soft condensed matter physics.

Maria Kilfoil Group

Structure, Dynamics, and Mechanical Properties in Soft Things!

Dynamics and mechanics in attractive colloids, forces on particles, and force transduction in cytoskeleton networks

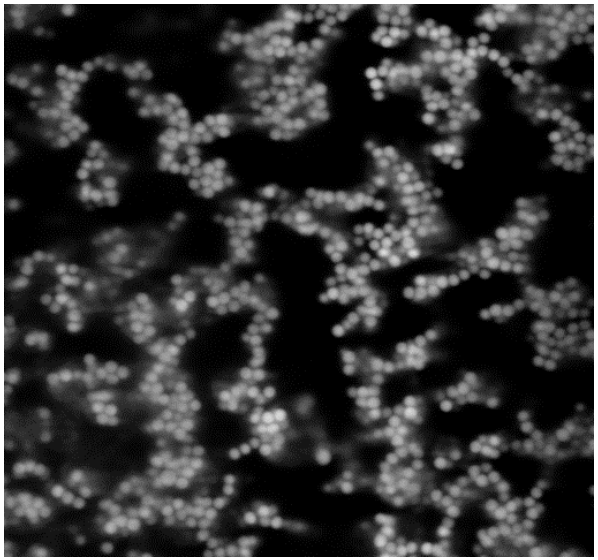
"Big Questions"

- Rigidity
  - -jamming
  - -glass transition, ergodicity breaking
- Self-Assembly and Pattern Formation
- Networks
- Driven Dynamics and Effective Temperature
- Interface with Biology – are there guiding principles?
  - -- membranes, surfactants, emulsions, polymers, l.c.'s

→ Notions from statistical mechanics play a special role

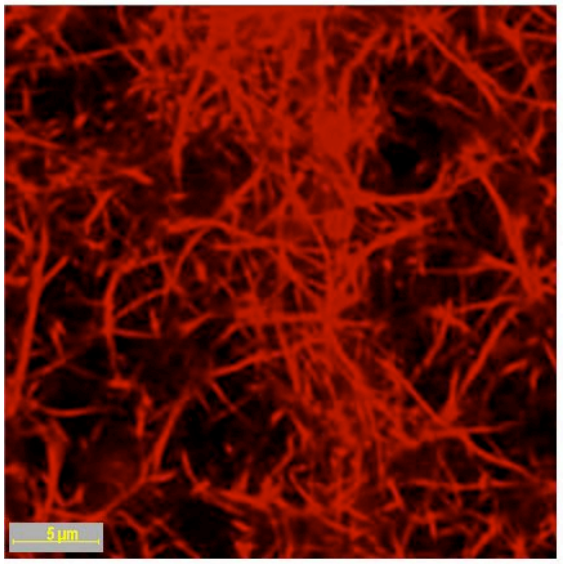
Networks: Origin of Rigidity

Colloidal gel



Confocal microscopy
40 x 44 μm

Cross-linked actin gel



Confocal image 32 x 32 μm

Soft Solids

Easily deformable → Low Elastic Constant: $\frac{\text{Energy}}{\text{Volume}}$

Atoms: $\frac{eV}{\text{Å}^3}$ ~GPa

Colloids: $\frac{k_B T}{\mu m^3}$ ~Pa

Colloidal Particles:
- Slow speed
- Large size (microns)

$$\tau \sim \frac{k_B T}{\eta a^3}$$

Colloids

1 nm - 10 μm solid particles in a solvent

Ubiquitous

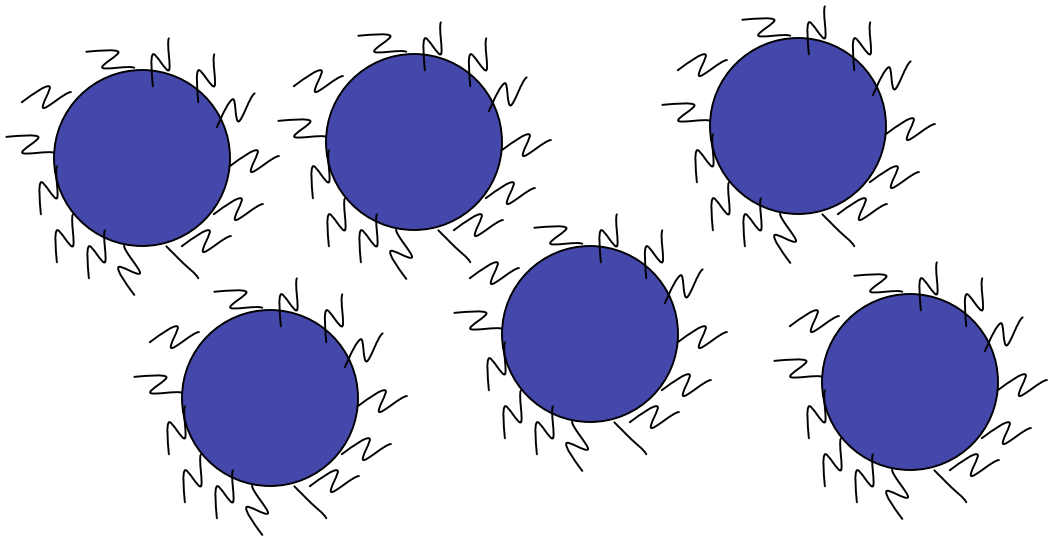
ink, paint, milk, butter, mayonnaise, toothpaste, blood

Suspensions can act like both liquid and solid

Modify flow properties

Control: Size, uniformity, interactions

Colloidal Particles

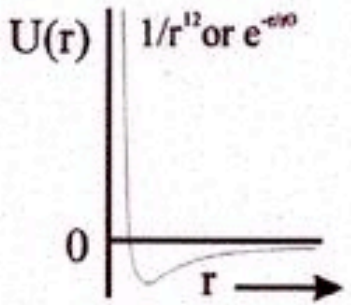


Stability:

- Short range repulsion
- Sometimes a slight charge

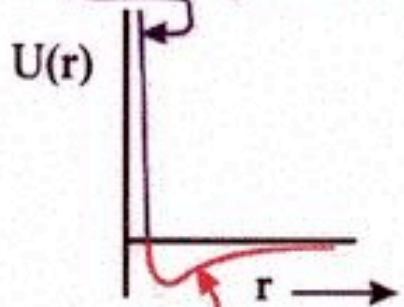
Interactions are highly tunable

Why Hard Particles?



typical interparticle potential

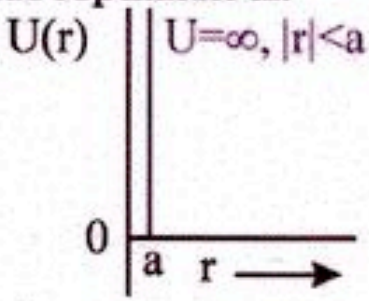
repulsion: liquid structure
liquid solid transition



attraction: liquid-gas transition

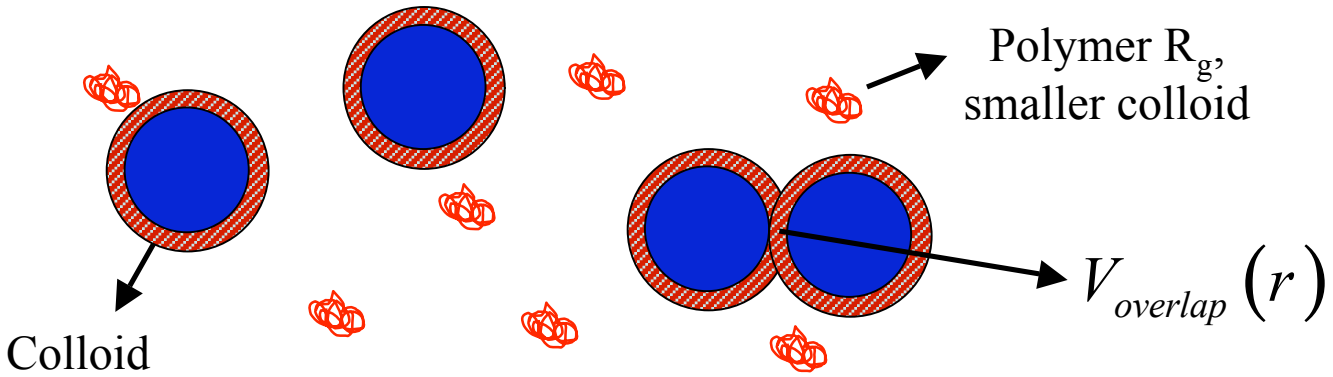
Most interesting things depend on repulsive part

simplest repulsion is:



The essence of the problem -- **Hard Spheres**

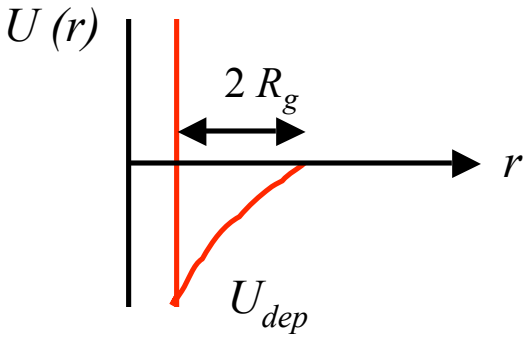
Depletion Interaction



Asakura & Oosawa 1954; Vrij 1976

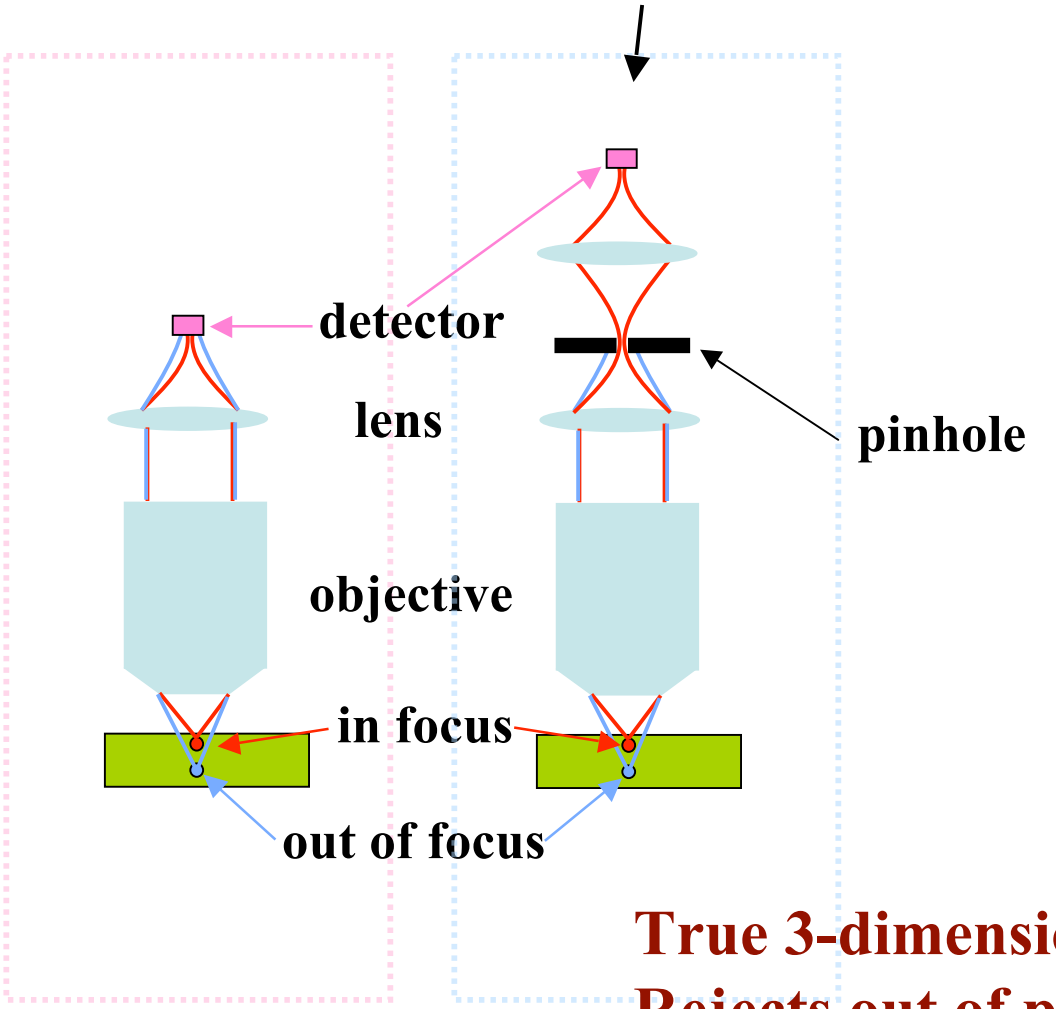
$$U(r) = \Pi(c) V_{overlap}(r)$$

$$V_{overlap}(r) = \frac{4}{3}\pi a^3 (1+\xi)^3 \left[1 - \frac{3r}{4a(1+\xi)} + \frac{r^3}{16a^3(1+\xi)^3}\right] \quad (\xi = R_g / a)$$



