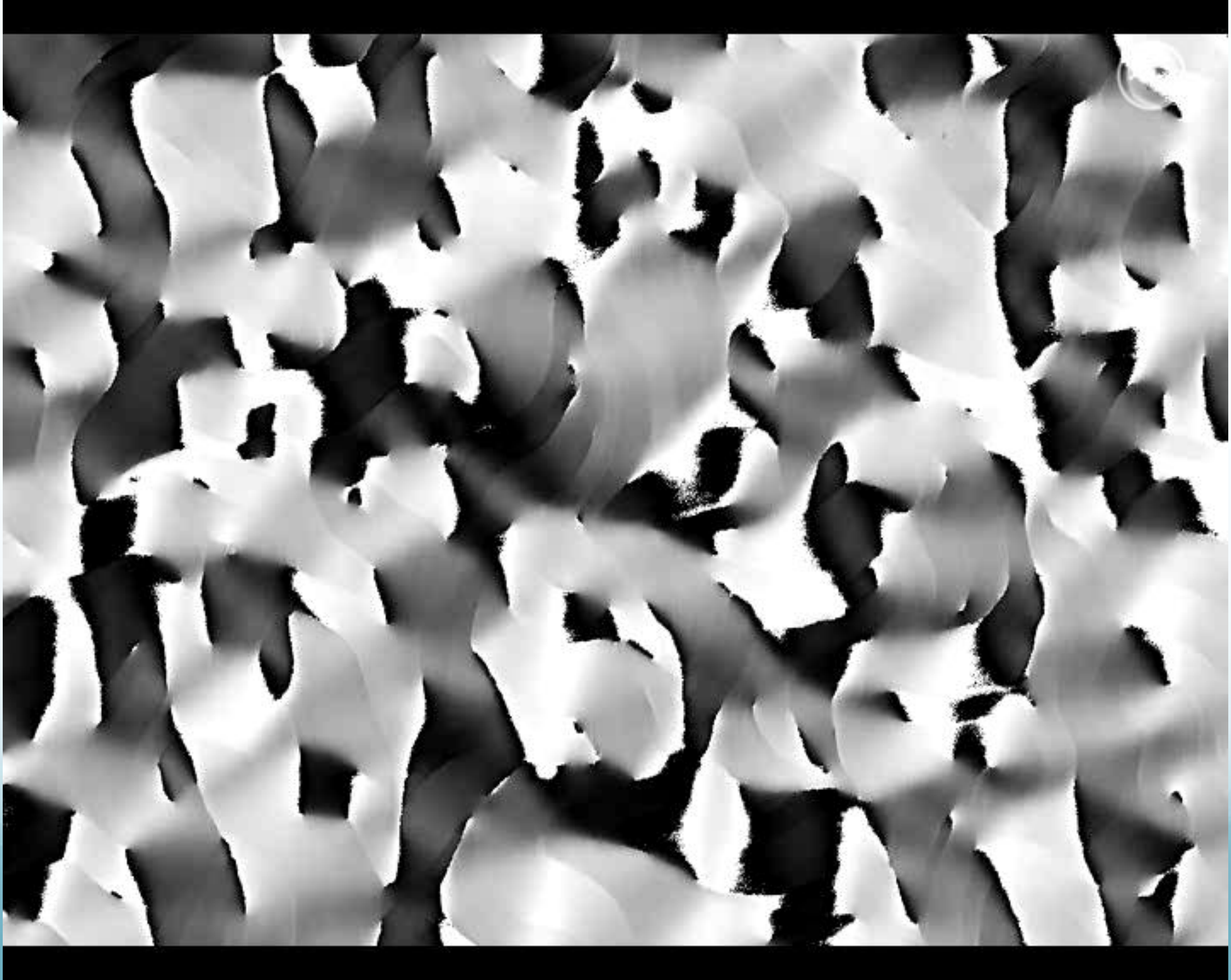
fracture line self-healing

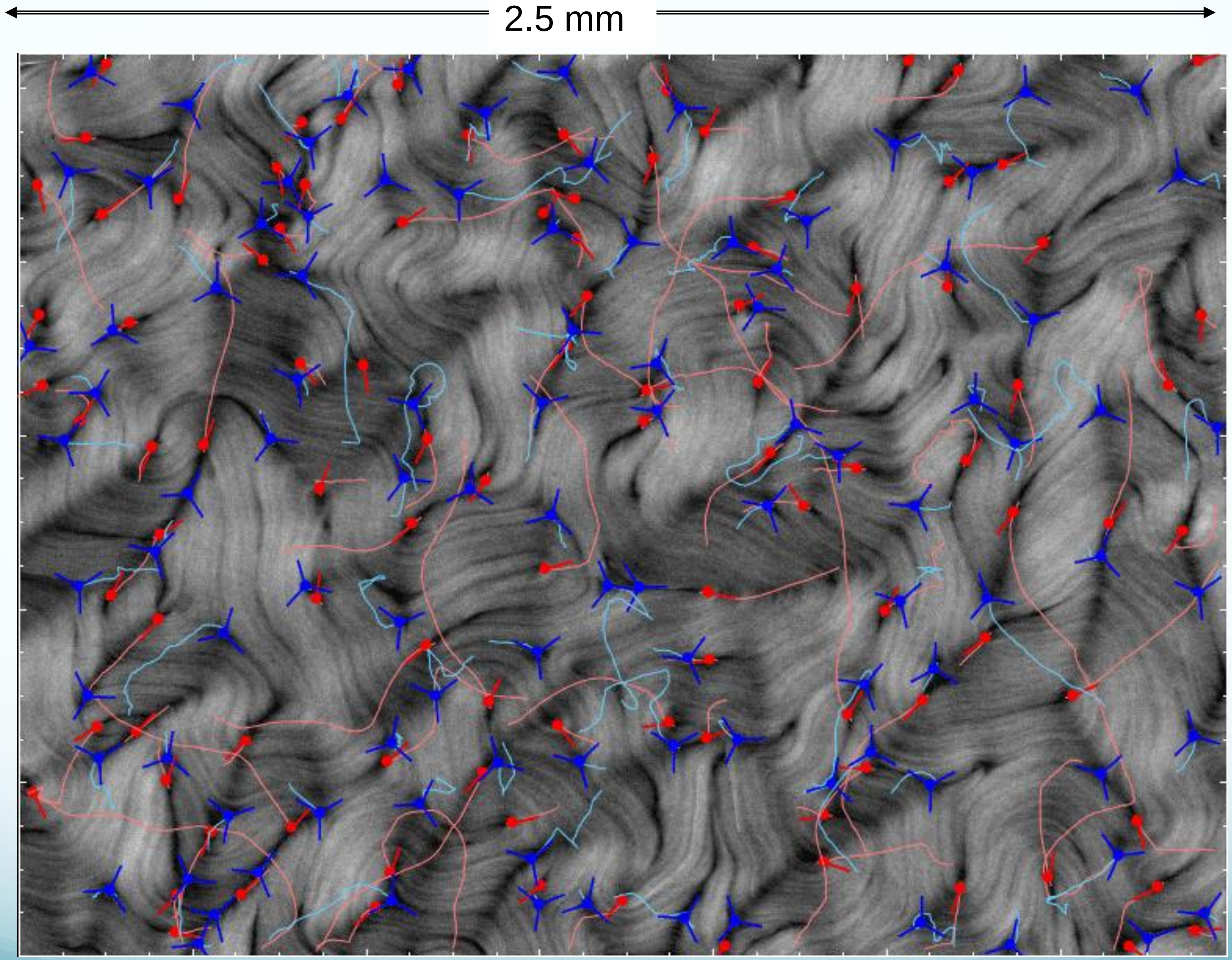
Annihilation of Defect Pairs



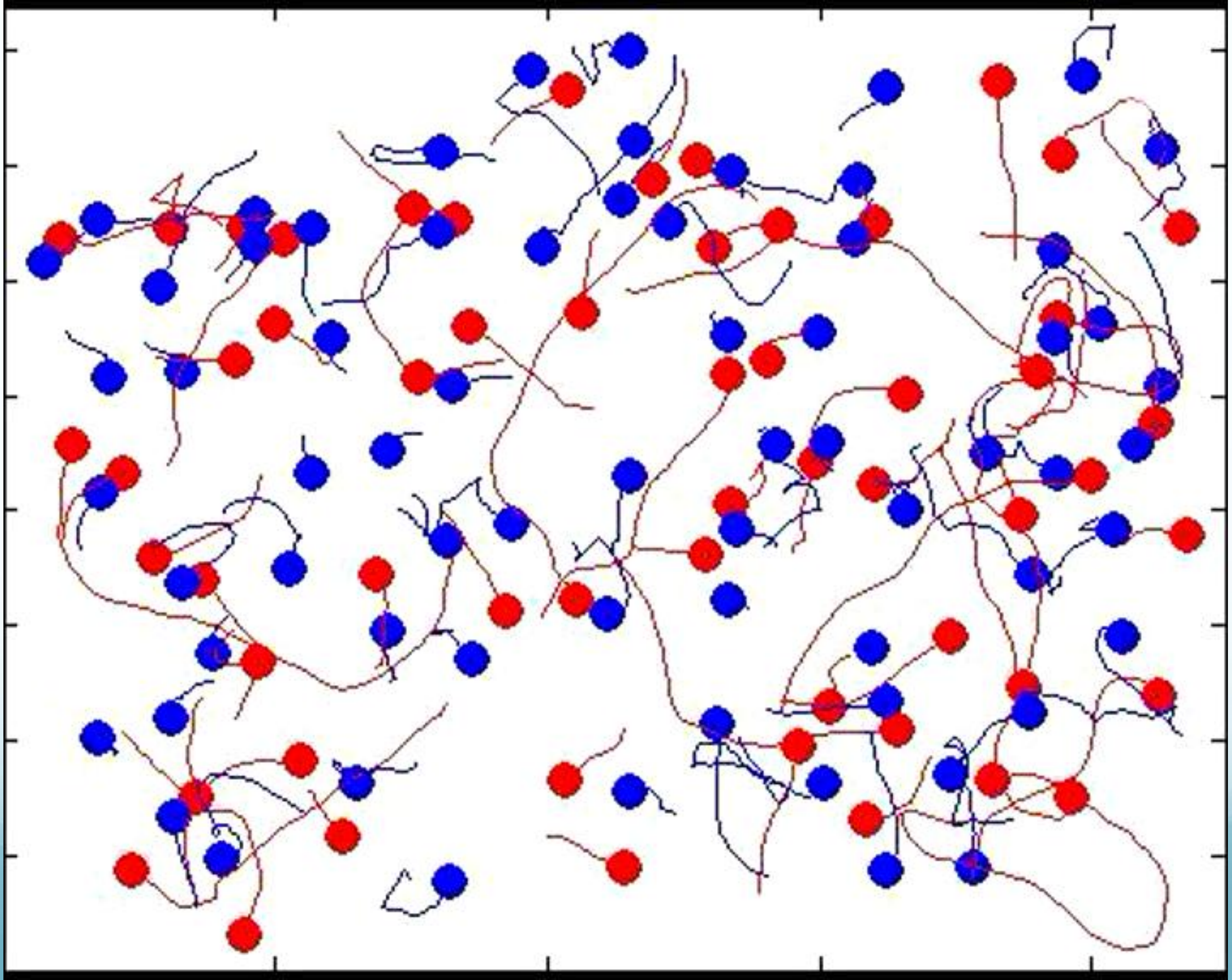
Steady state – rate of defect creation is equal to rate of defect annihilation