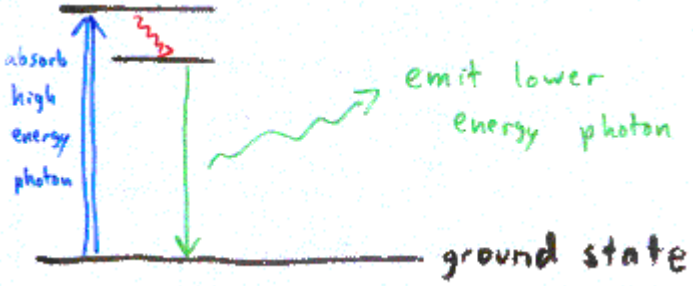
Experiments in this area can now approach the transparency of computer simulations

Confocal Microscopy



True 3-dimensional imaging
Rejects out of plane light

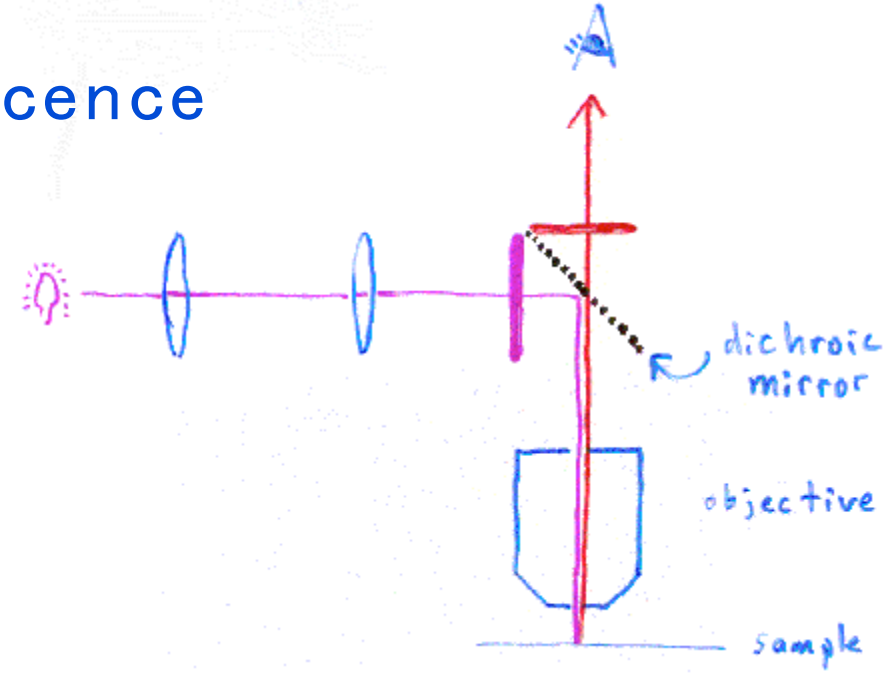
What is fluorescence?



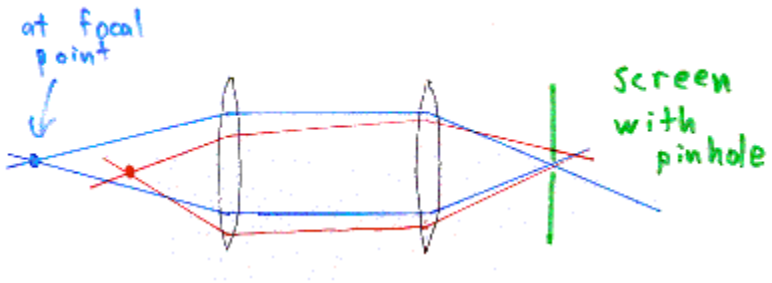
→Can attach fluorescent dye molecules to specific parts of your sample

→Can use more than one type of dye to distinguish two different parts of your sample

How does a fluorescence microscope work?



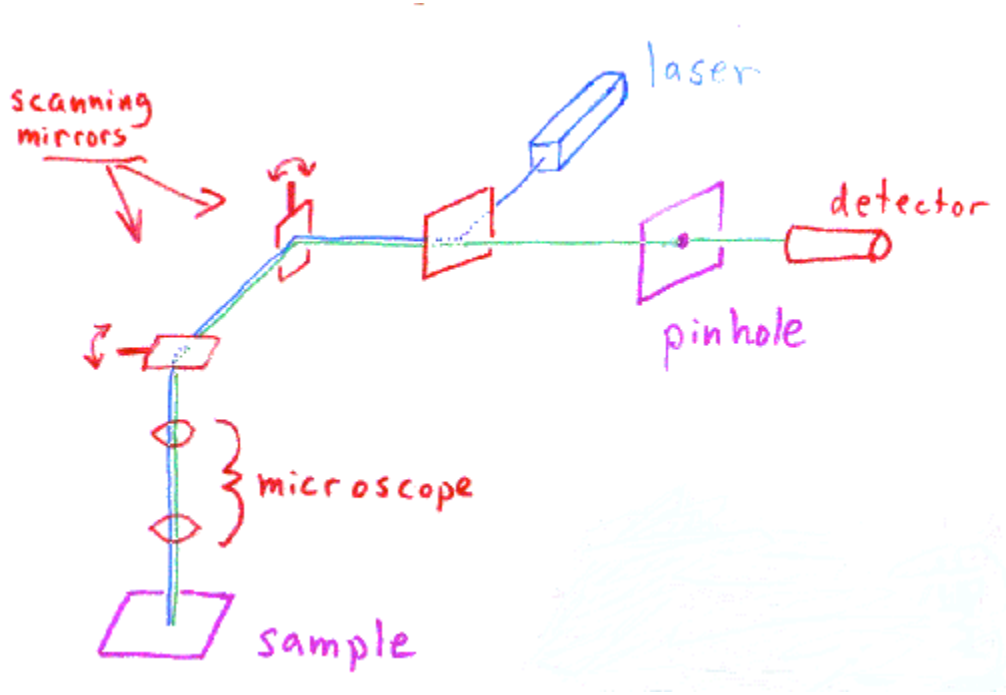
And the leap to confocal microscopy?



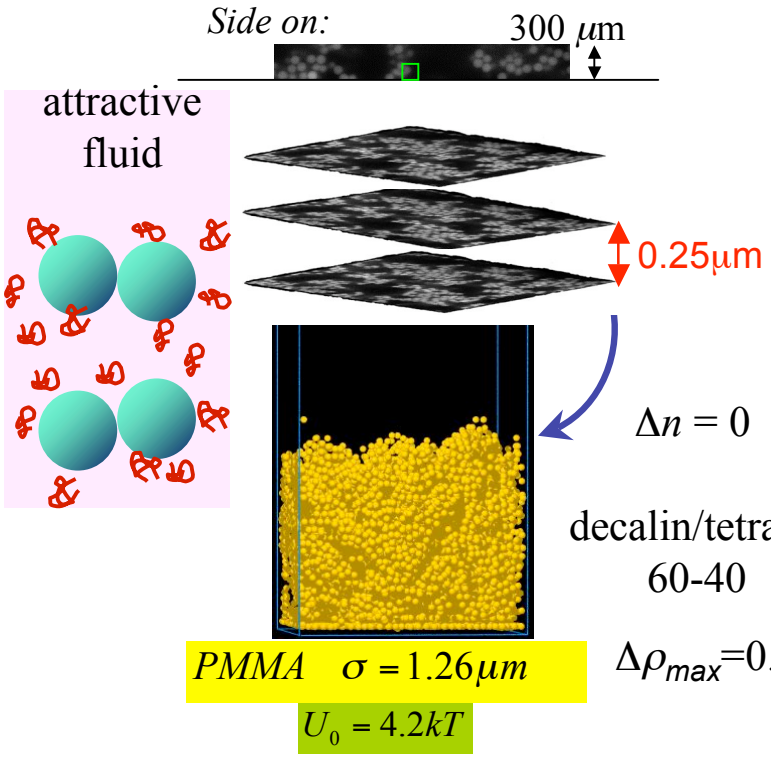
- Red and blue are two different sets of rays of light (not different λ's)
- Pinhole to reject out of focus light
- Solves one of the problems with regular microscopy:
  all of sample is fluorescing → hazy images

Focal point of objective lens and pinhole are "**con**jugate points"

How a confocal microscope works:



Invented by:
Minski, 1962


Side on:
300 μm
attractive fluid
0.25μm
Δn = 0
decalin/tetralin
60-40
PMMA σ = 1.26μm
U0 = 4.2kT
Δρmax=0.263 g/cm3

Movie of Colloidal Gel

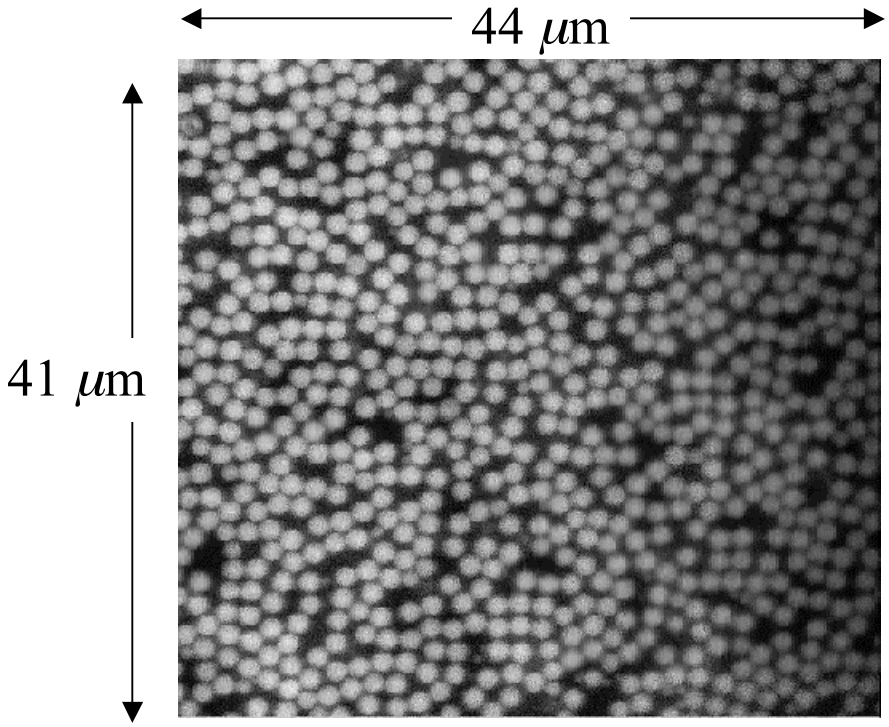
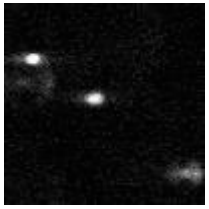
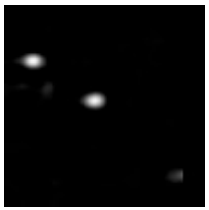
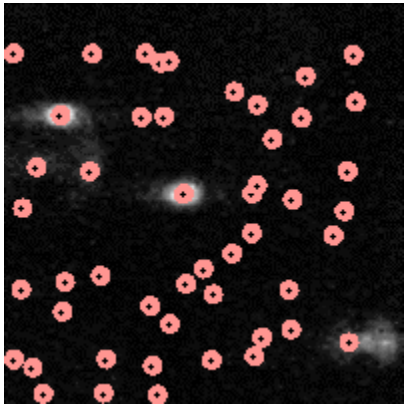
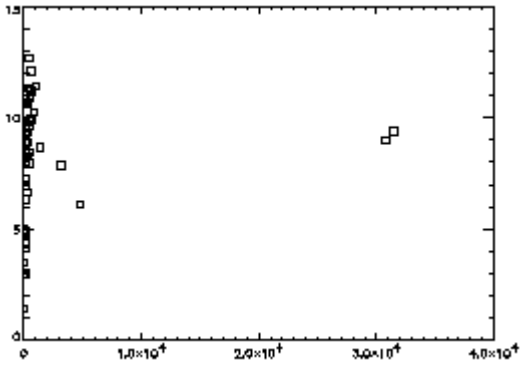