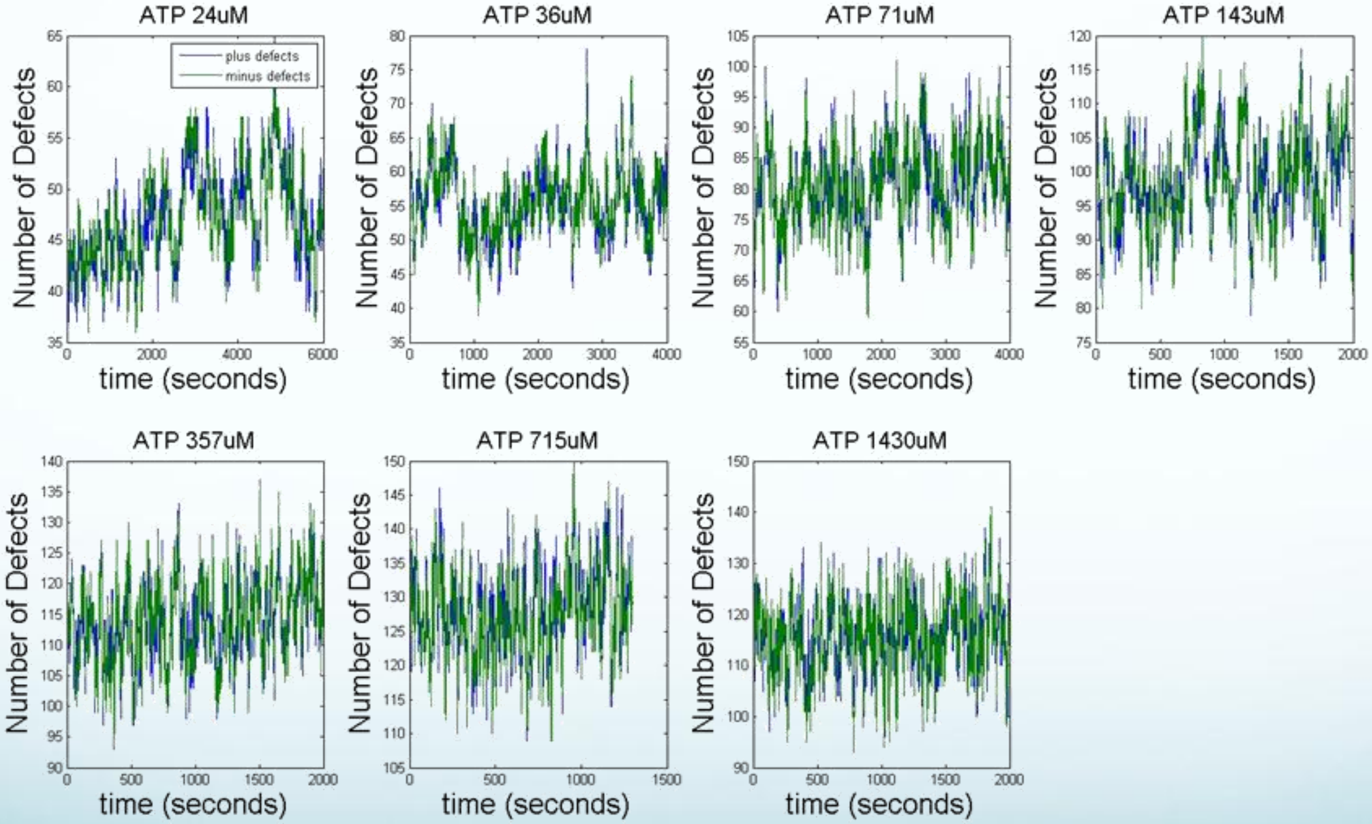




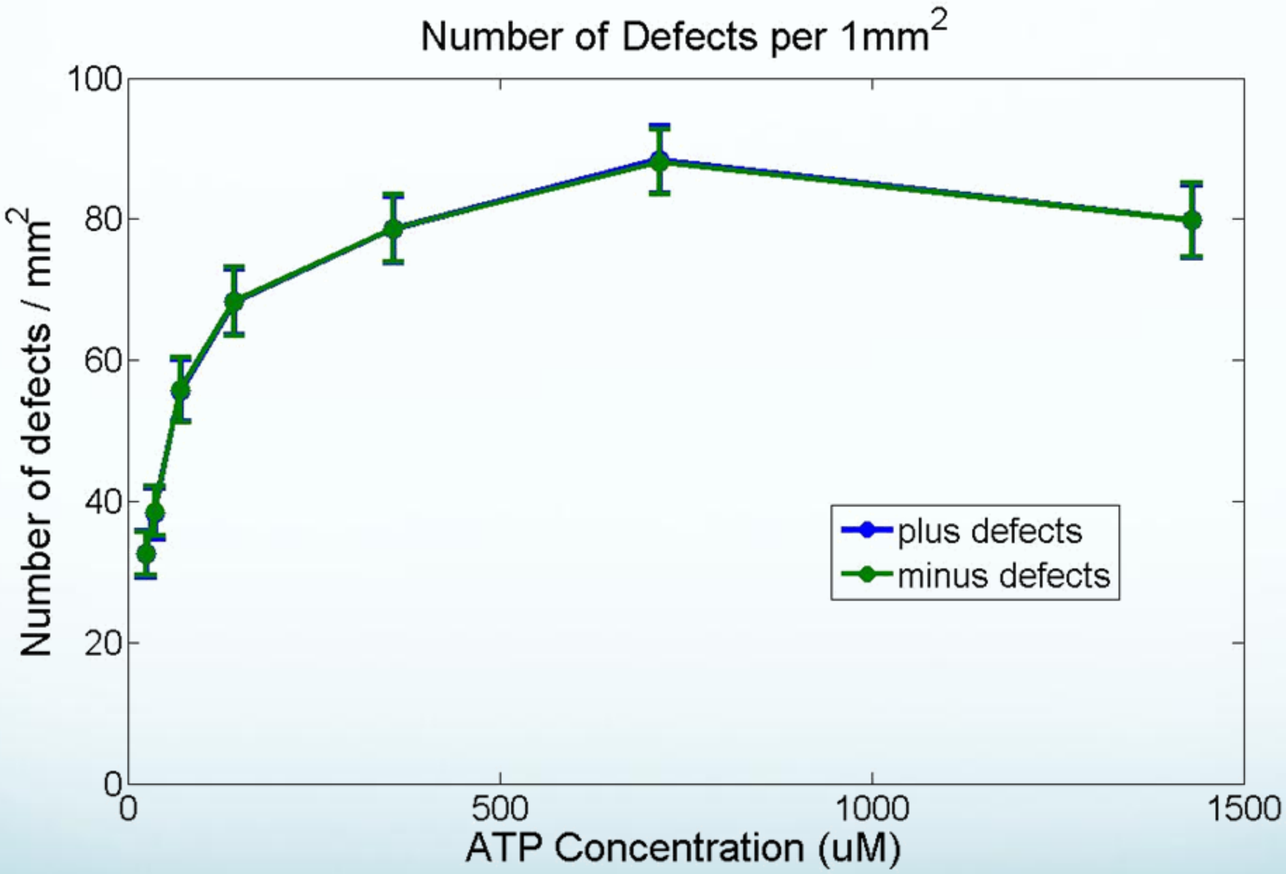
steady-state rate of defect creation and annihilation



Number of Defects vs Time

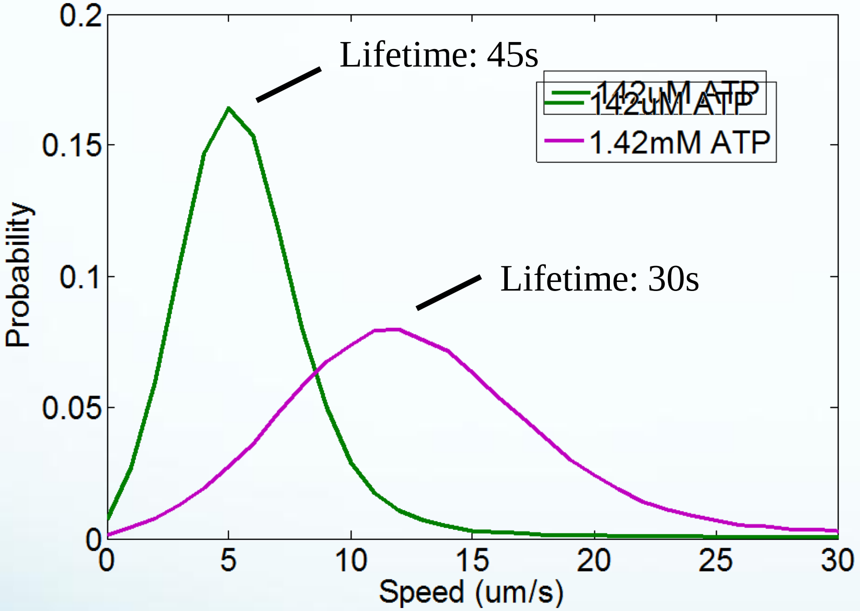


Defect Density



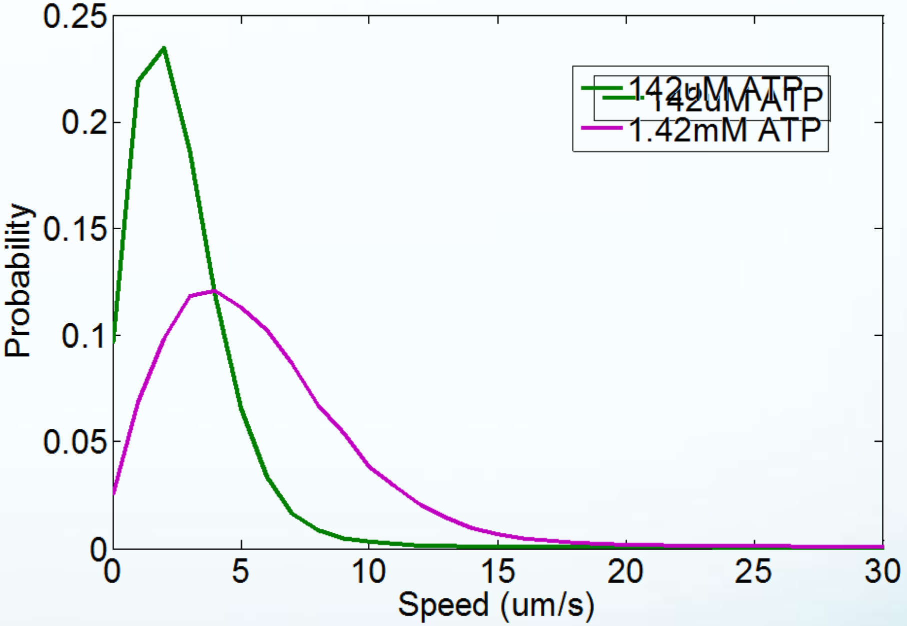
Tunable Defect Speeds

Speed of +1/2 Defects


Lifetime: 45s

Lifetime: 30s

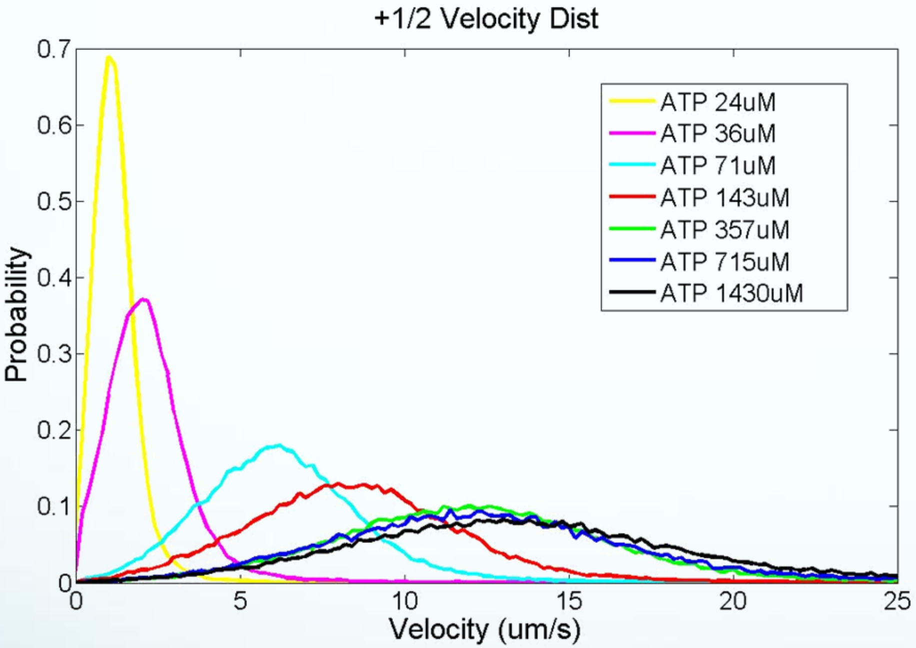
Speed of -1/2 Defects

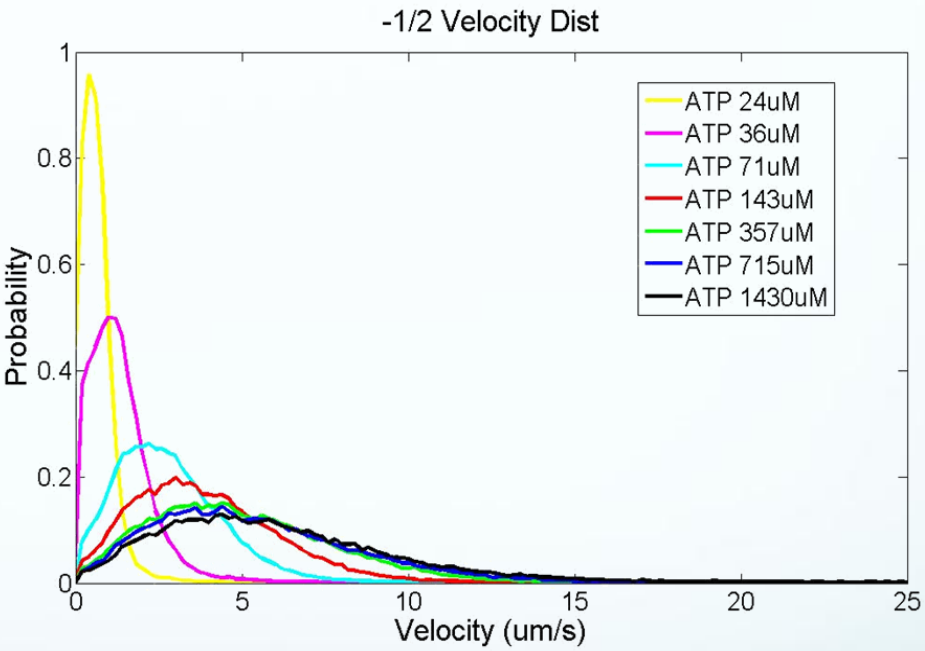


+1/2 Defects stream faster than -1/2 defects.
System is tunable – [ATP] tunes activity

Speeds from inter-frame displacements.

Tunable Defect Speeds

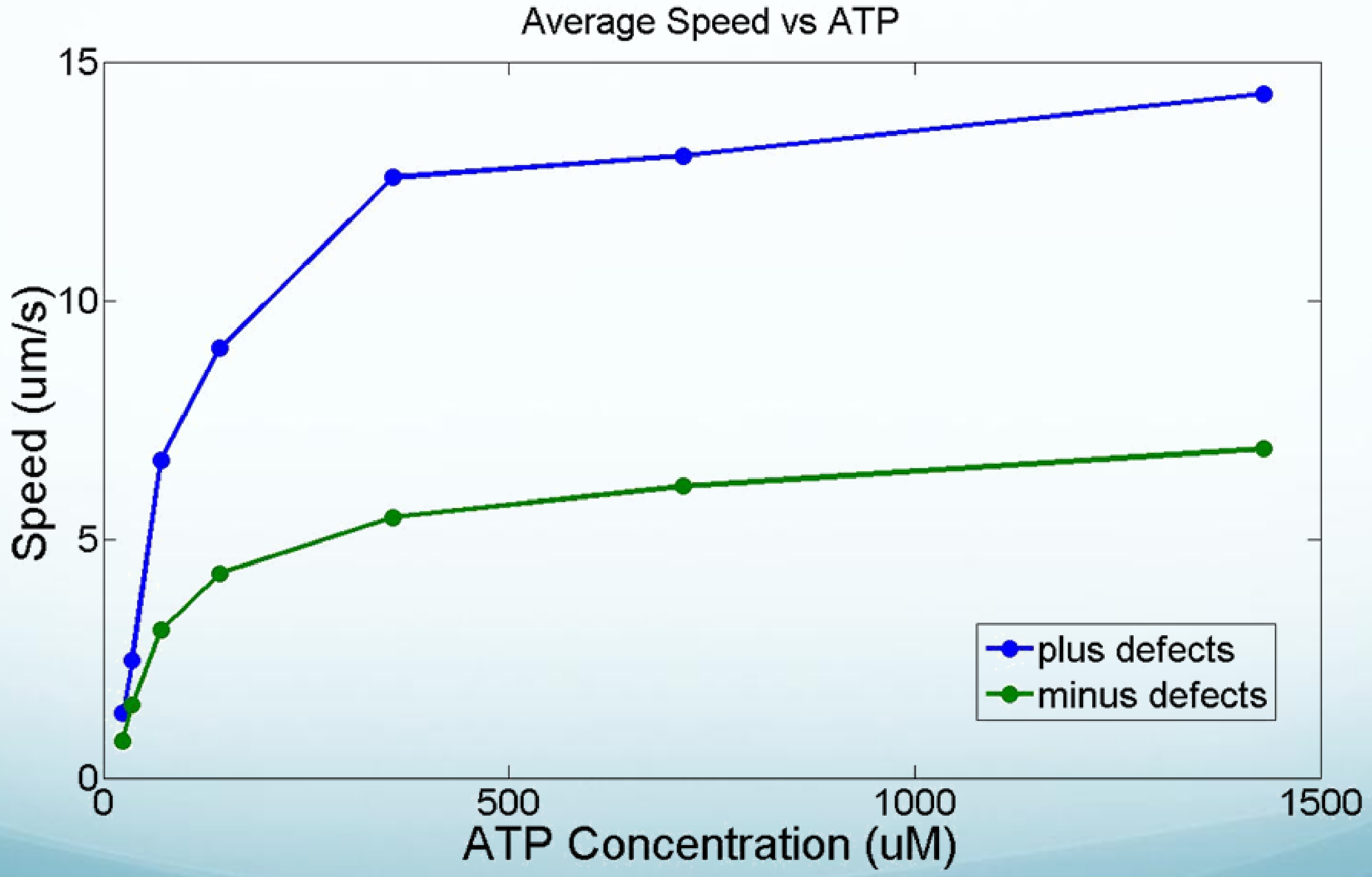




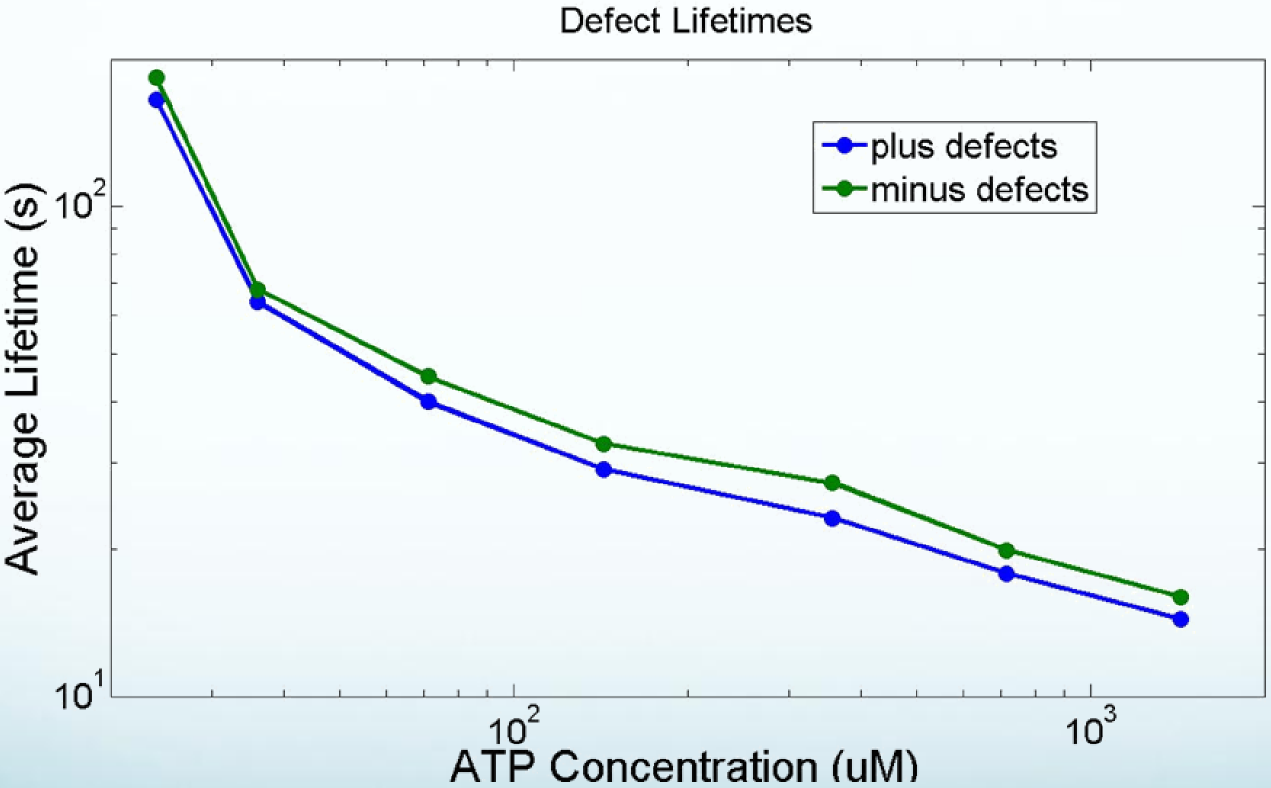
+1/2 Defects stream faster than -1/2 defects.
System is tunable – [ATP] tunes activity

Speeds from inter-frame displacements.

Average Speed vs ATP

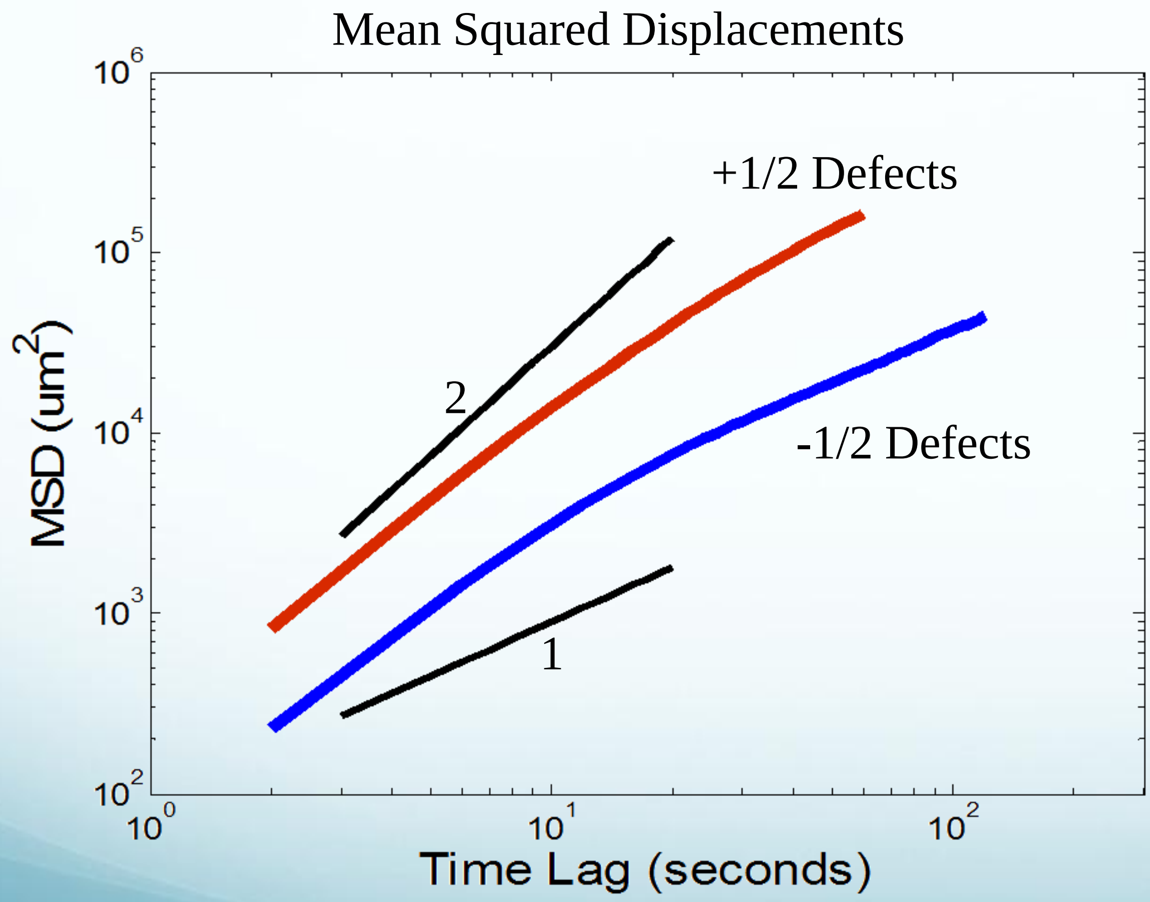


Defect Lifetimes



The average lifetime of a defect vs ATP concentration.

Defect MSDs

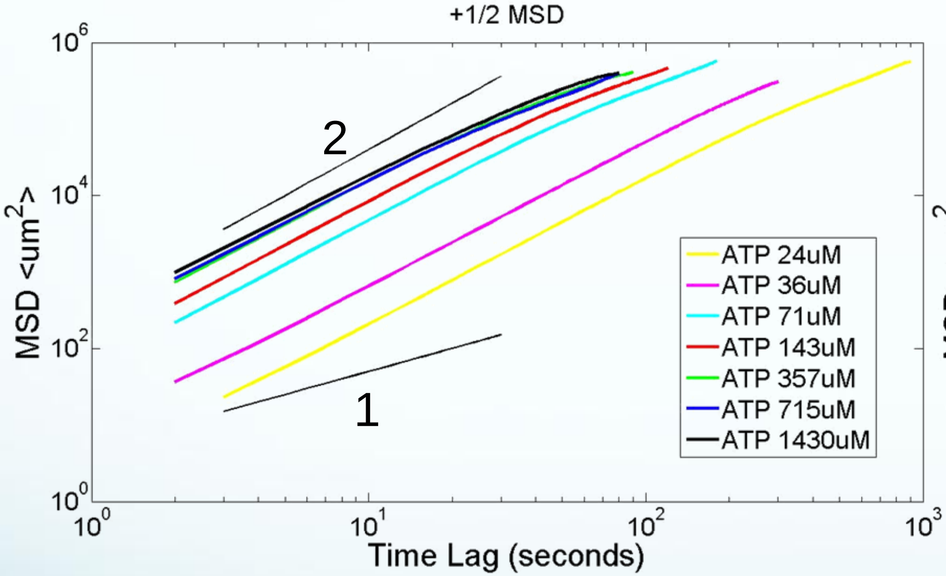


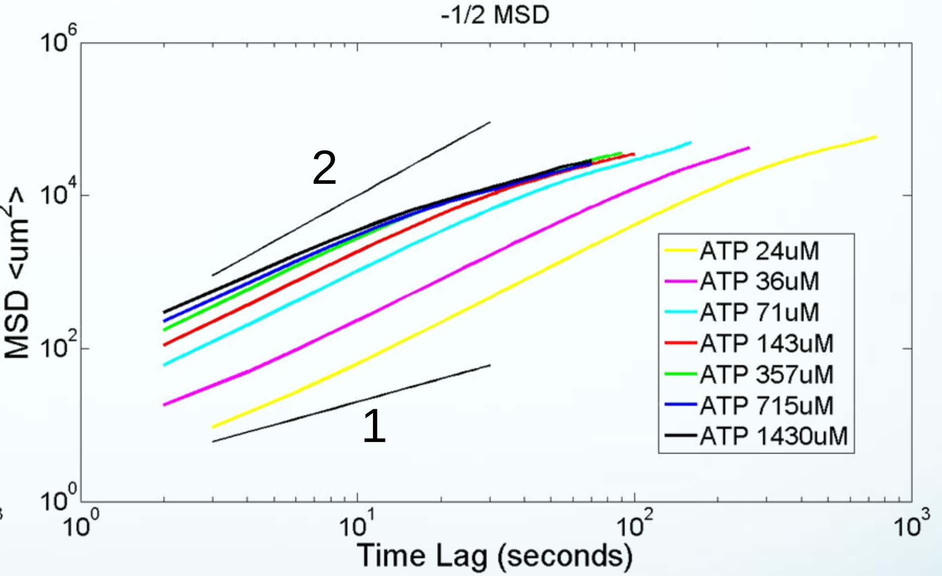
Asymmetric +1/2 defects drive motion of -1/2 defects.

-1/2 defects exhibit Brownian-like dynamics due to random kicks by +1/2 defects.