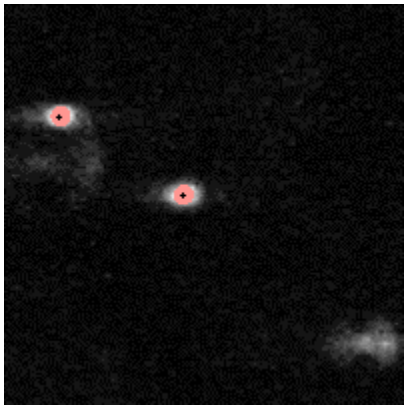
Figure out how to identify particles









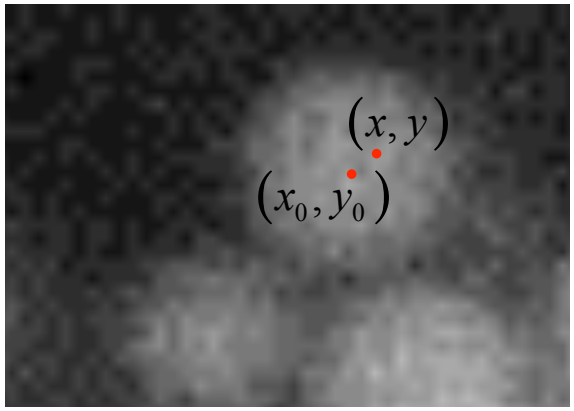


Refining location estimates

$$\begin{pmatrix}\varepsilon_x\\ \varepsilon_y\end{pmatrix} = \frac{1}{m_0}\sum_{i^2+j^2\le w^2}\begin{pmatrix}i\\ j\end{pmatrix}A(x+i, y+j)$$

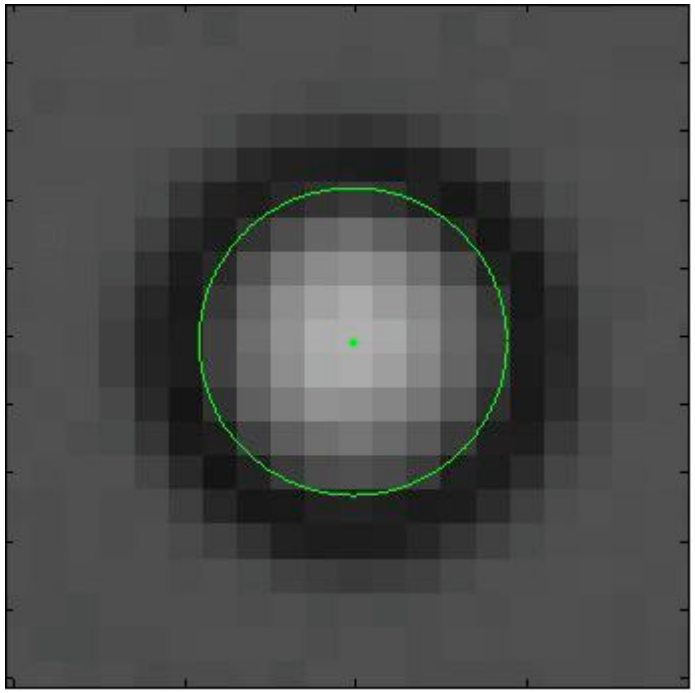
Offset from (*x*,*y*) to the brightness-weighted centroid of the pixels in a region around (*x*,*y*)

- ideally, locate particle centroids to better than ½ pixel
- HOWEVER: suffers from poor noise rejection and includes false identifications
- reduce standard deviation of pixel measurement to better than 1/10 pixel
  → other information gathered can be used
- Useful for distinguishing spheres from noise and for estimating their displacements from the focal plane

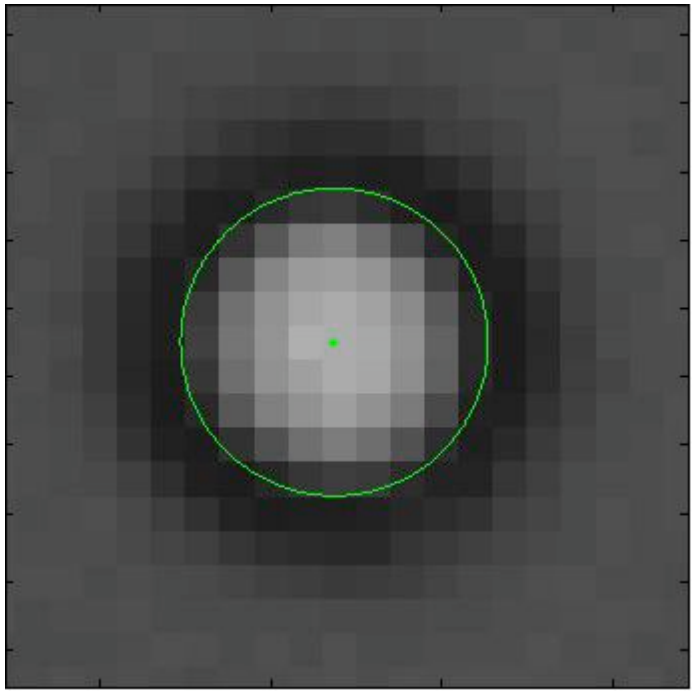


Refined location estimate is then $(x_0, y_0) = (x + \varepsilon_x, y + \varepsilon_y)$

Multiparticle tracking



Immobile bead

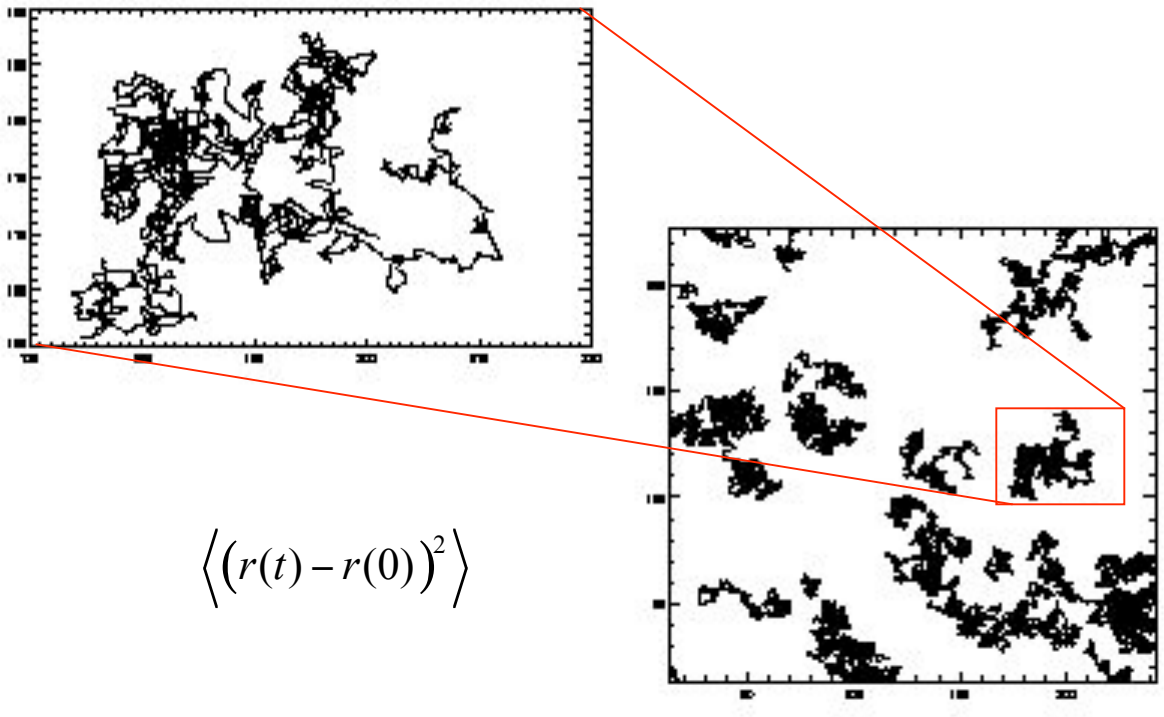


Relatively mobile bead

temporal resolution:
frame rate 1/30 sec or faster

→ individual tracks are minutes long!

Link particles in each frame to form trajectories

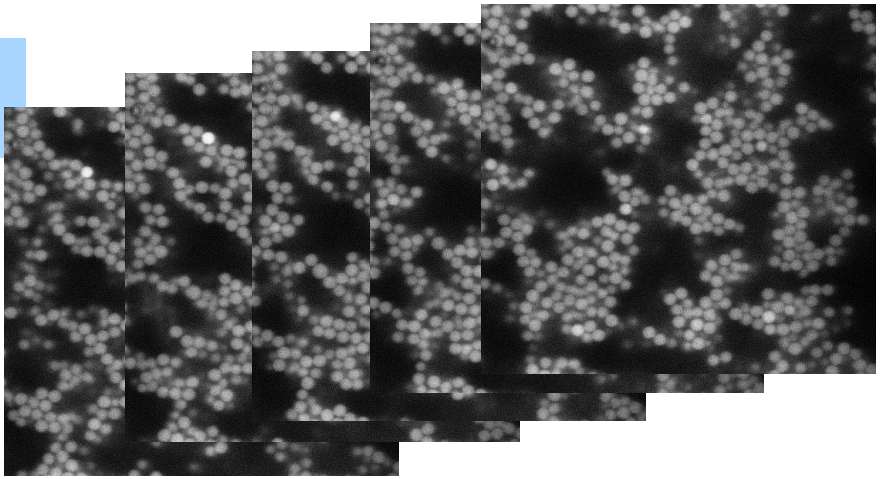


$$\left\langle \left(r(t) - r(0) \right)^2 \right\rangle$$

3D - Tracking in Depth:
Find the particles for all of your data

• distribution of data in the (m_0, m_2) plane reflects the sphere's positions along the direction normal to the imaging plane