Data for 1.42mM ATP

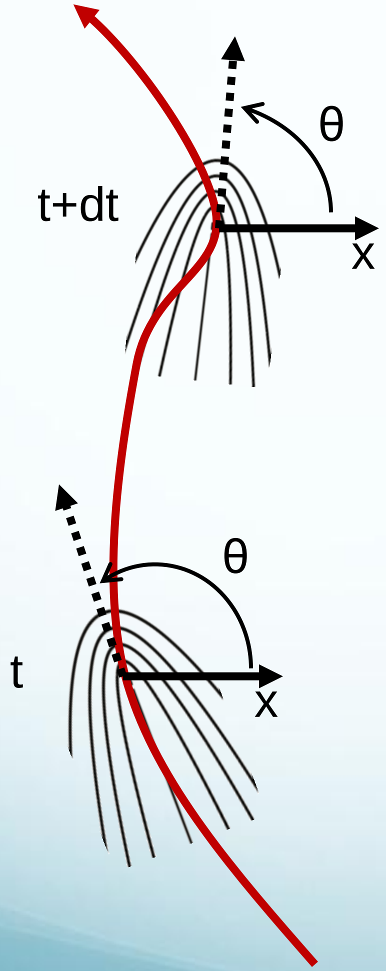
Defect MSDs vs ATP



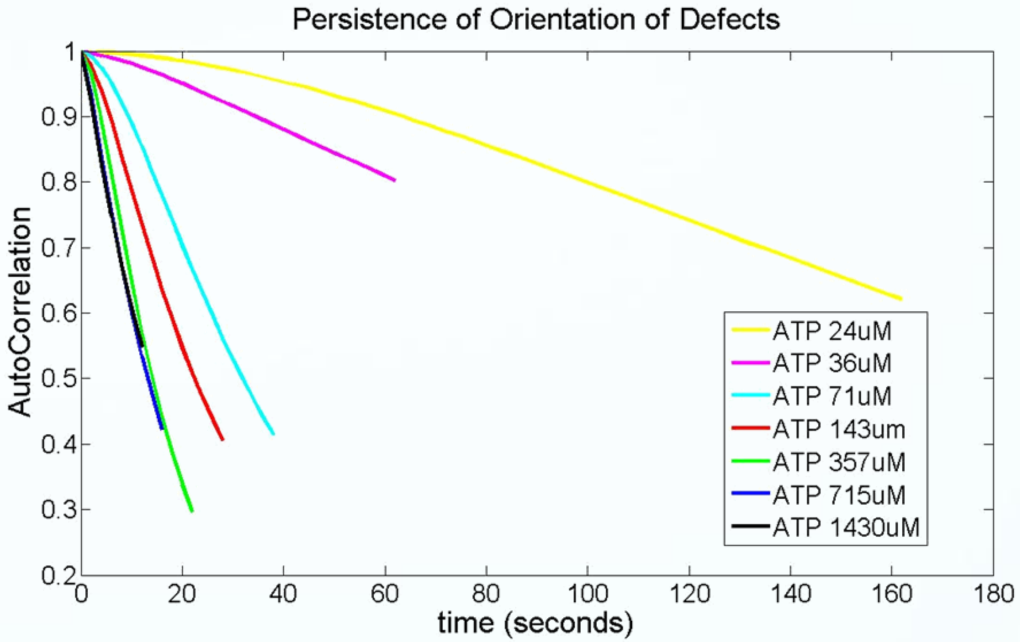


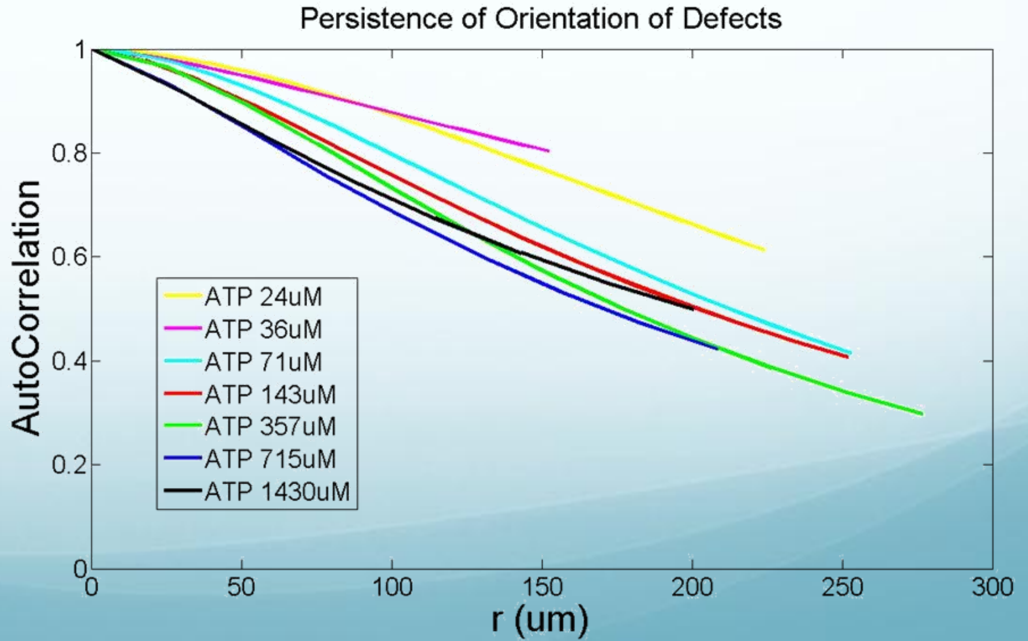
Persistence of Orientation

< θ(t) * θ(t+dt) >

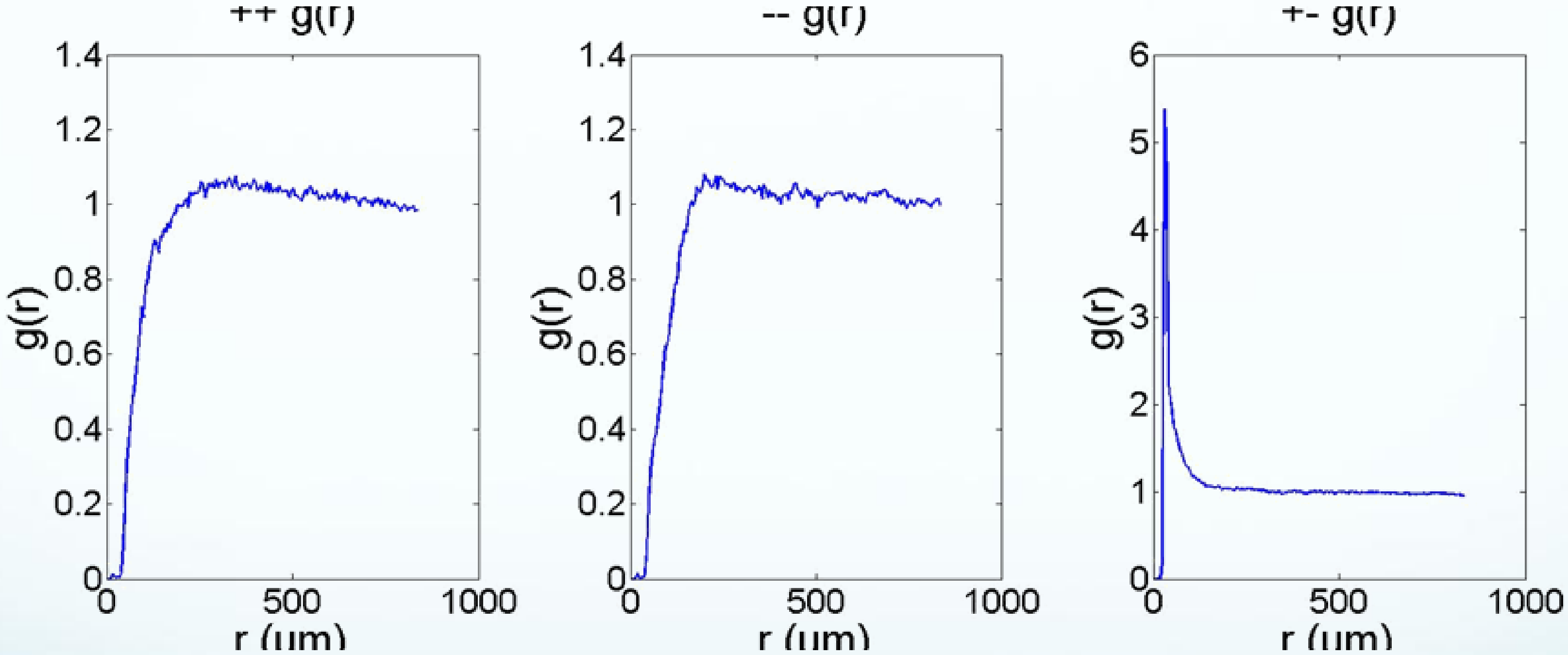


+1/2 Defect Trajectory

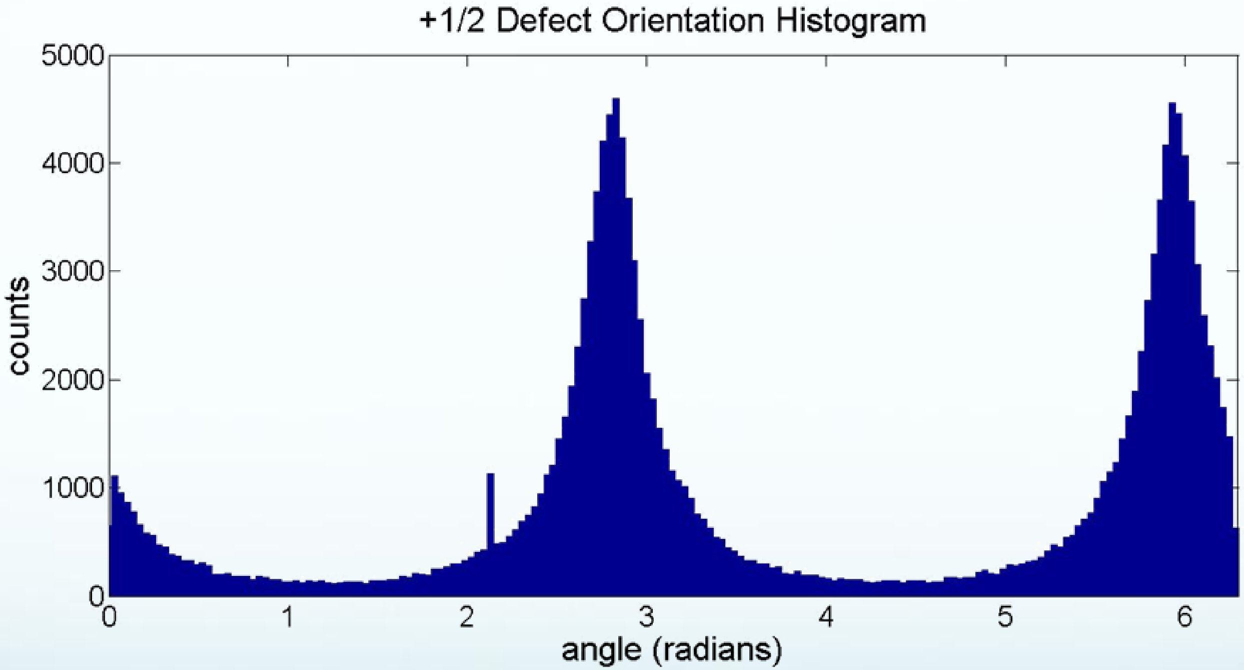




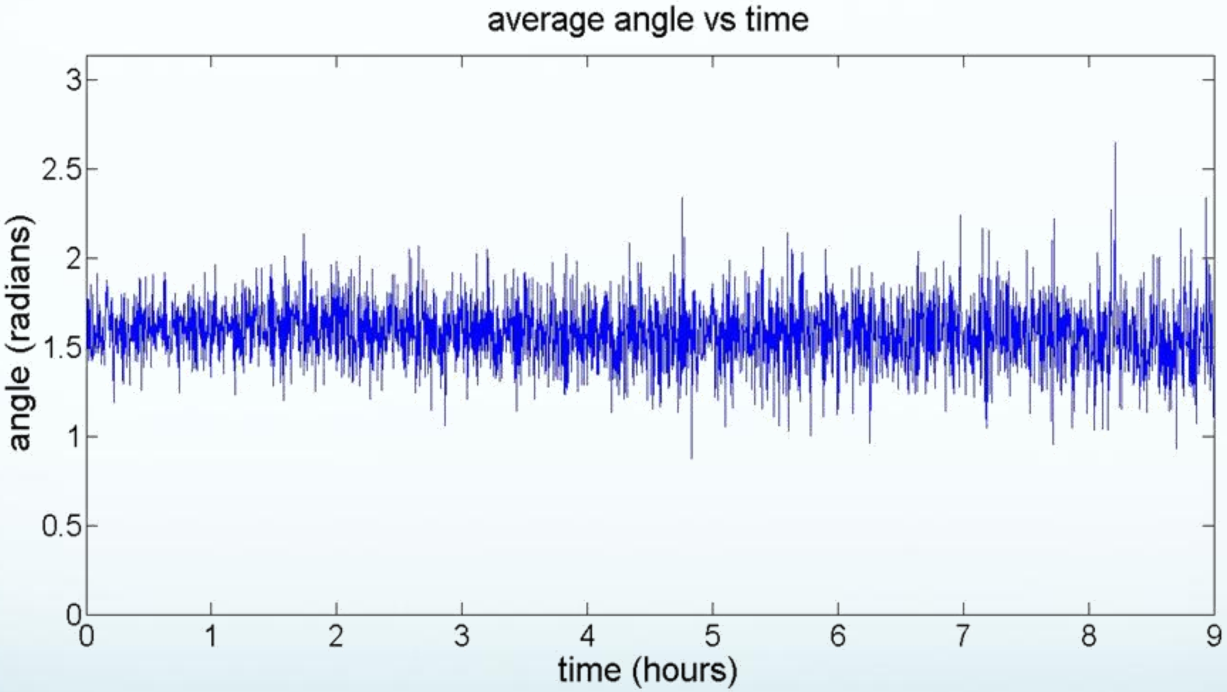
Spatial structure of active nematic defects



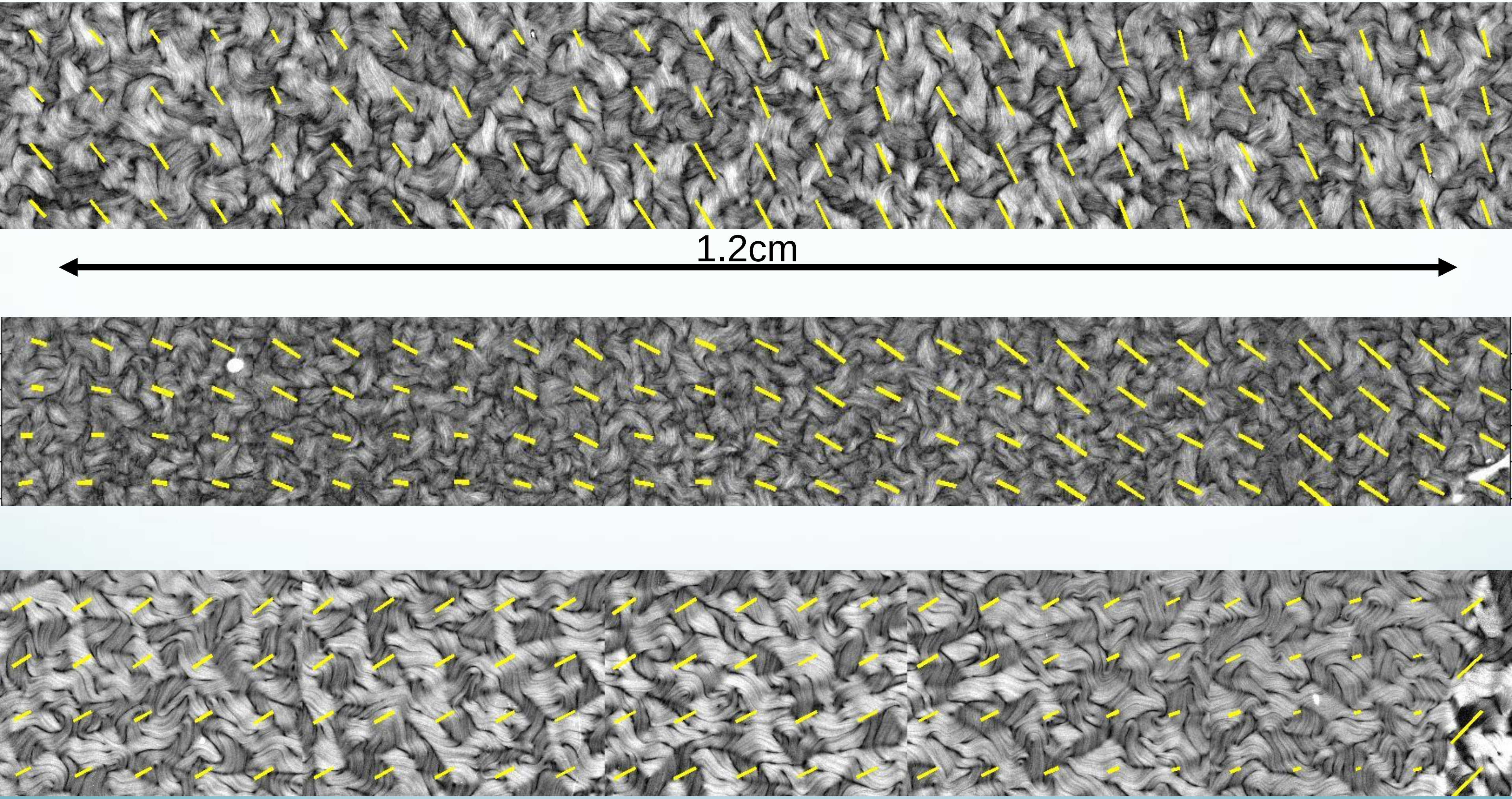
+1/2 defect from a nematic phase



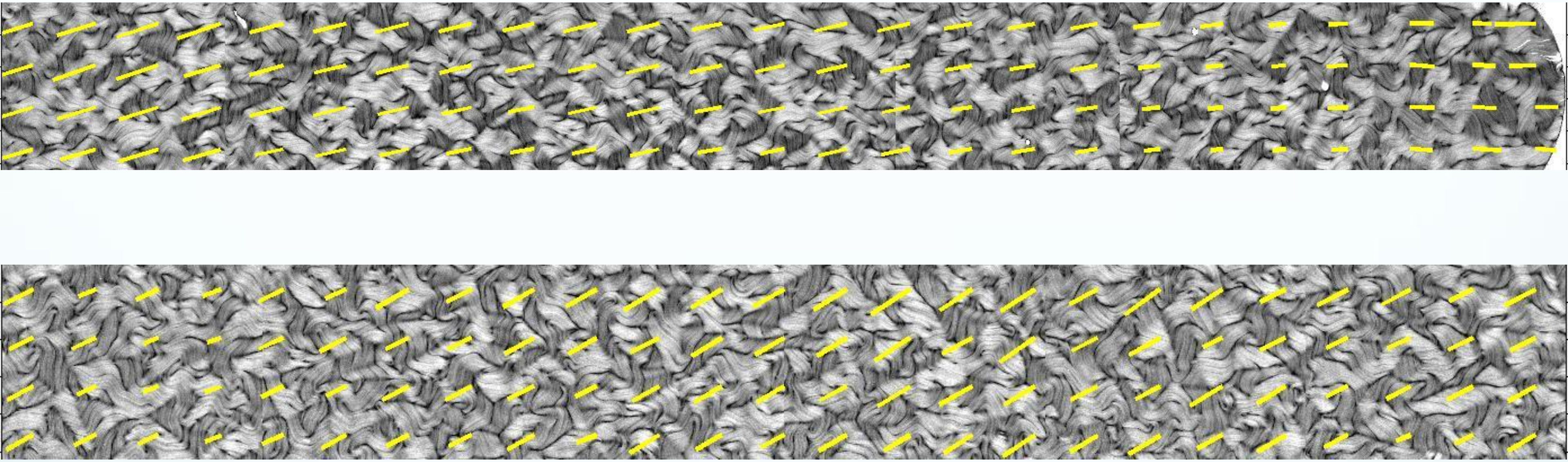
Time evolution of nematic director



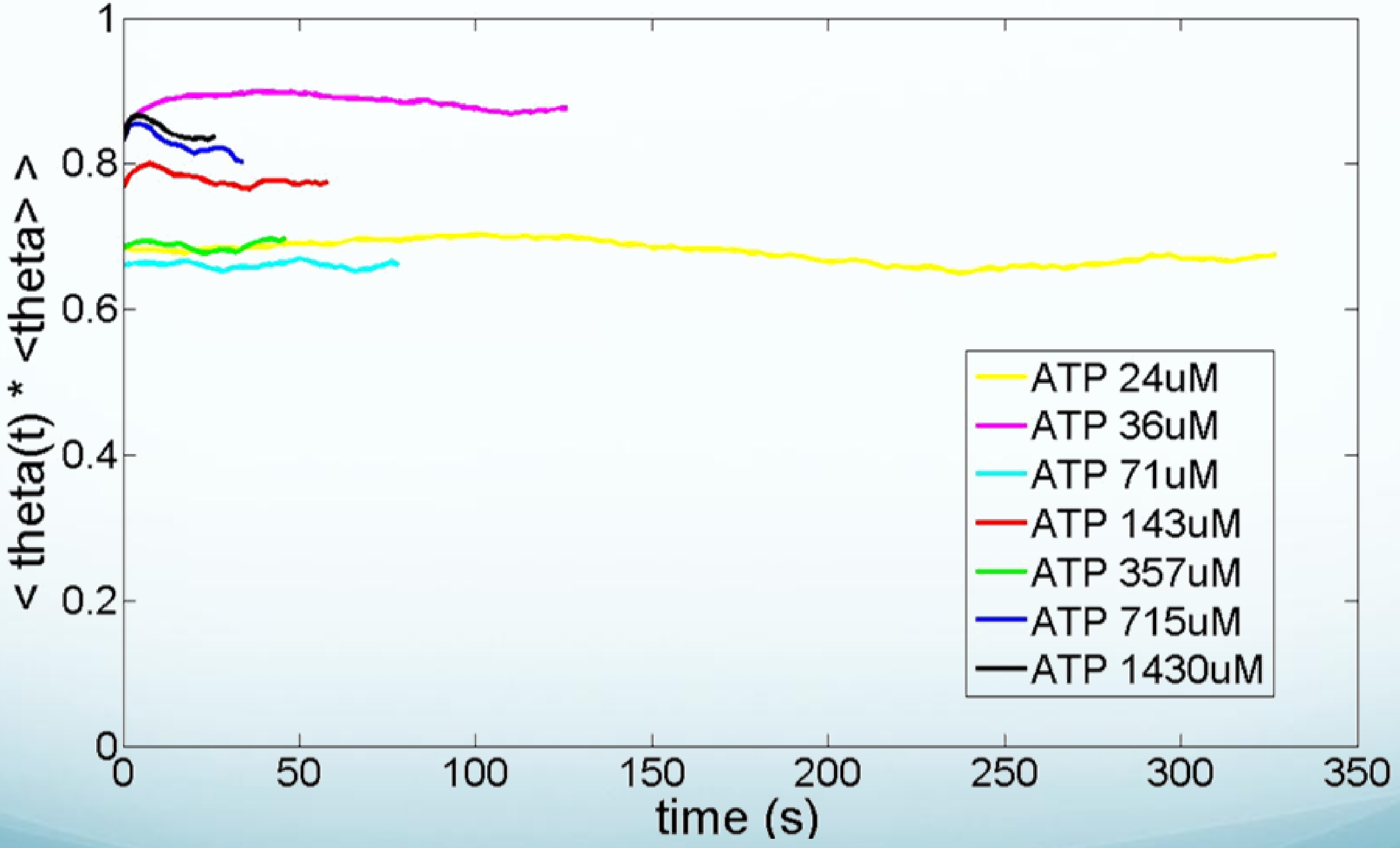
Large Spatial Coherence



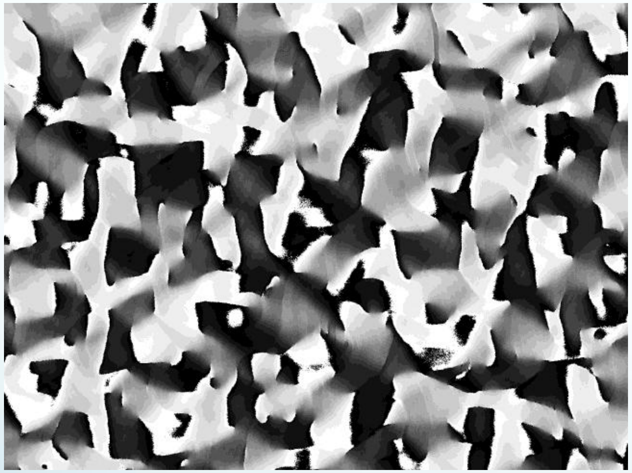
Large Spatial Coherence

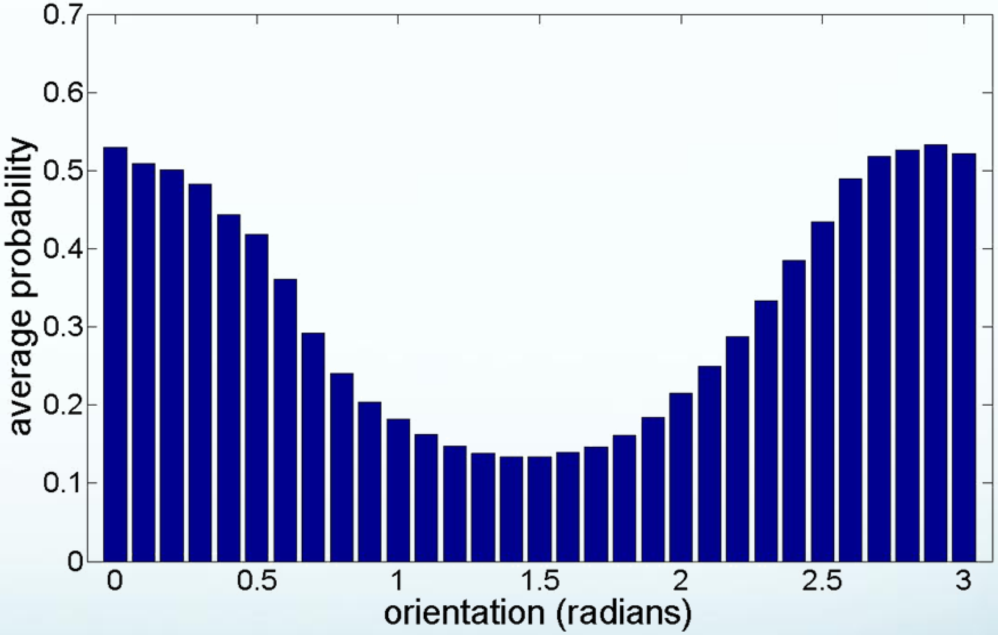


Defect orientation does not depend of the defect age



Average Nematic Director Orientation

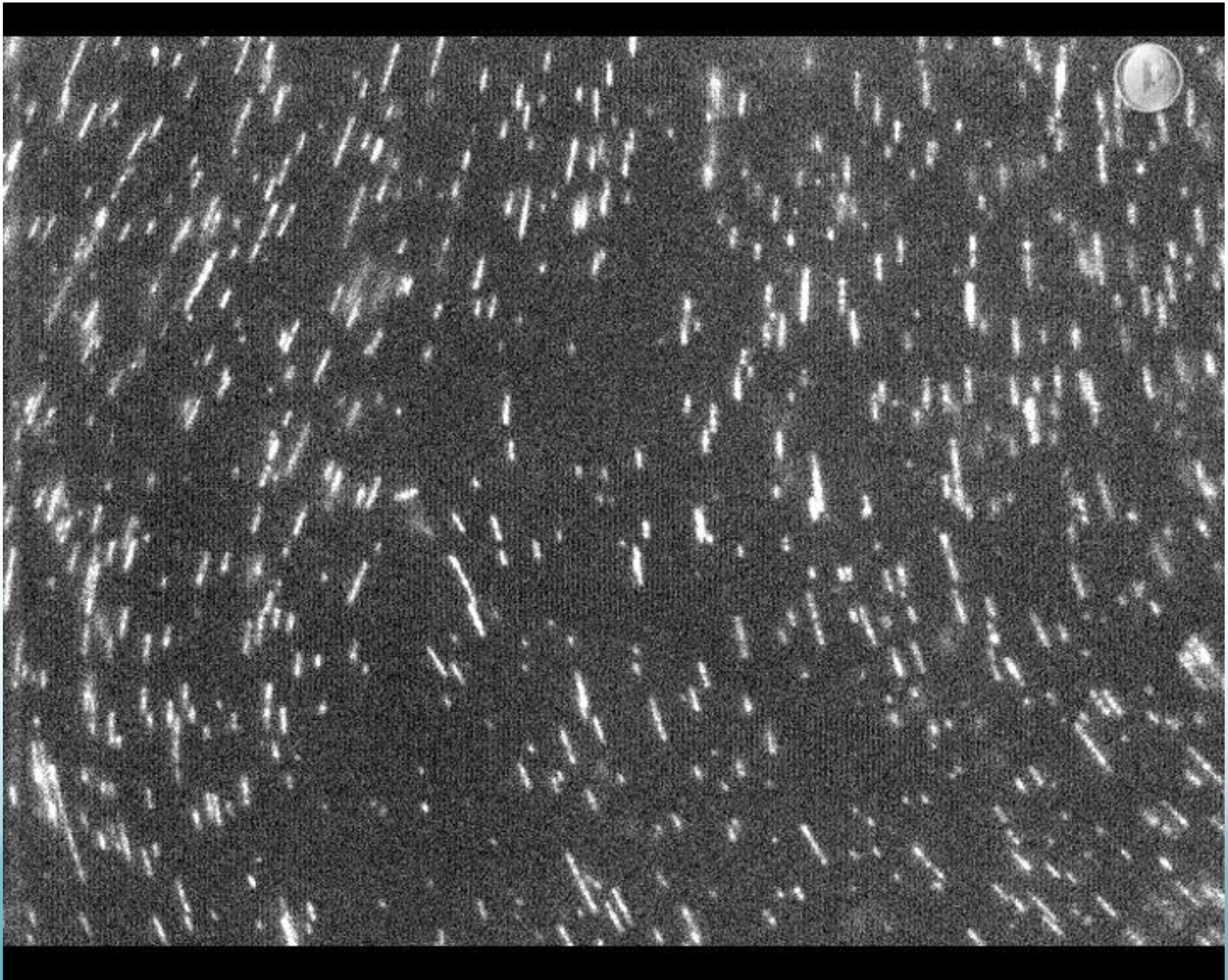




2D active nematics

- bend deformation is unstable – gives rise to defect generation
- steady state – balanced rate of defect generation and annihilation.
- at larger scales defect organize into a nematic recovering long range order
- defect velocity is determined by activity coefficient (ATP conc)

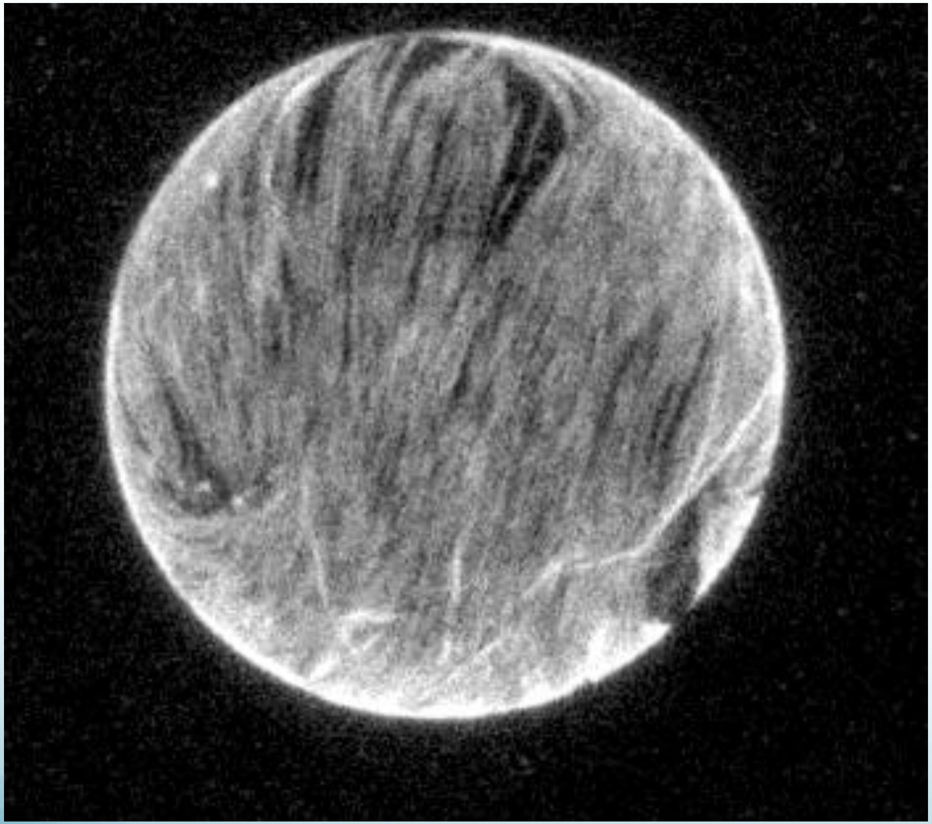
correlate flow velocity and director dynamics

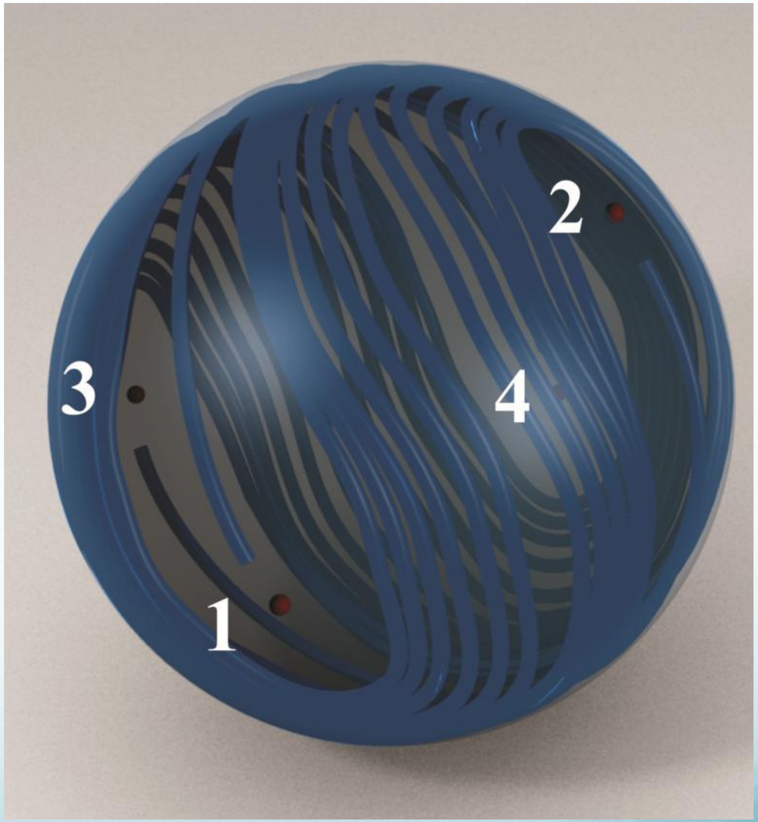


Motile defects on a spherical surface

Constraint on defect dynamics

- minimize elastic interaction energy
- move with preferred direction
- move with speed determined by activity coefficient (ATP concentration)



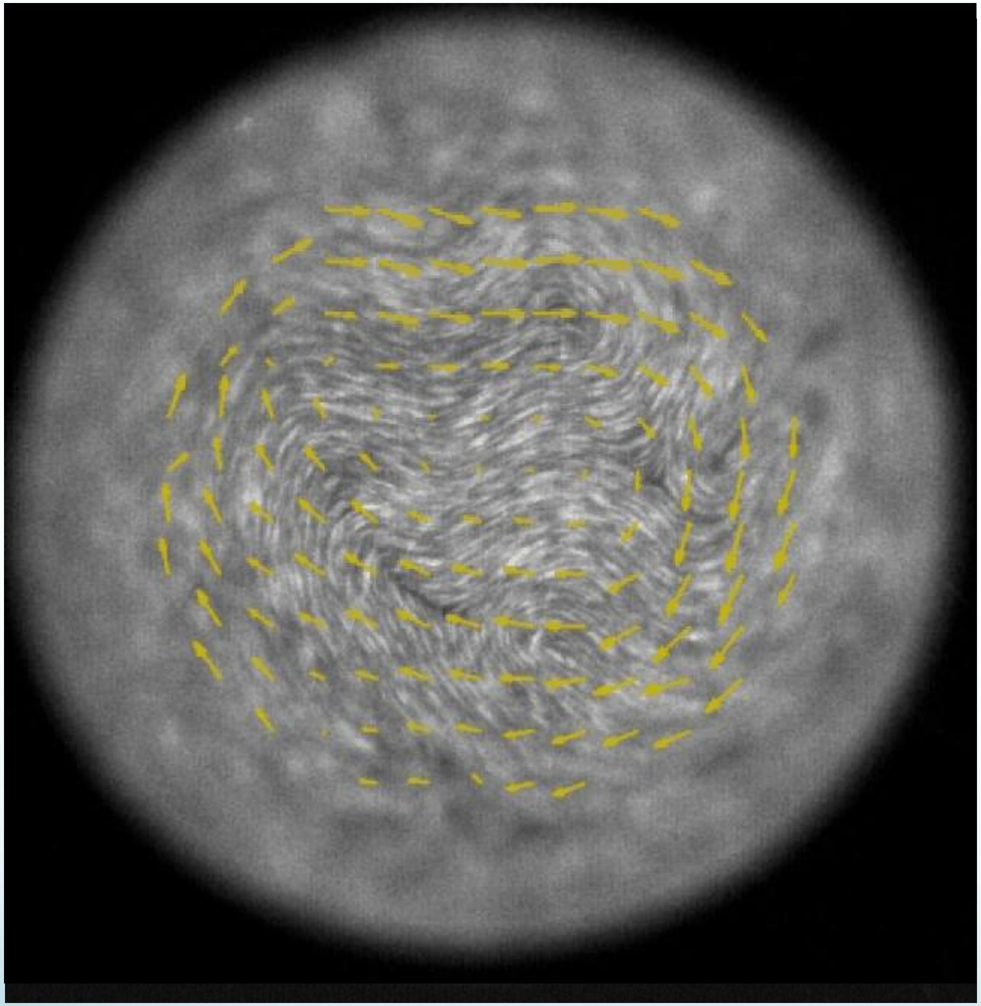


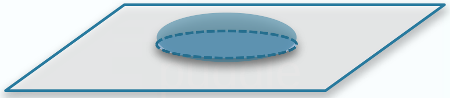
What is the defect dynamics on spherical surface?