$\Delta z = 0.25\mu m$
$d = 1.26\mu m$

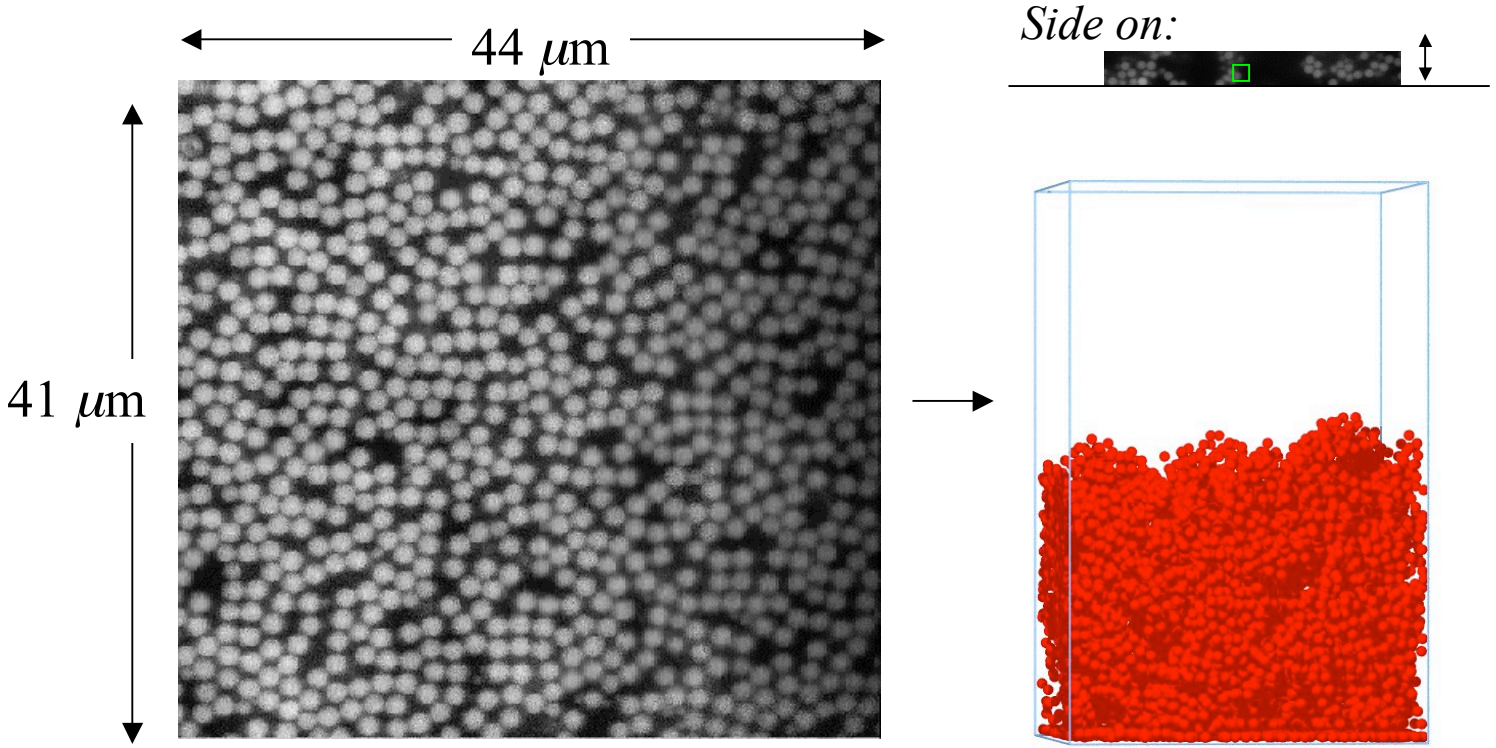


• • •

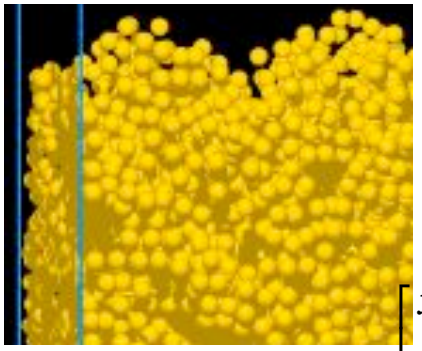
• identify centroid locations that belong to the same sphere along z
• values of z for the ith frame fall in a Gaussian distribution about the centre along z

$$z = \sum_i P(z_i \mid m_0, m_2) z_i \rightarrow \begin{bmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ \vdots & \vdots & \vdots \end{bmatrix} (t)$$

3D - Tracking in Depth:
Find the particles for all of your data



Analyze the 3D data to do your science



$$\begin{bmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ \vdots & \vdots & \vdots \end{bmatrix}(t)$$

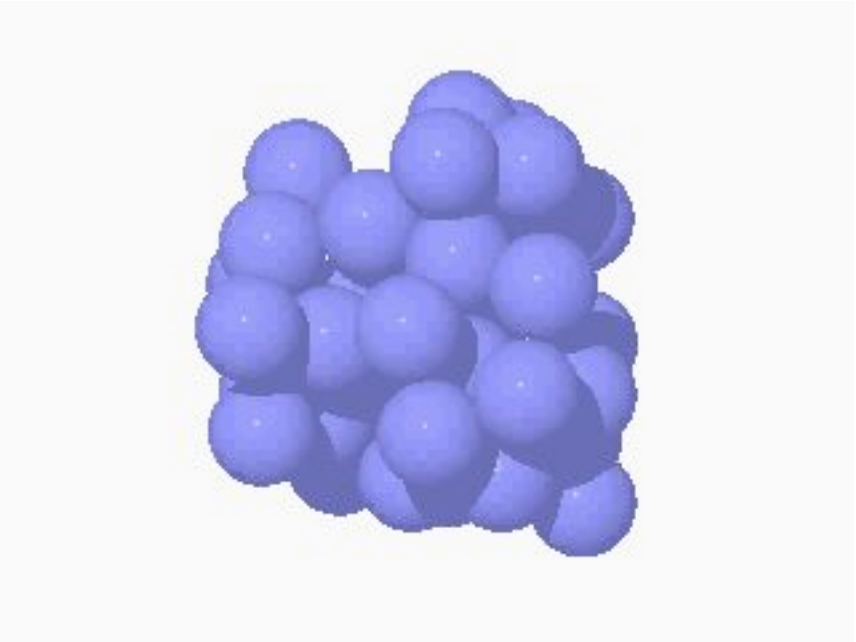
$\left\langle \left(r(t) - r(0)\right)^2 \right\rangle$

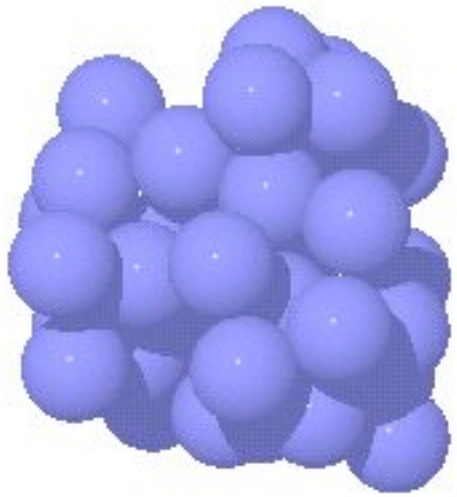
Dynamics

Spatial Correlations and Order
g(*r*)

Structure

Removal of Centre-of-Mass motion of all particles

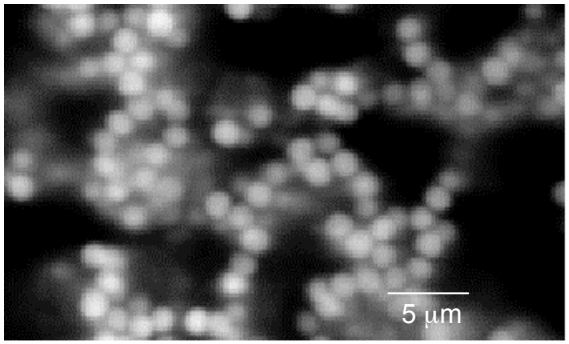




Non-equilibrium soft solids - colloids and cell mechanics

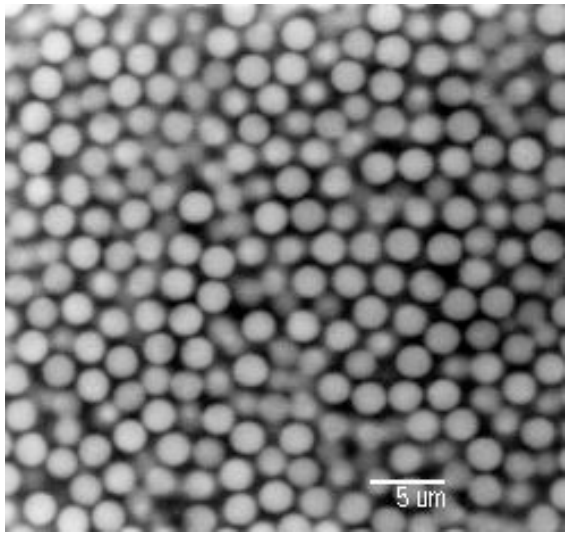
Images of colloidal gels and glasses

Gel



Network of attractive colloidal particles

Glass

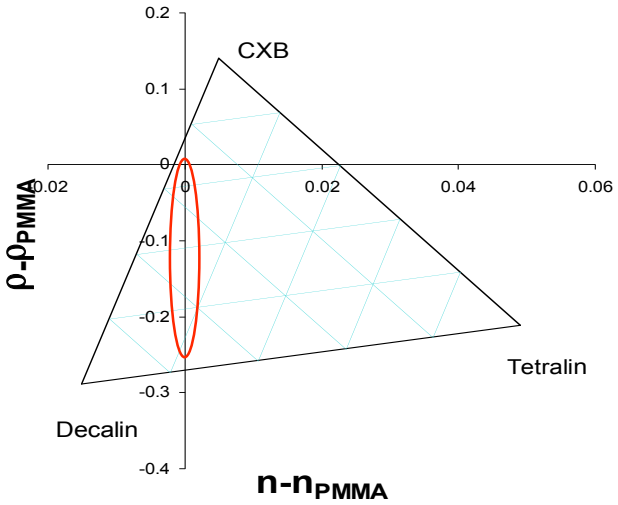


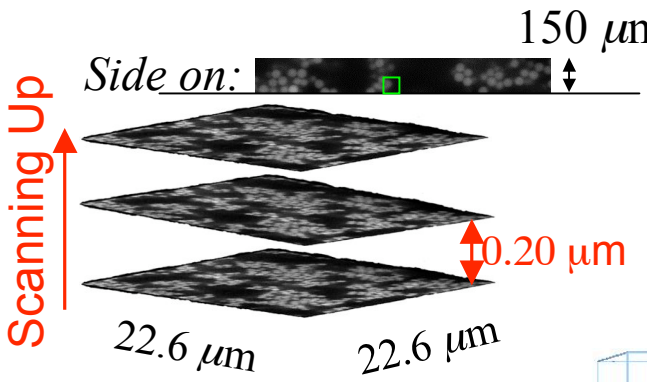
Glass formed due to caging

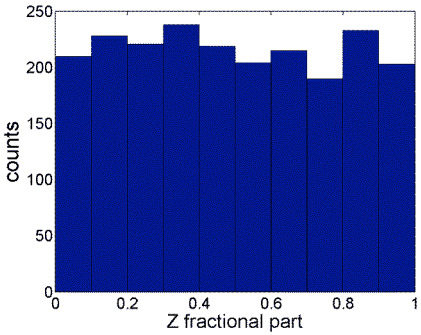
Full 3D structure gained by confocal microscopy

System: PMMA (~1μm) in Refractive index-matching and buoyancy- tunable suspending fluids