Are trajectories chaotic or periodic?

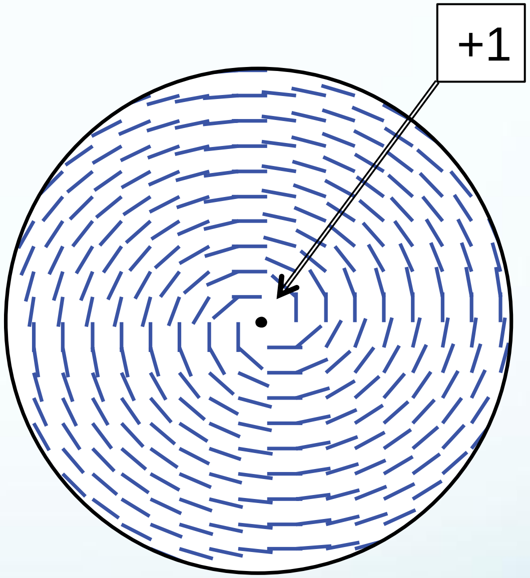
Active MT liquid crystals on a 2D circular membrane

- persistent unidirectional circular flows (> 24 hrs)





“Dome” droplet



Total charge = ½ + ½ + ½ – ½ = + 1

Can two clocks synchronize through hydrodynamic interactions?

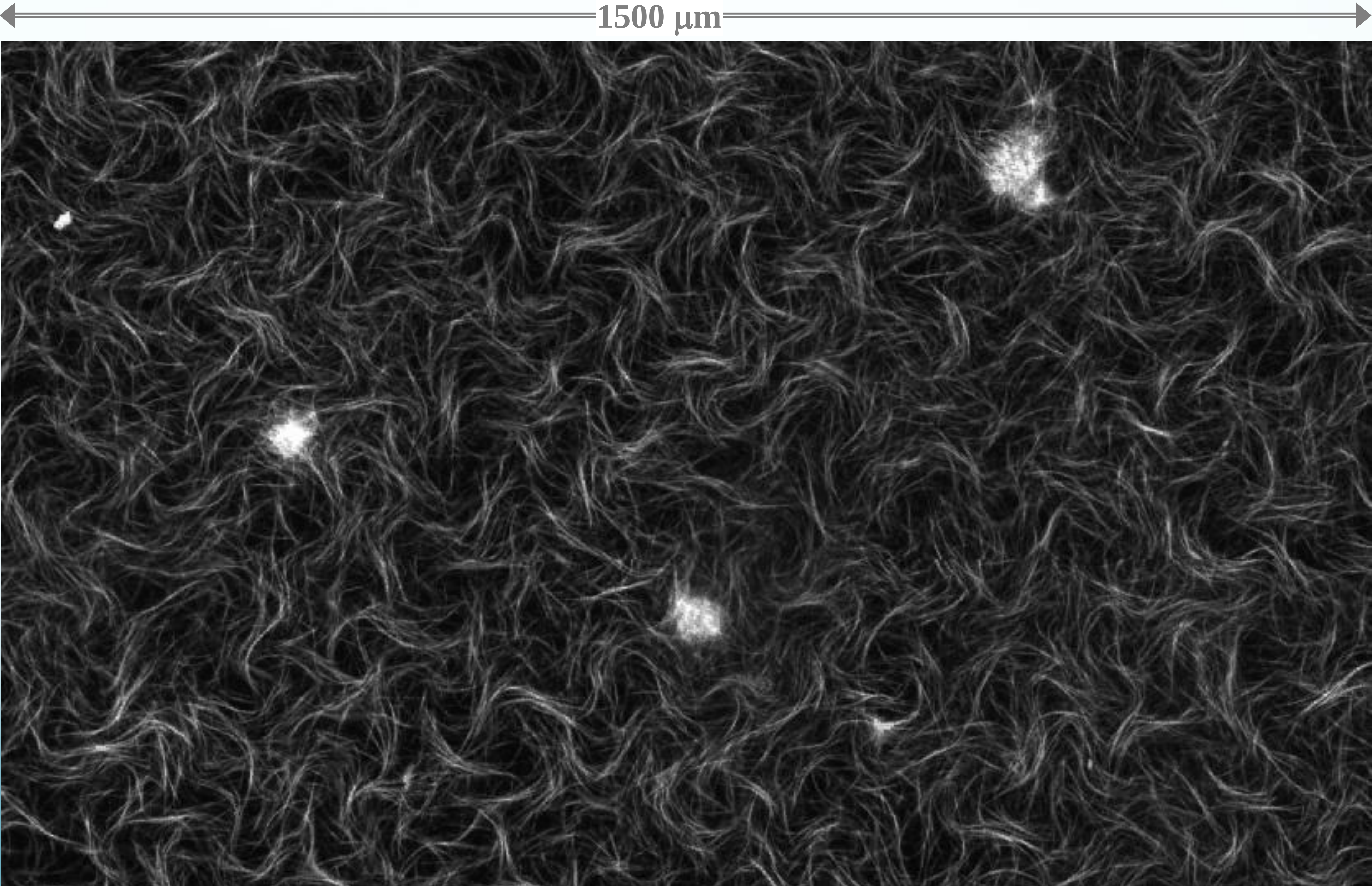
What is dynamics of active nematics on a annulus?

Isotropic active gels: solid or liquid?

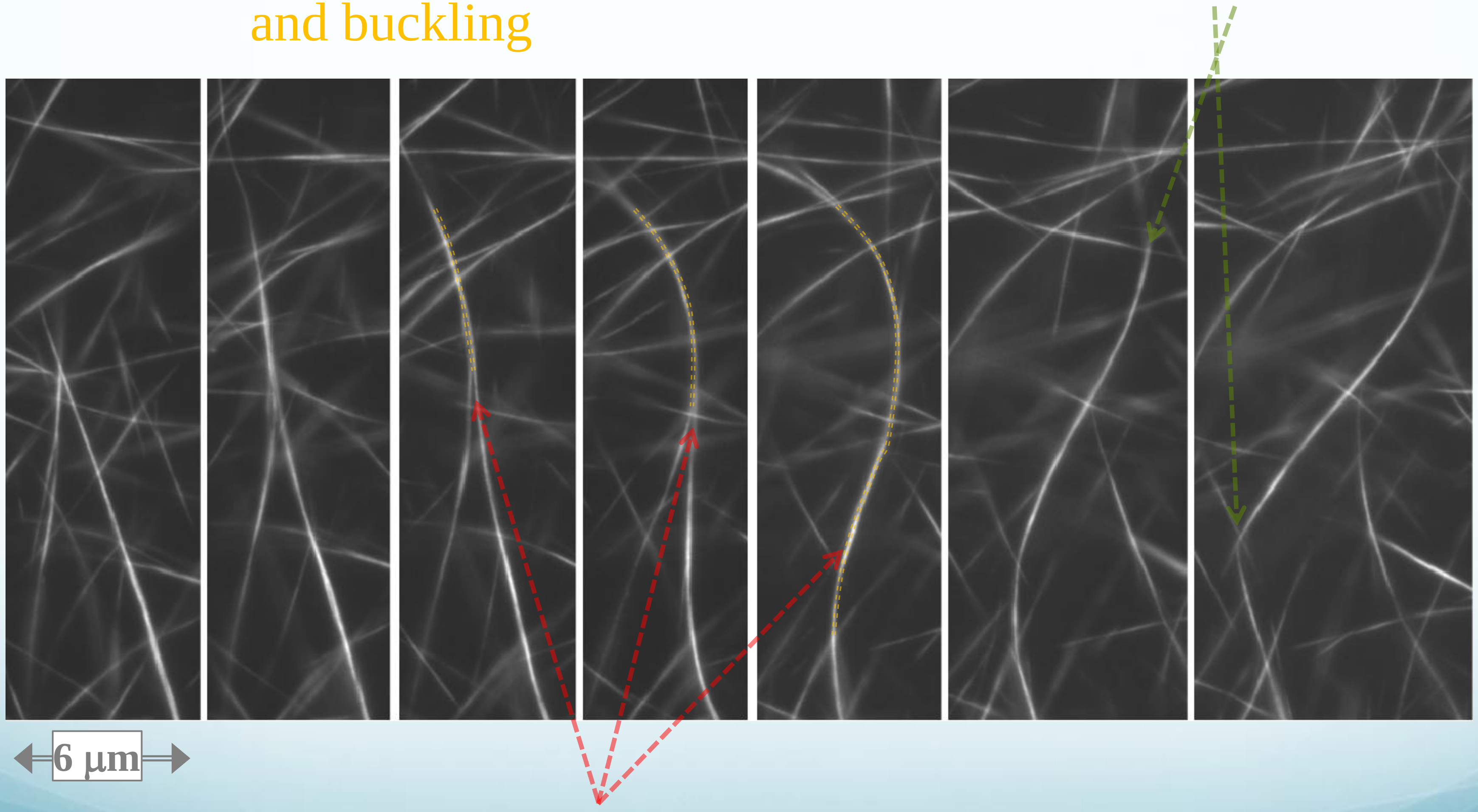
Daniel Chen

Daniel Blair

Active Isotropic Gels in 3D



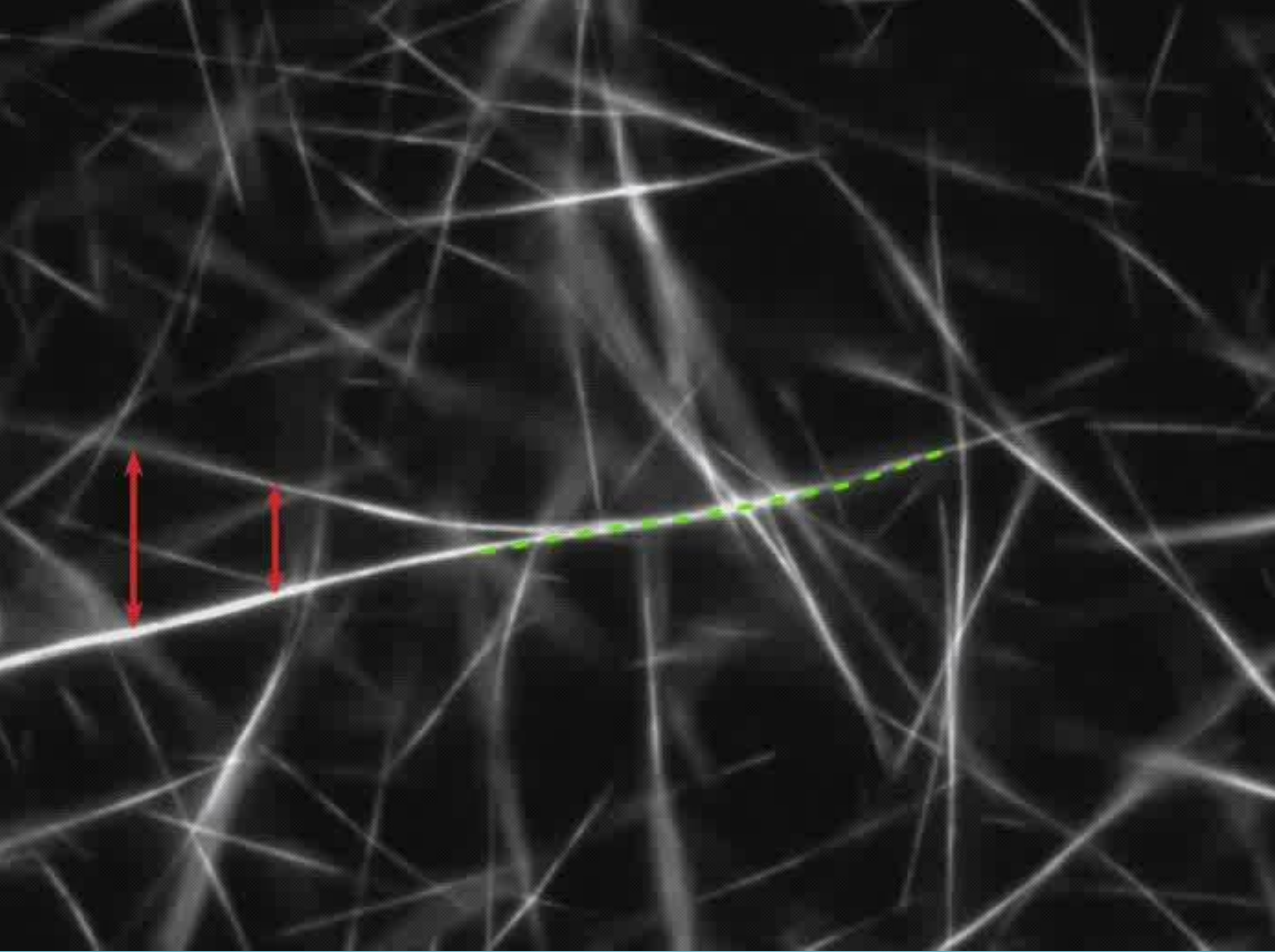
MT dynamics in active gels



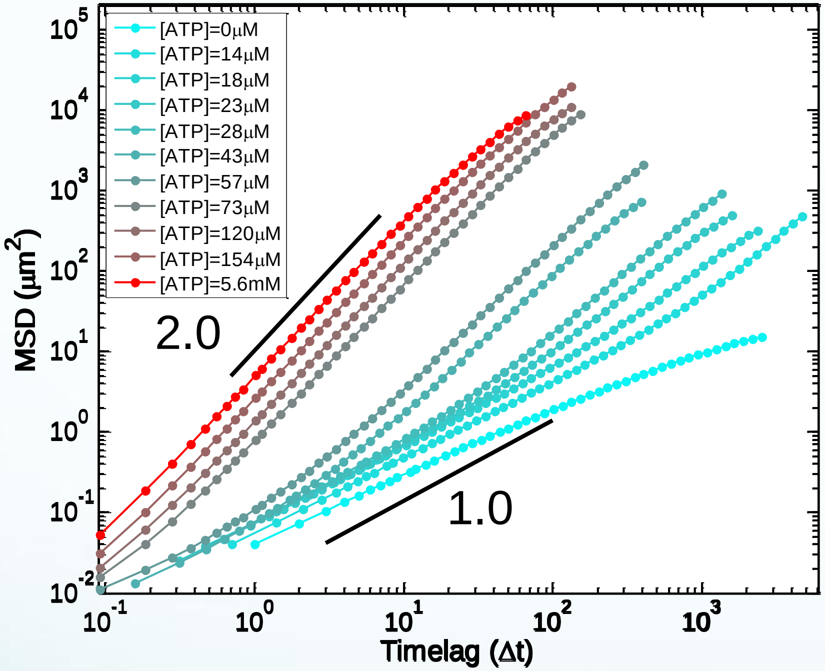
extension, polarity sorting
and buckling

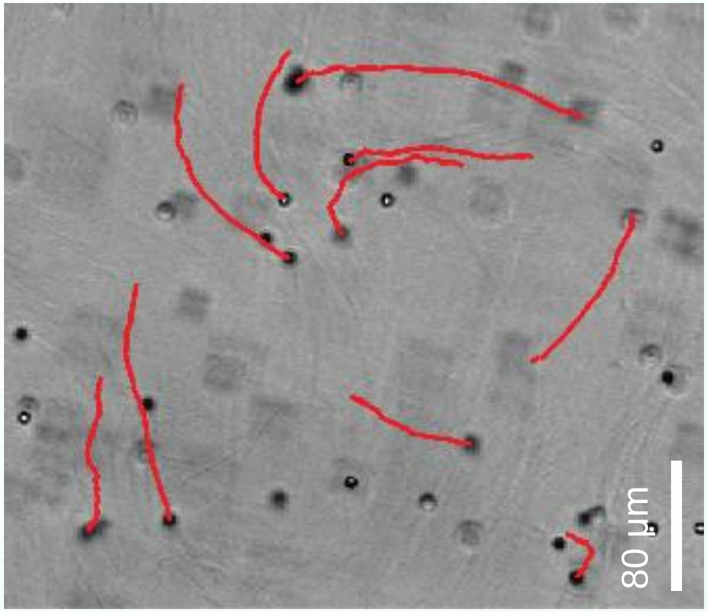
bundle fracture

bundle merging



Fluid Flow ATP-dependence: Particle MSD

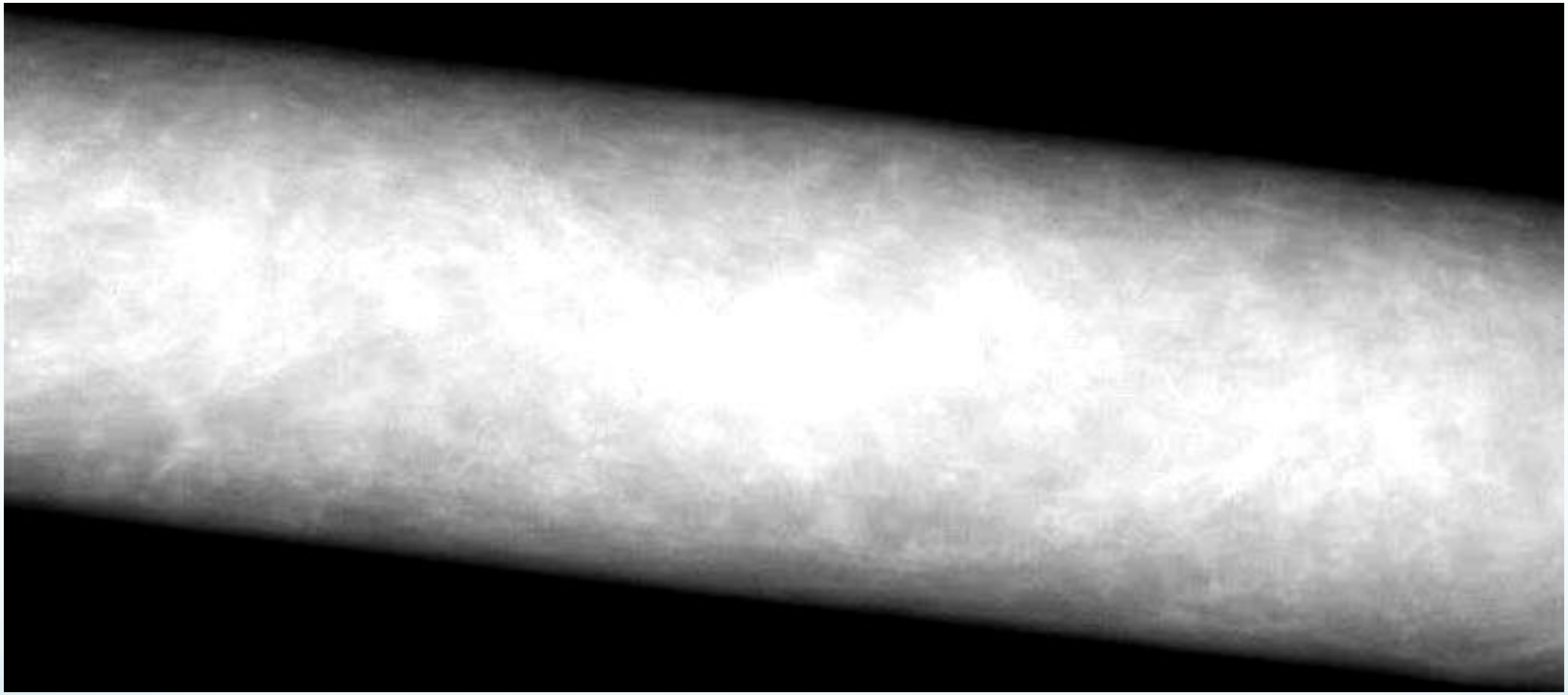




Totally tunable from subdiffusive to ballistic (equilibrium to non-equilibrium)

Recap, so far…

- assembly of isolated extensile MT bundles
- high bundle concentration – tunable active isotropic gels characterized by spontaneous internal flows, enhanced transport and mixing

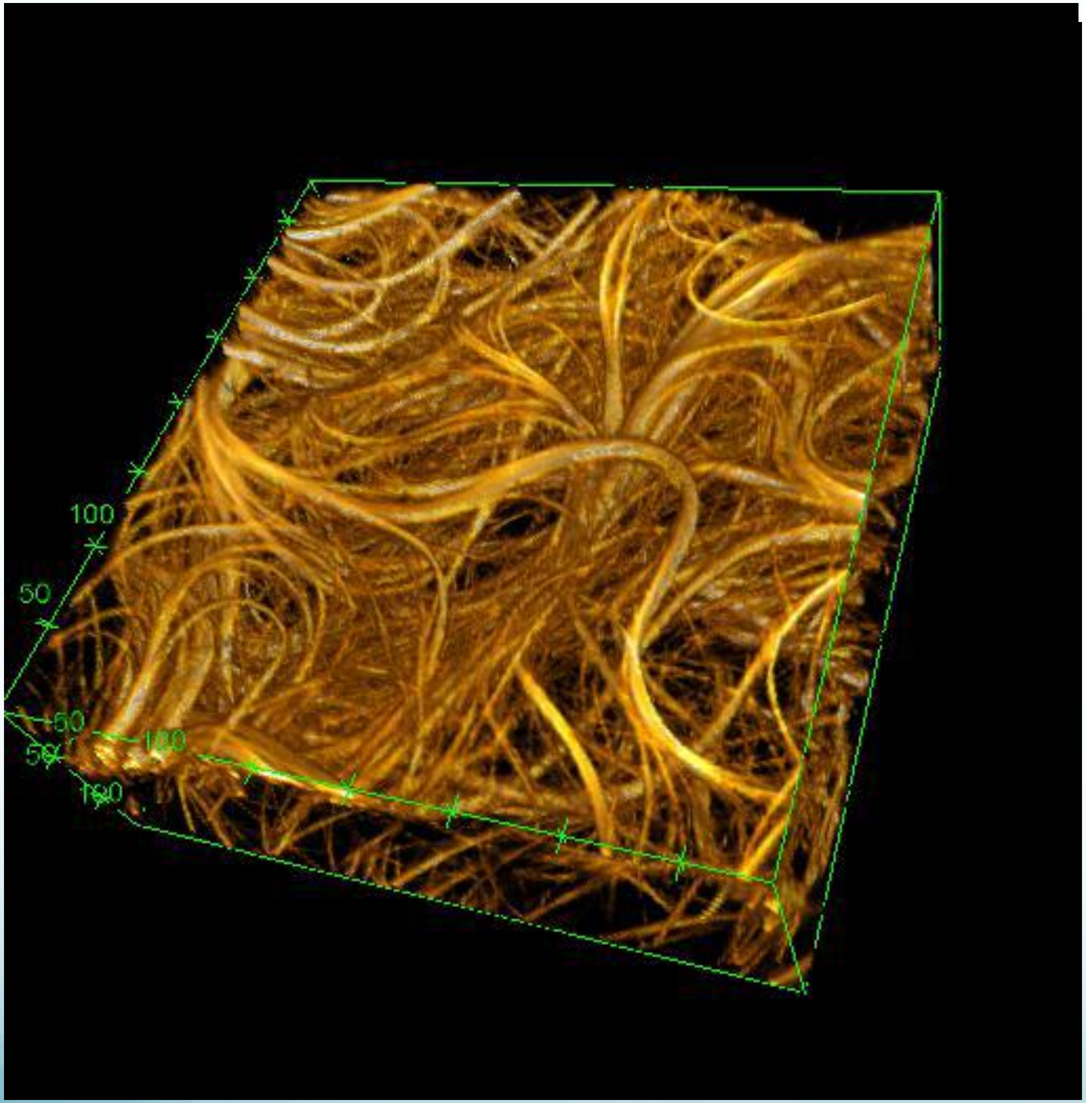


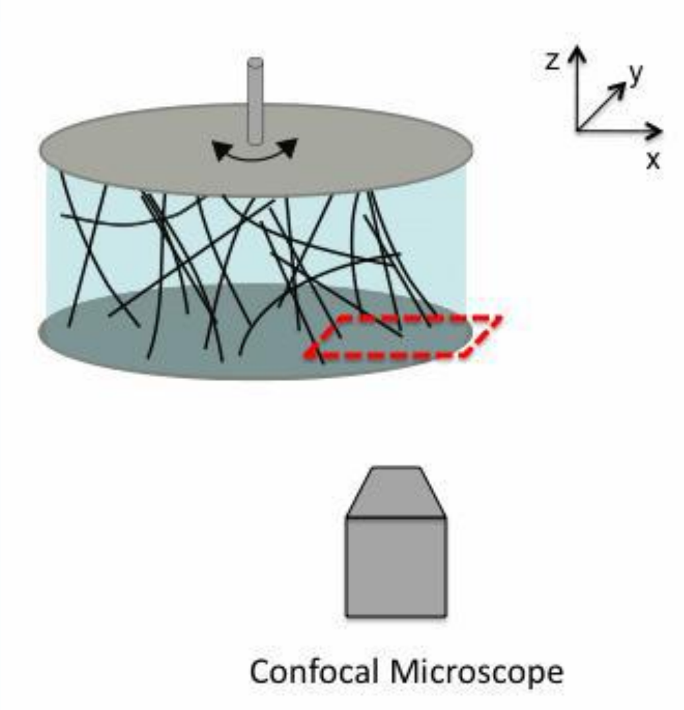
Active gels in confined geometries – emergence of spontaneous macroscopic flows

Soft materials that exerts force on their boundaries to produce macroscopic force

How does the observed behavior depend on filament concentration?

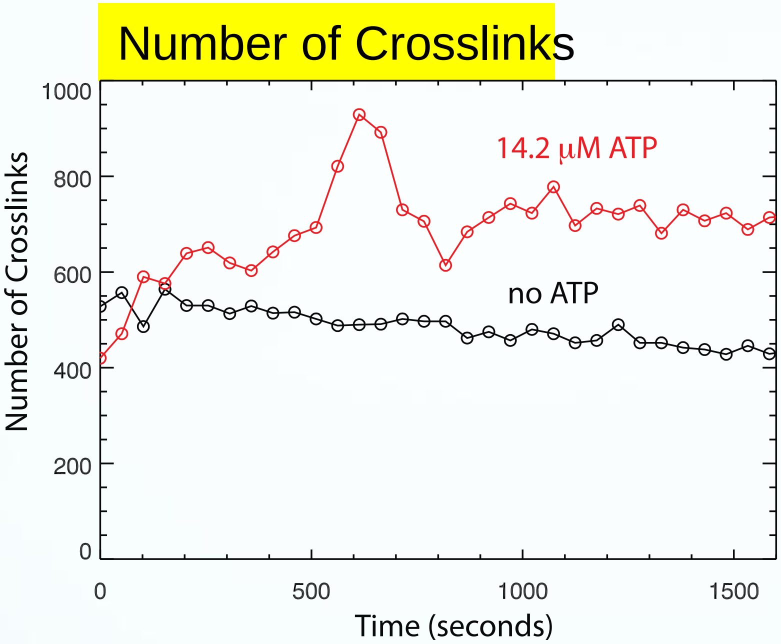
Confocal Rheology of Active Networks



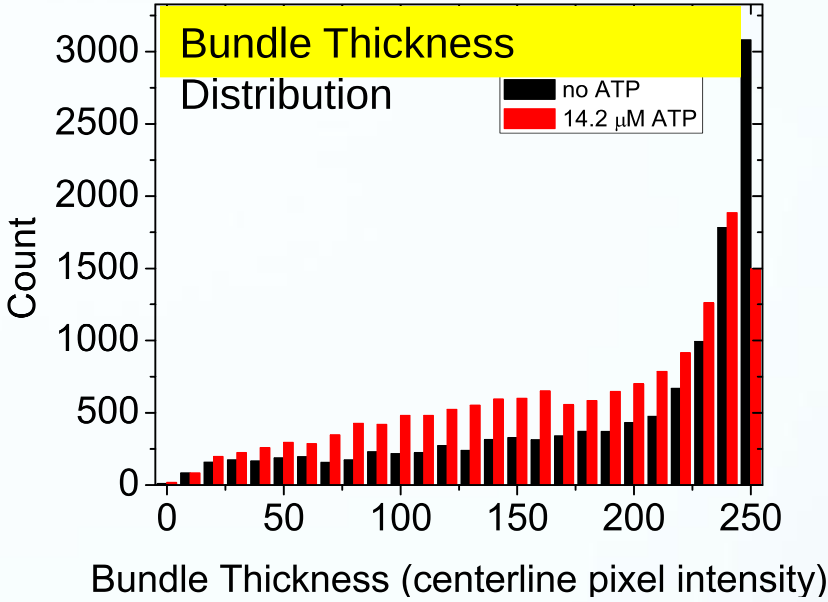


Dan Blair (Georgetown University)