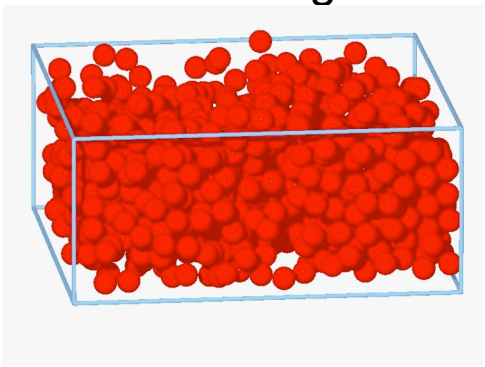
Decalin/Tetralin/CXB



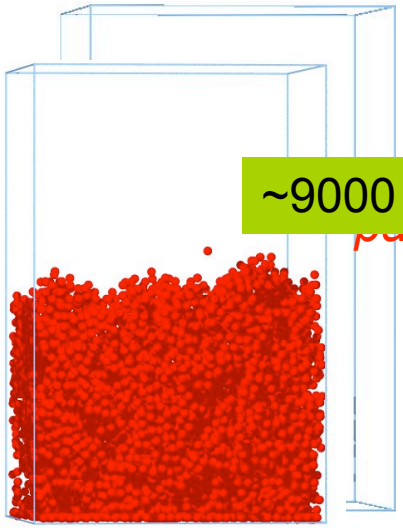




tracking



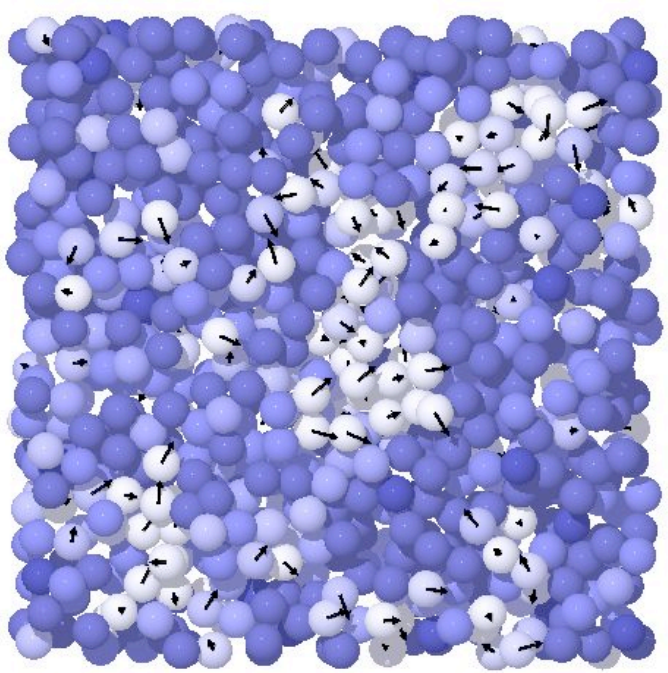
reconstruction



~9000 particles

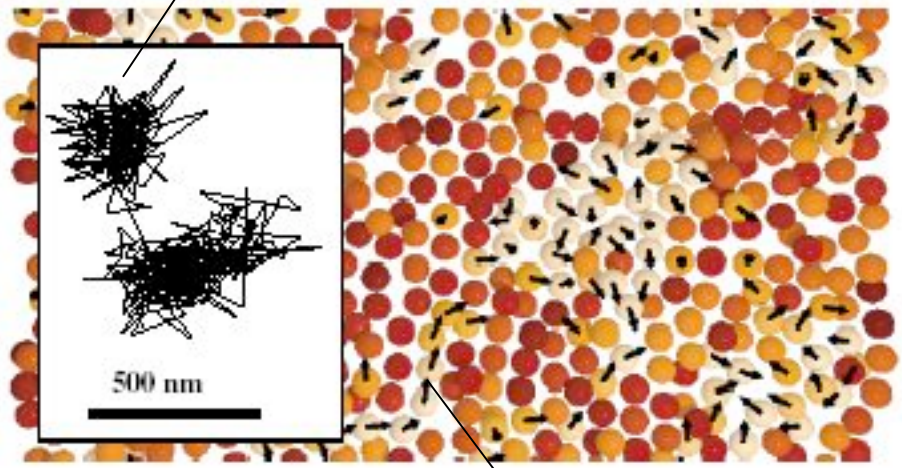
Highly Localized Motion in Gels

Confining effect of neighboring particles in a colloidal gel



Not really cooperative motion

Trajectory of particles caged by their neighbors

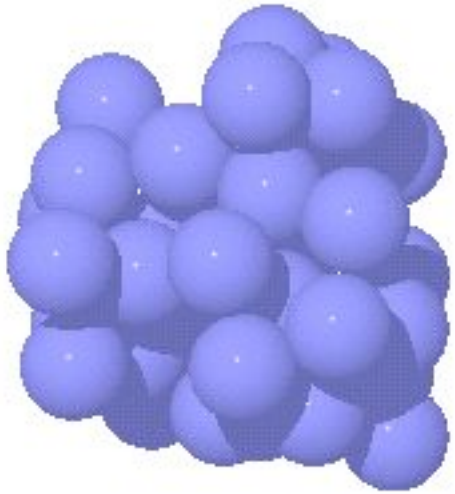


Cooperative motion

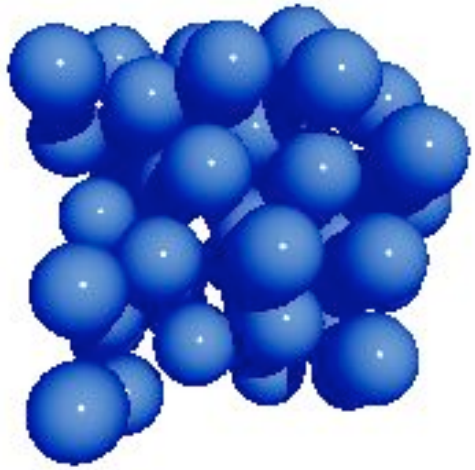
Eric R. Weeks *et al.*, *PRL* vol 89, 095704 (2002)

Caged Particles in Glasses and Gels

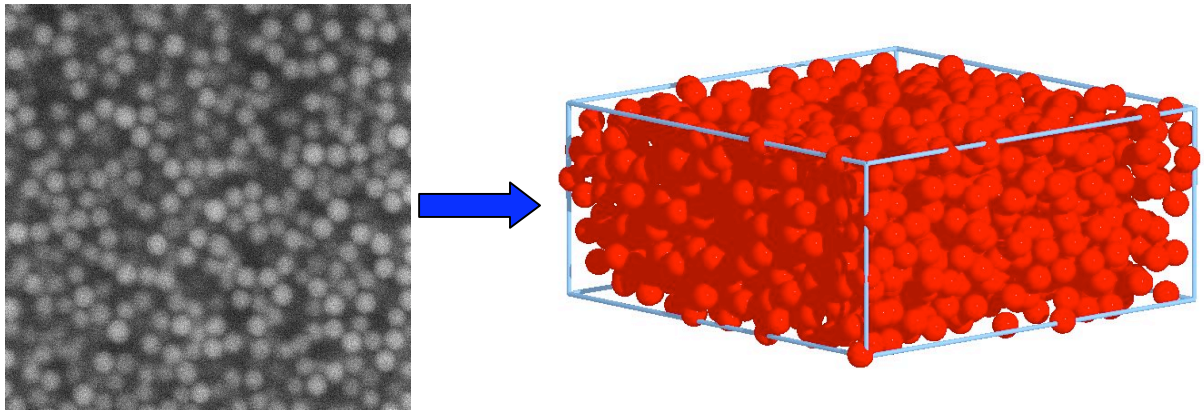
Effect of crowding of particles plus interparticle attraction in a colloidal gel



Cage effect of neighboring particles in a colloidal glass



Direct Measurement of the Distinct Part of van Hove Correlation Function in Colloidal Gels and Glasses



Yongxiang Gao, Maria Kilfoil

Space time correlation function

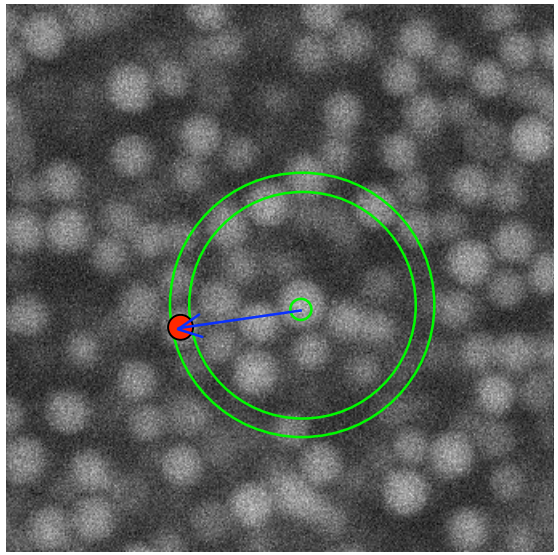
Self part

$$G_s(r,\tau) = \frac{1}{N}\left\langle \sum_{i=1}^{N} \delta\left[r - |\, r_i(0) - r_i(\tau)\,|\right]\right\rangle$$

$$\approx \frac{1}{\left[\frac{4}{6}\pi < \Delta r^2(\tau) >\right]^{3/2}} \exp\left[-\frac{r^2}{\frac{4}{6} < \Delta r^2(\tau) >}\right]$$

Distinct part

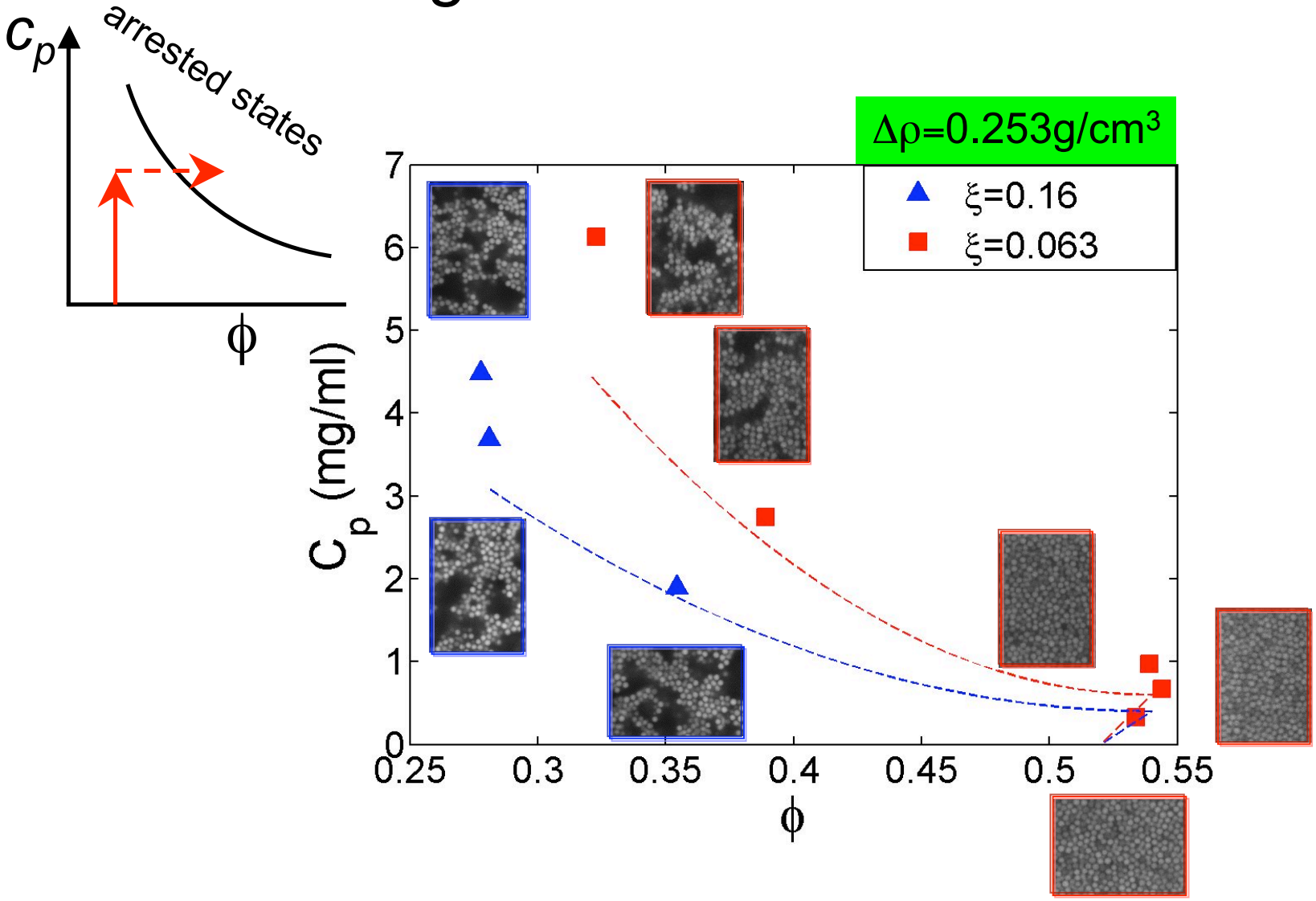
$$G_d(r,\tau) = \frac{1}{N}\left\langle \sum_i \sum_{j\neq i} \delta\left[r - \left|r_i(0) - r_j(\tau)\right|\right]\right\rangle$$



$t_0+\tau$

τ=28 mins

Gels and glasses subject to gravitational force



Dielectrophoresis basis

Dielectrophoresis can be used to induce a force on a **neutral** particle with a **non-uniform electric field**

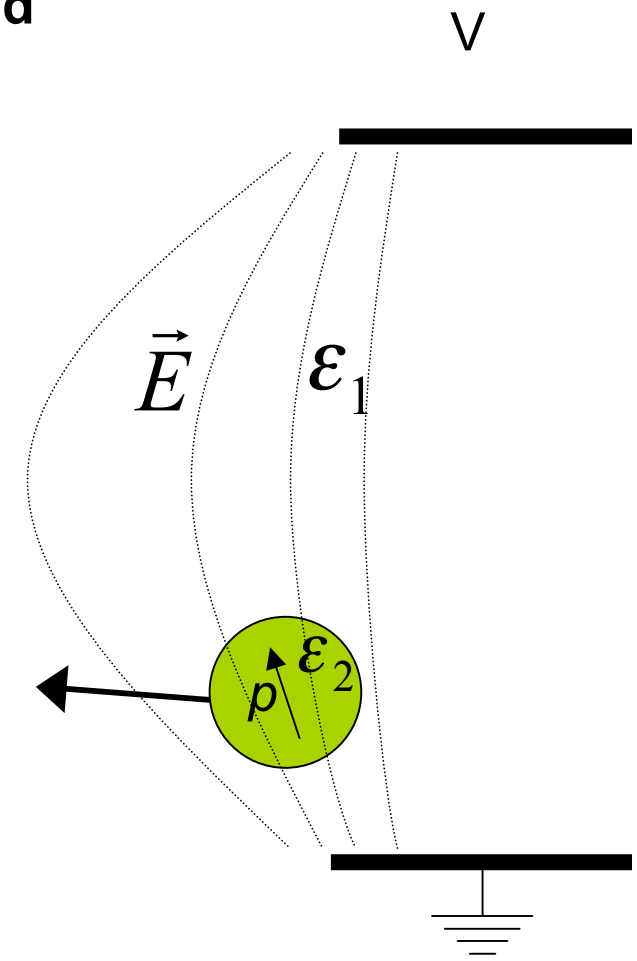
$$\vec{p} = 4\pi a^3 \varepsilon_1 \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\varepsilon_1} \vec{E}$$

$$\vec{F} = \vec{p} \cdot \nabla \vec{E}$$

$\nabla \times \vec{E} = 0$ so the force goes as $\frac{1}{2} \nabla E^2$

$$\vec{F}_{DEP} = 2\pi a^3 \varepsilon_0 \varepsilon_1 \frac{\varepsilon_2 - \varepsilon_1}{\underbrace{\varepsilon_2 + 2\varepsilon_1}} \nabla E^2$$

Clausius-Mossotti factor



Pohl, H. A., *Dielectrophoresis*, Cambridge University Press, Cambridge (1978)

Dielectrophoresis basis

So we could use this **tunable** force to replace other, less easily tunable forces.