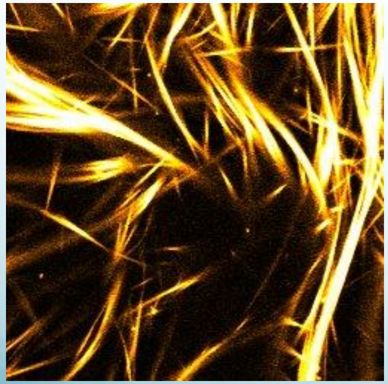
Network Morphology ⇔ Rheology



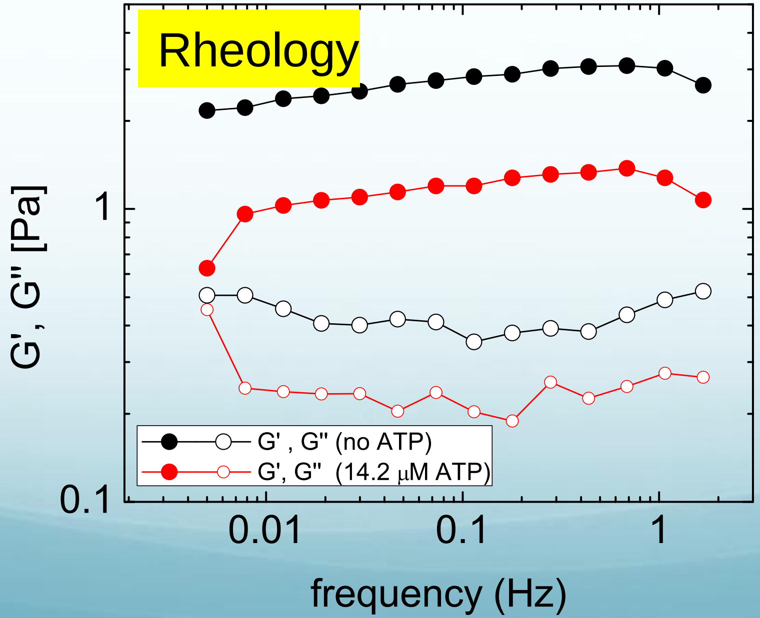
Number of Crosslinks



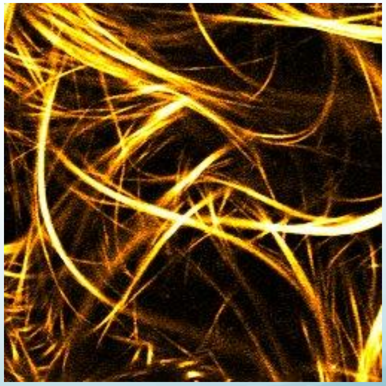
Bundle Thickness Distribution



No ATP

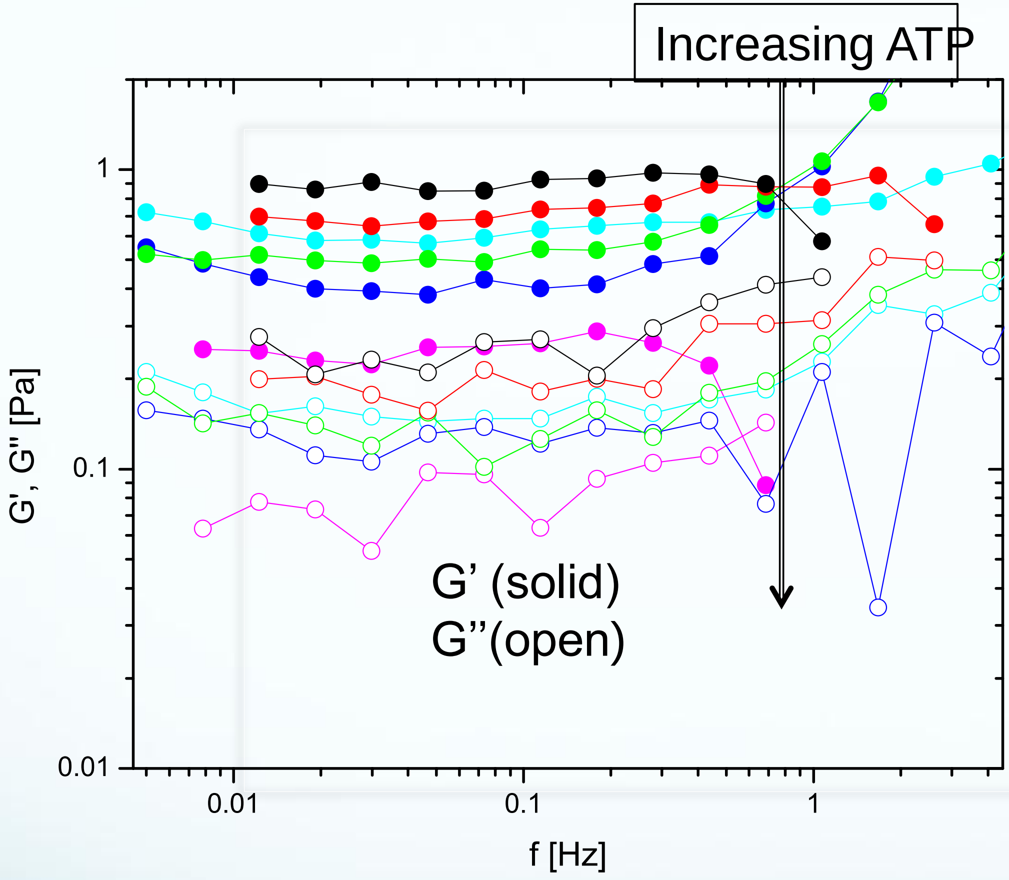


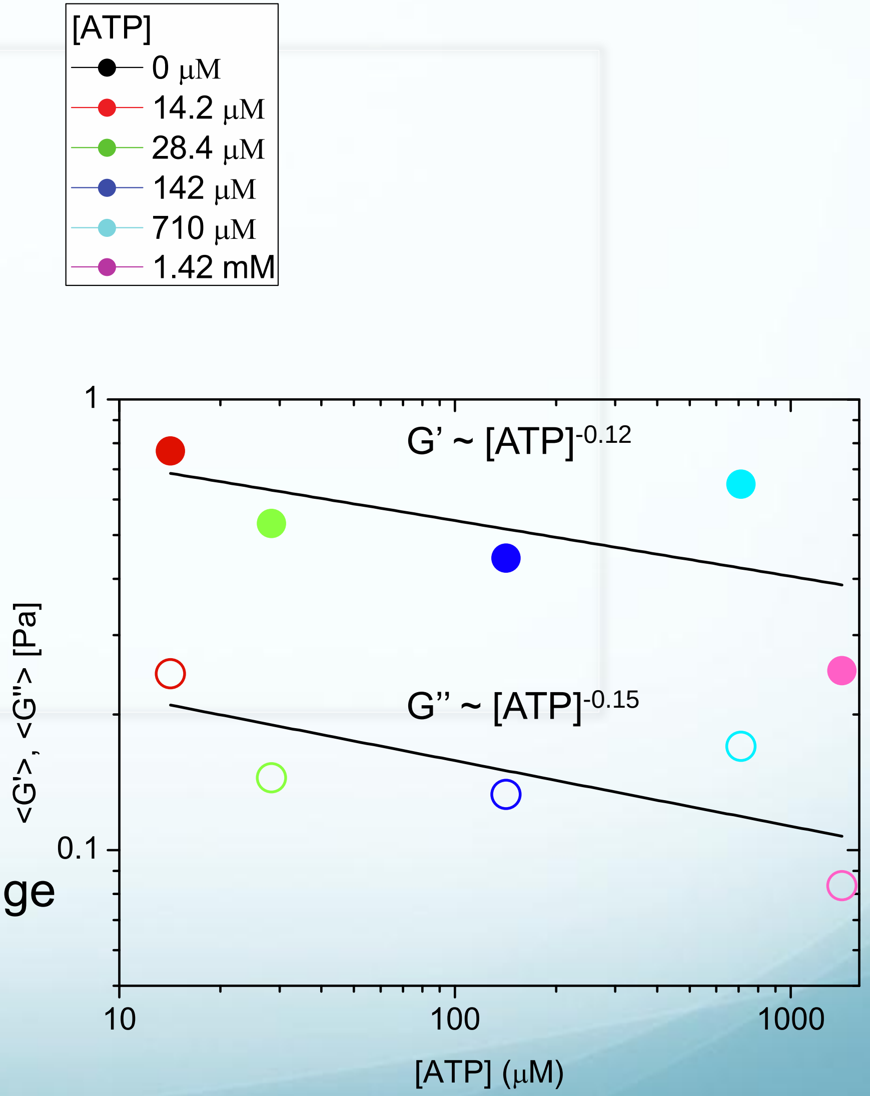
Rheology



14.2 uM ATP

Linear Viscoelastic Moduli of Active Network





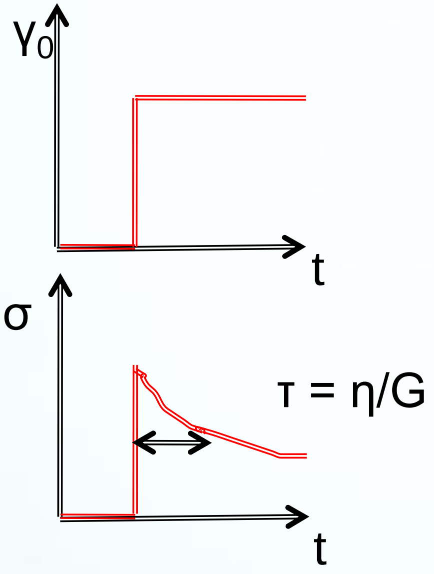
Network is a gel (G' > G'') over entire [ATP] range

G''/G' ~ 0.3, damping independent of [ATP]

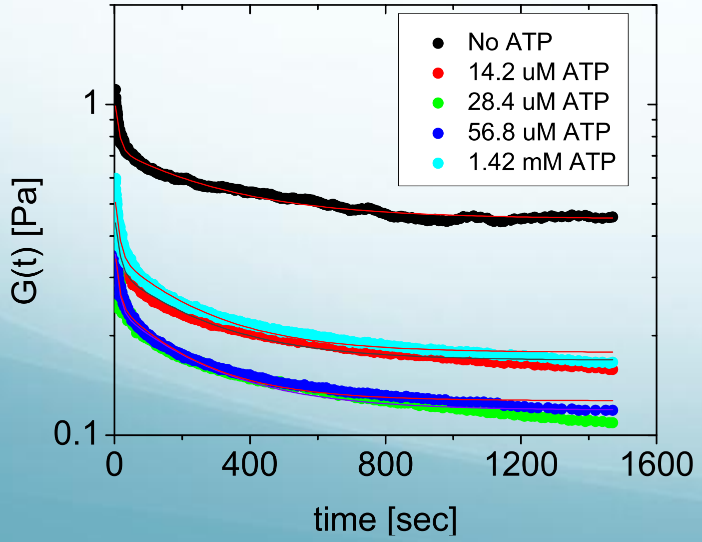
No relaxation at low frequencies.

Step Strain ⬄ Anomalous Stress Memory

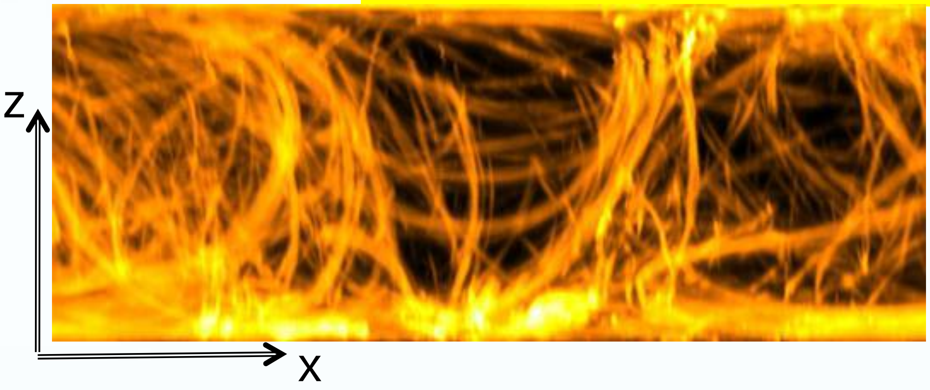
Step strain



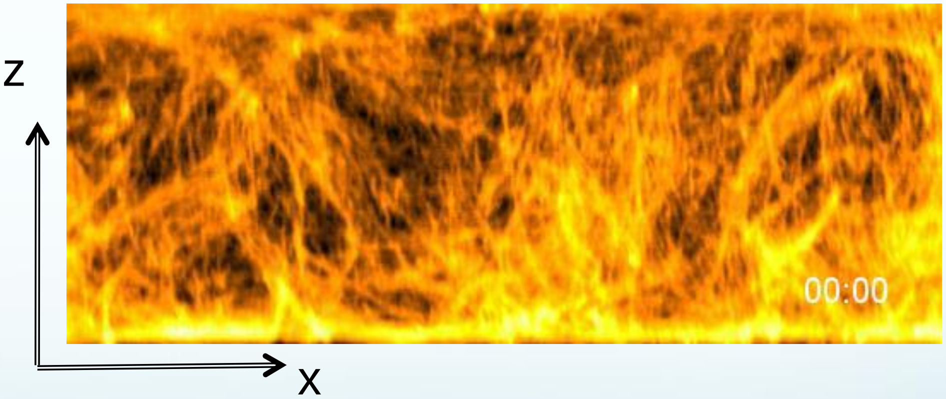
$\tau = \eta/G$



No ATP, Step strain γ_0 =

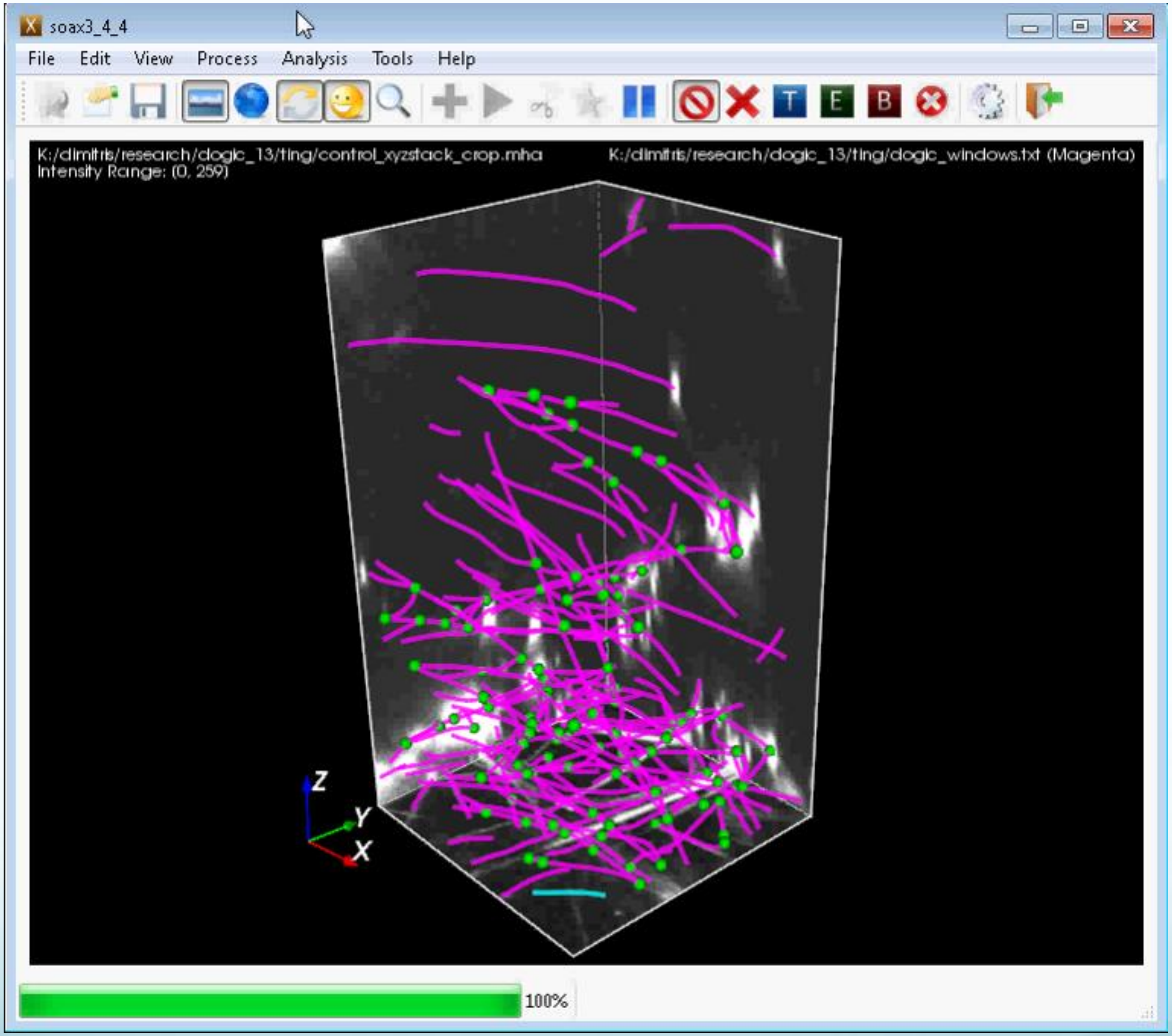


28.4 µM ATP, Step strain γ_0 = 100%



Recoil despite total turnover of network

Direct visualization and analysis of network dynamics



K:/dimitris/research/dogic_13/ting/control_xyzstack_crop.mha
Intensity Range: (0, 259)

K:/dimitris/research/dogic_13/ting/dogic_windows.txt (Magenta)

Active Snake Analysis: Ting Xu, Demetrios Vavylonis, Xiaolei Huang (Lehigh Universit

Active Networks perform work