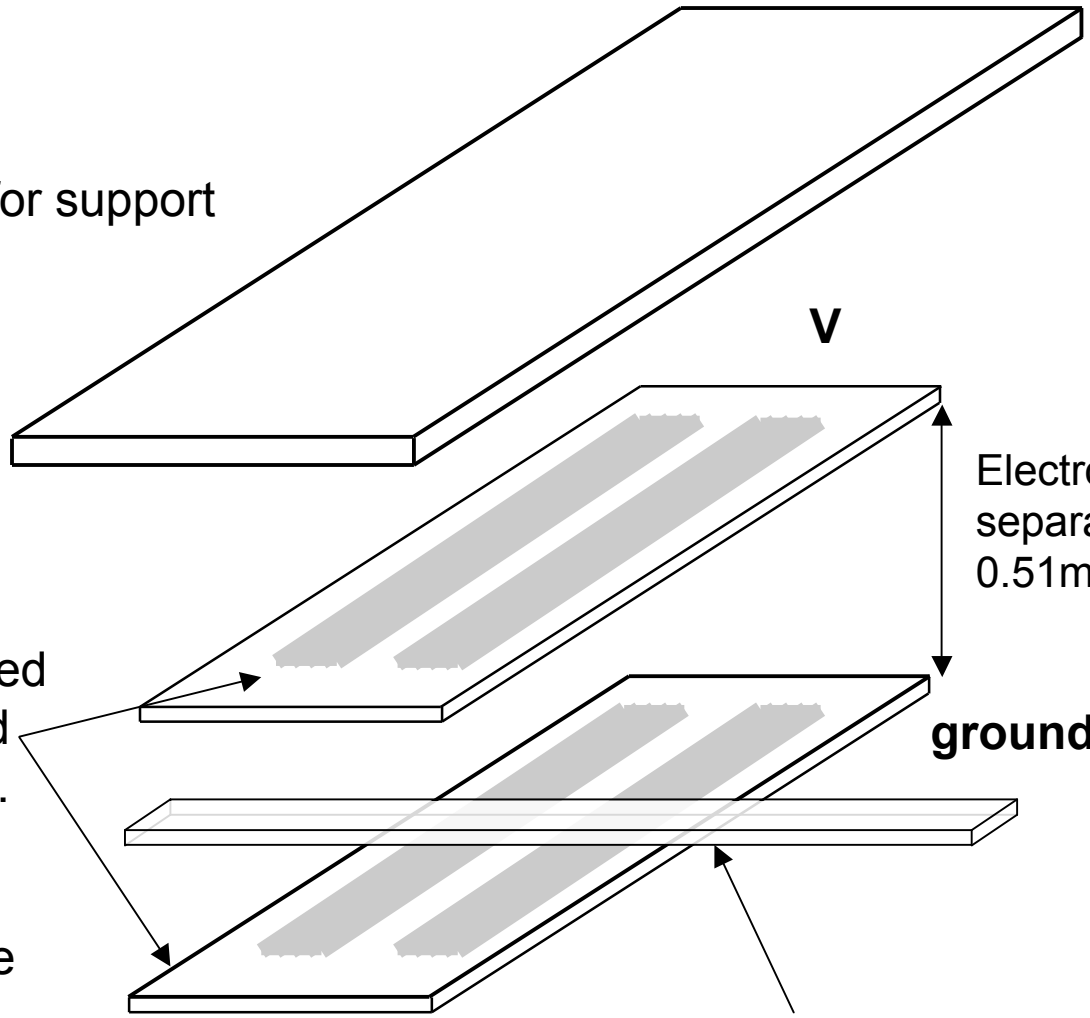
Example: Gravity and gel collapse

A lot of work is required to change the density mismatch.

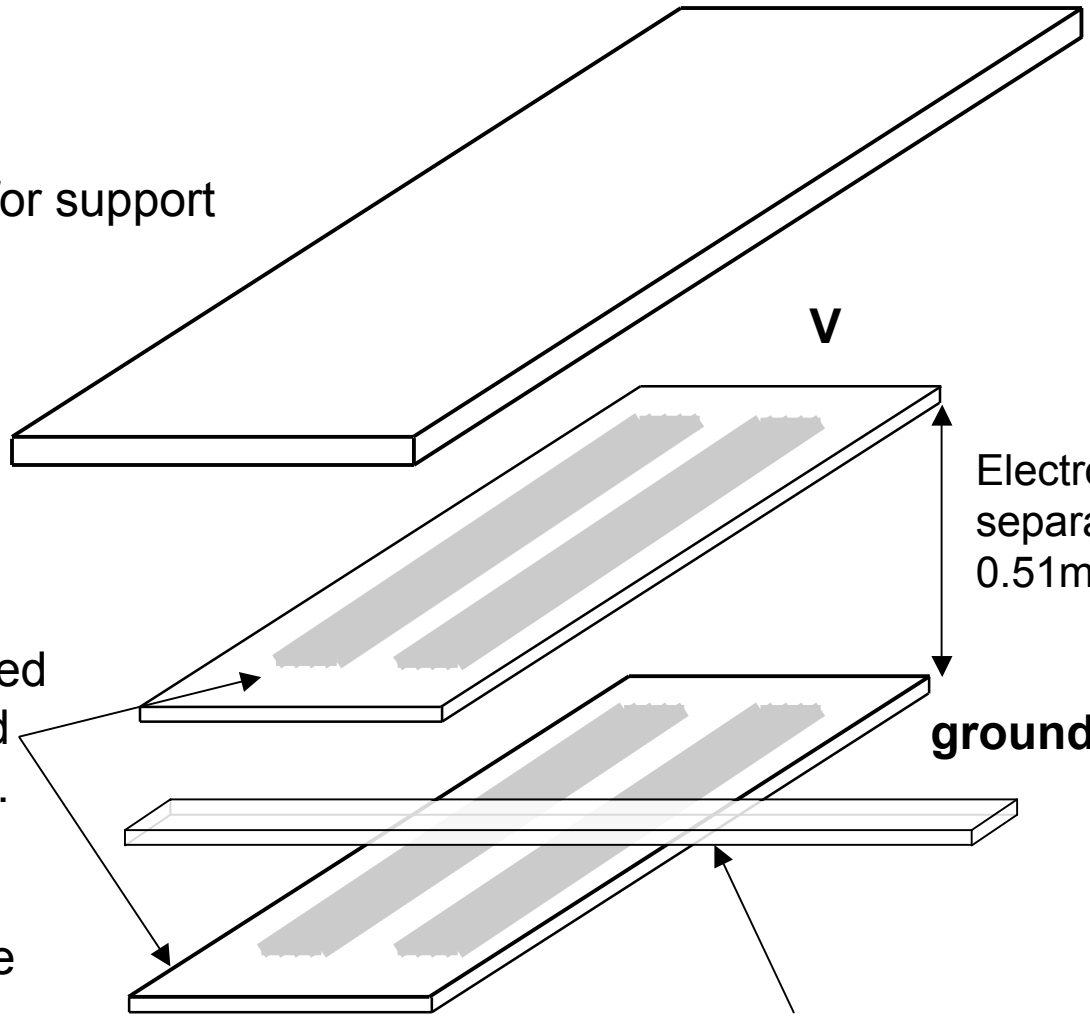
But: $F_{DEP} \sim \nabla E^2$ not trivial to get *F* **constant** in space.

We designed a 40 electrode cell, so that the electric field gives a **uniform, unidirectional force**

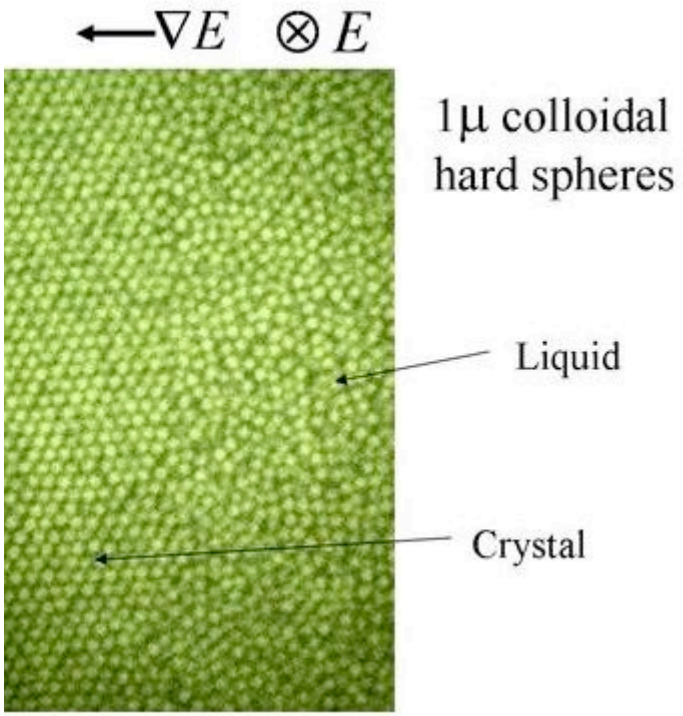
2 electrode cell



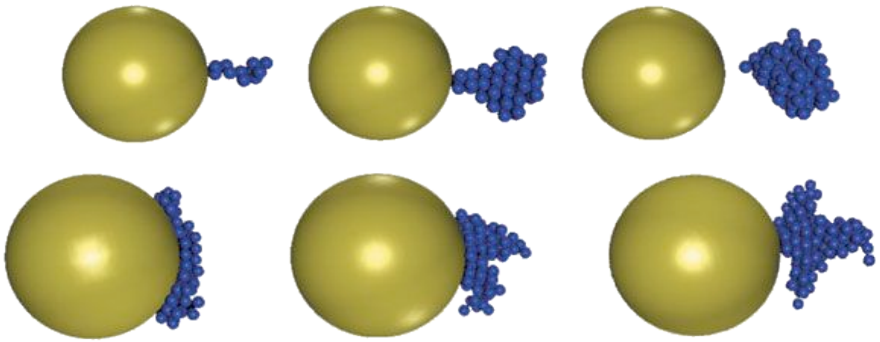
2 electrode cell



Order-disorder transitions in colloids

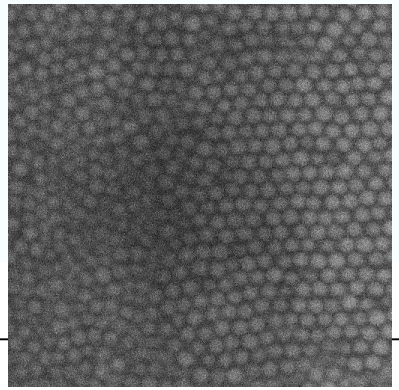


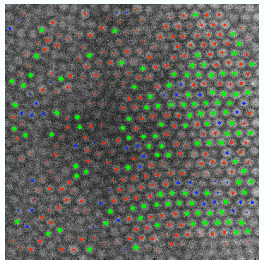
Heterogeneous Crystal Nucleation



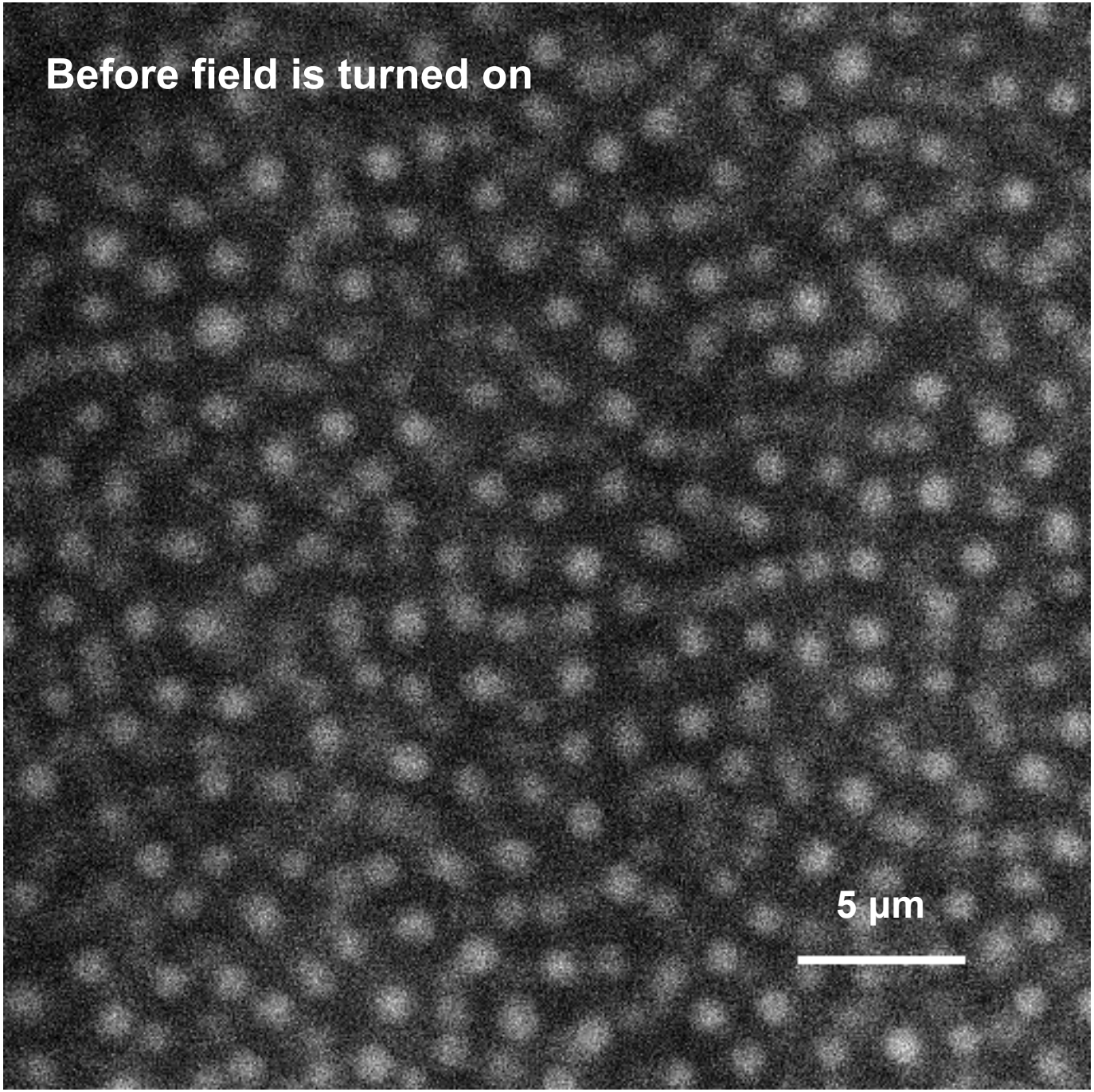
Nucleation and crystallization is a typical near-equilibrium phenomenon that is not well understood. The goal of our current experiment is to understand heterogeneous nucleation which, unlike homogeneous nucleation, occurs on either “impurity” particles or walls.

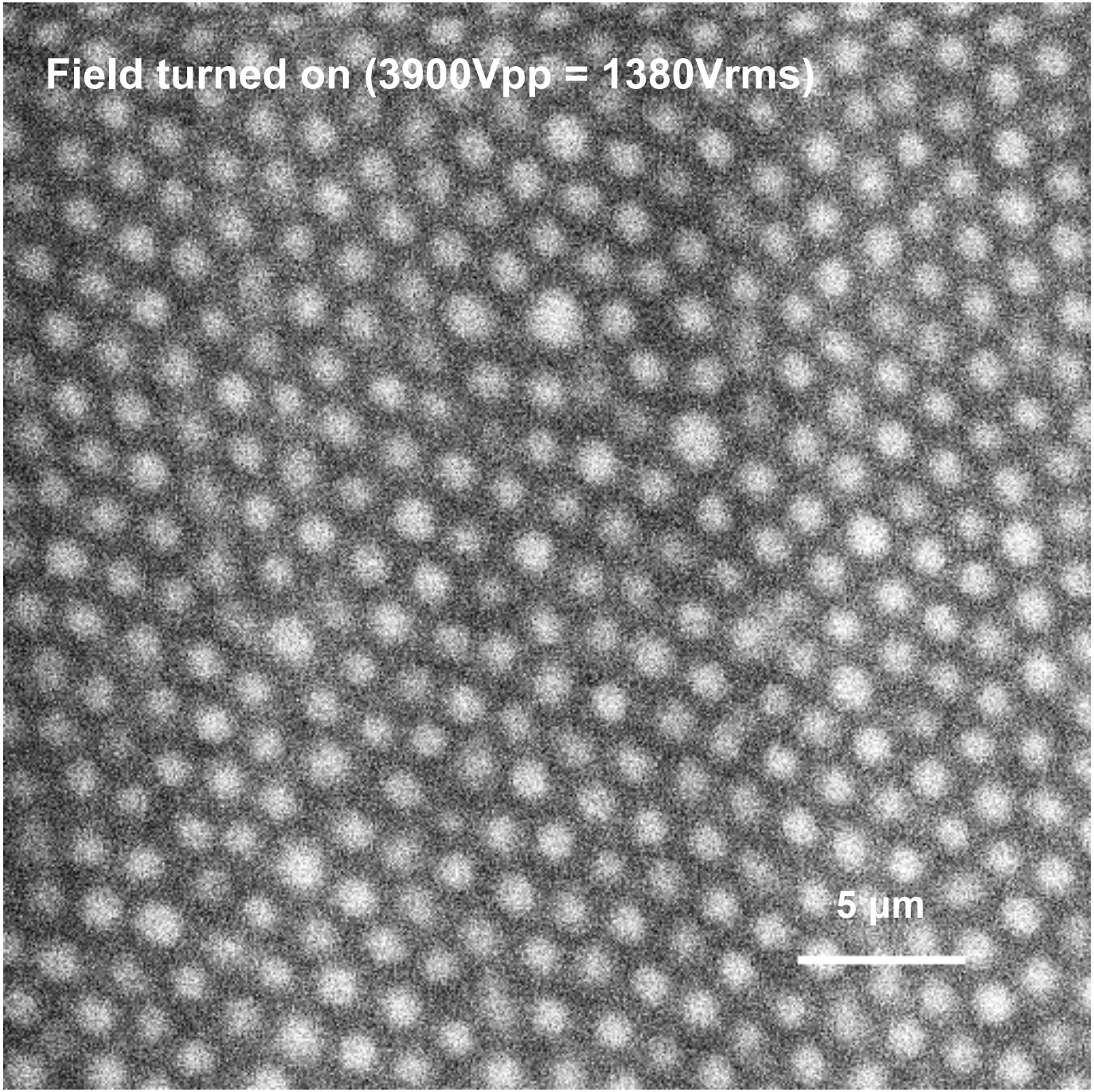
We can realize this by adding bigger particles, as seed particles, into an original suspension of uniformly sized smaller particles. By changing the ratio between the native and introduced particles, we can study how the size of the seed particles affects the nucleation process. If the seed particles have the same size as the original particles, homogeneous nucleation is recovered. It is predicted by recent theory work that in such heterogeneous nucleation, the nuclei will form on the surface of the seed particles as shown in the figure above. The nucleation rate in this situation is several orders of magnitude larger than that in homogeneous nucleation. This has not been experimentally tested.



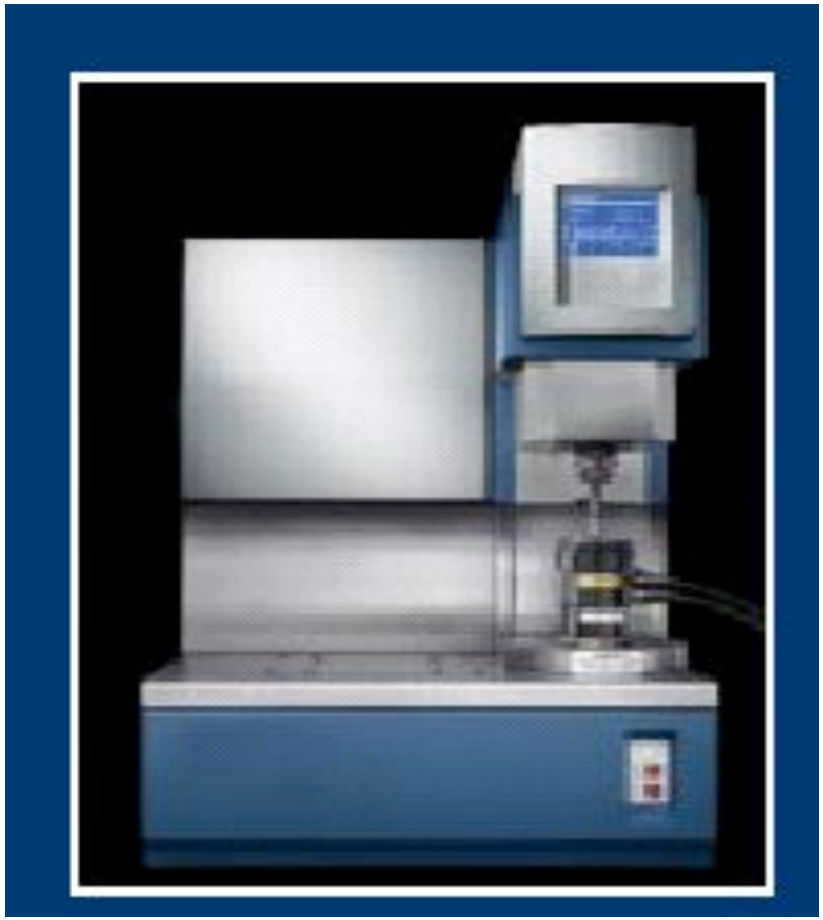


RQMP

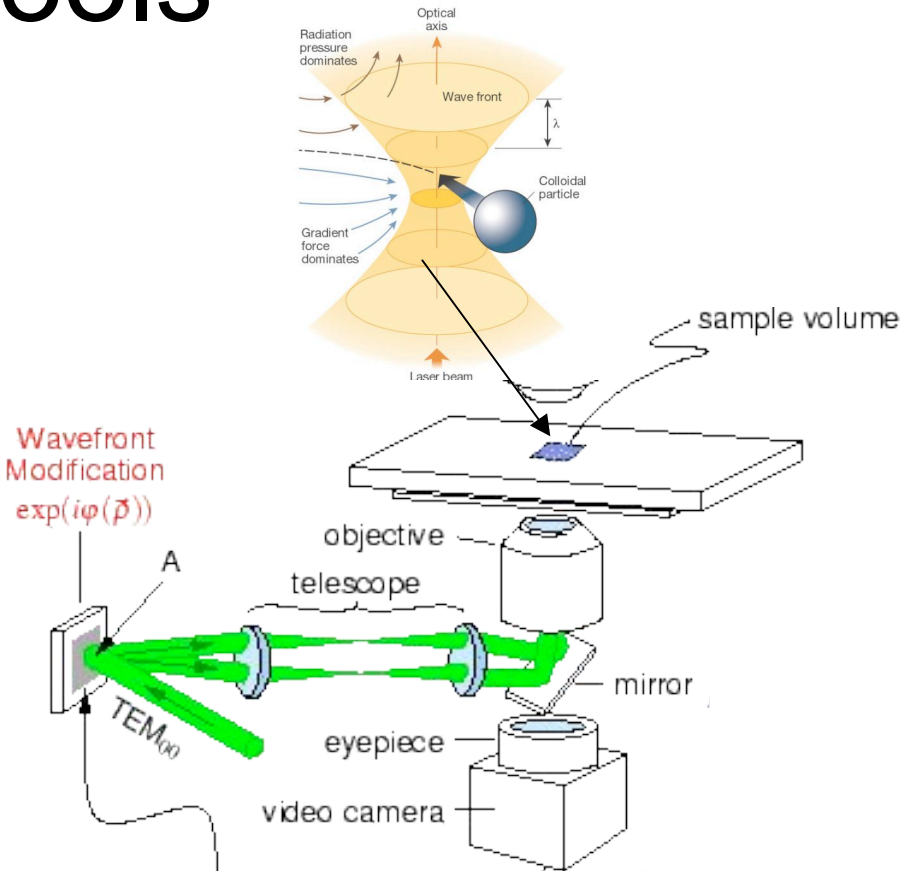

Before field is turned on
5 μm


Field turned on (3900Vpp = 1380Vrms)
5 µm

Other Soft Matter Measuring Tools

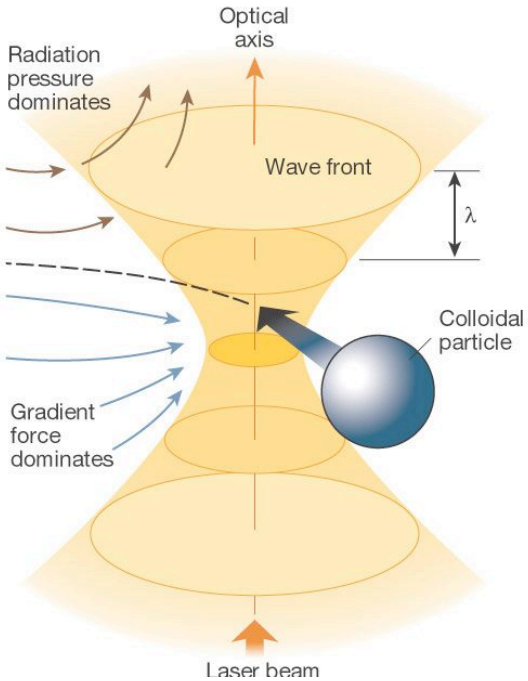


TA Rheometer used to obtain viscoelastic shear moduli



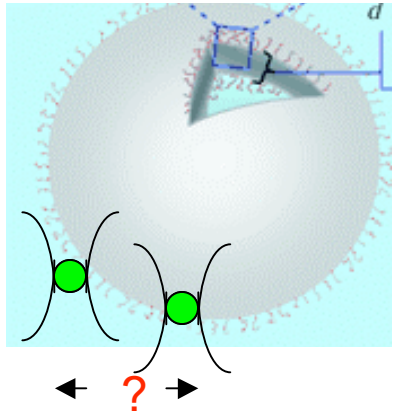
Optical tweezers – coupled to confocal microscope
Two traps for manipulation

Optical Tweezers



Grier, *Nature*, **424**,810 (2003)

Enable manipulation of mesoscopic objects



Response

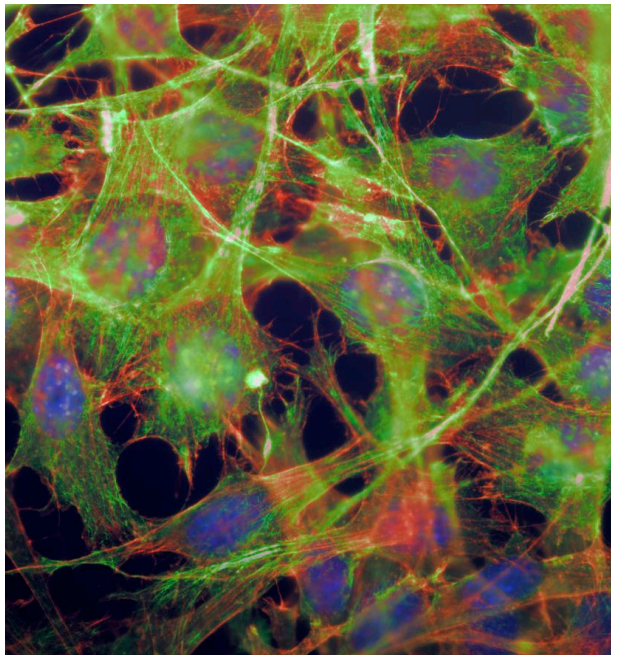
→ Mechanical properties

Use of probe particles in biology

- Use **thermal** fluctuations to measure properties
- Small particles → pore size distribution
- Large particles → rheology
- Probe structural heterogeneities at micron scale
- *In vivo* → Must use **driven** microrheology
  - Non-linearity
  - Active components

The cytoskeleton and microtubules

- The cytoskeleton is a polymer network that can span cell volume
- It consists of actin filaments, microtubules and intermediate filaments
- It gives the cell mechanical strength and is involved in many cell activities such as cell motion and cell division



http://www.uic.edu/classes/bios/bios100/lectf03am/cytoskeleton.jpg

Motivation

- Study transduction of forces across the cell
- Examine microtubule-actin interactions
- Actin has been well studied, as networks and single filaments
- Microtubules have been studied mainly as single filaments

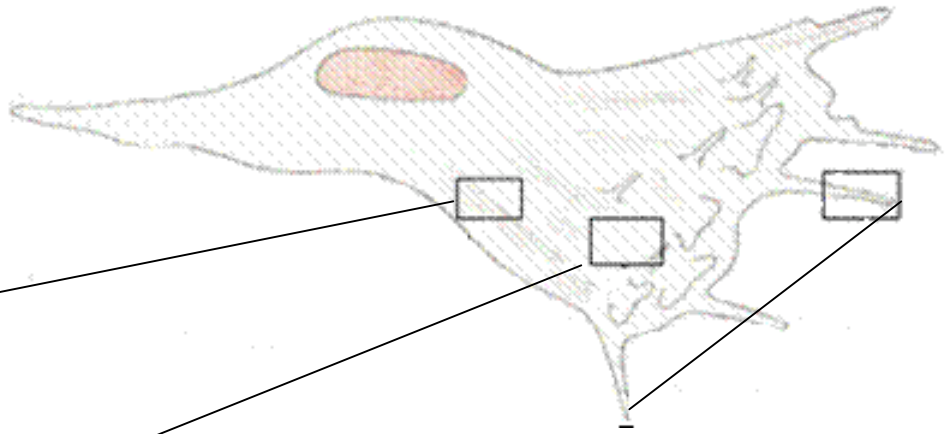
Schaap *et. al.* Eur Biophys J (2004),

Elbaum *et. al.* PRL (1996)

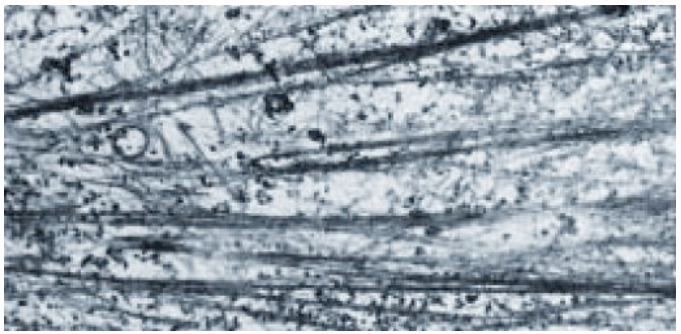
Cytoskeletal F-actin Networks

Maintain cell integrity

Generate forces in cell motility



Contractile Bundles

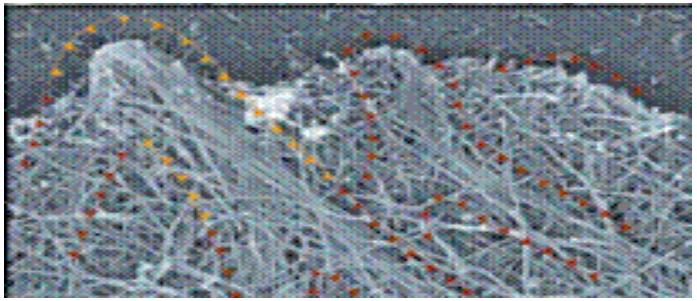


Cramer, JCB 1997

Network

Hartwig, JCB 1990

Protrusive Network



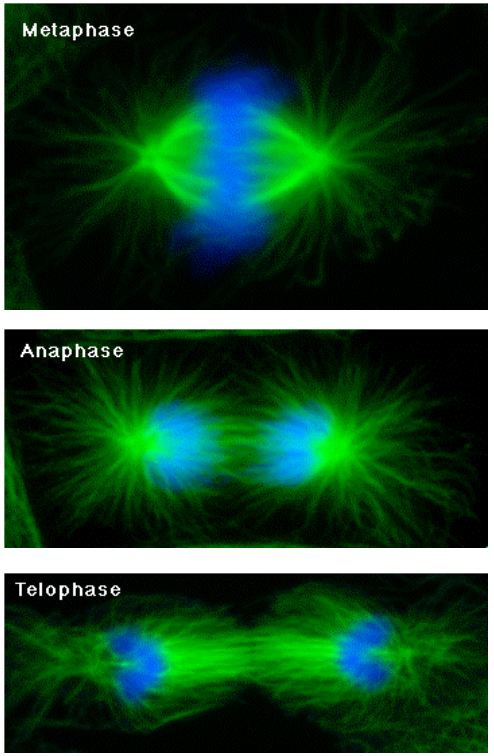
Svitkina, JCB 1998

Dynamic,
Heterogeneous

COMPLEX MATERIAL!

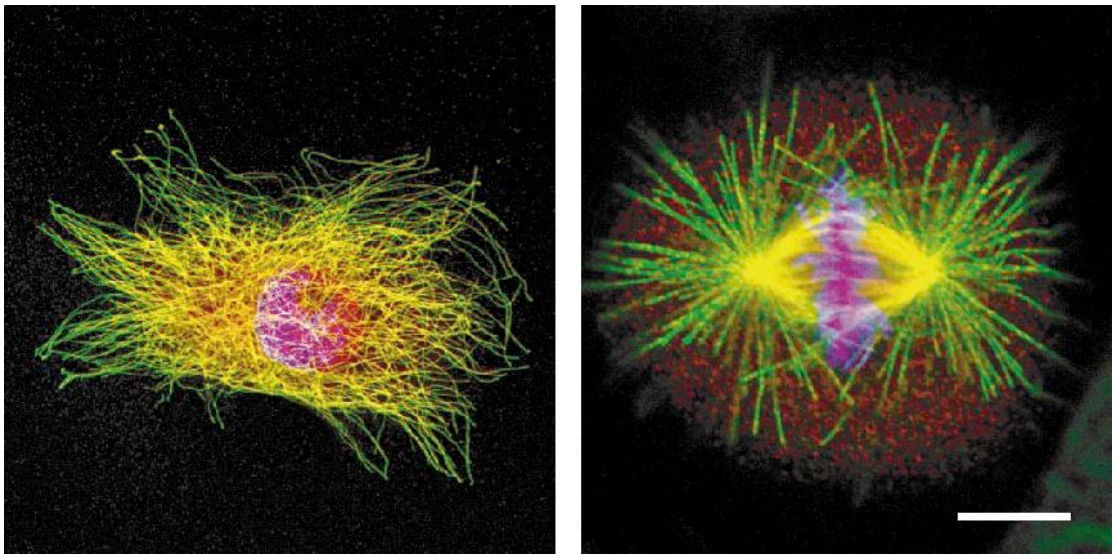
Microtubules

- Structure:
  - Diameter: 25 nm
  - Length: up to hundreds of micrometers
  - High persistence length, >1mm
- Main functions:
  - Intrinsic motility (motor proteins)
  - Cell division (chromosome separation)



Mitchison Group
Harvard med. school

Interphasic cell Mitotic cell



Tournebize et al. Nature Cell Biology (2000)

Scale bar = 10 μm

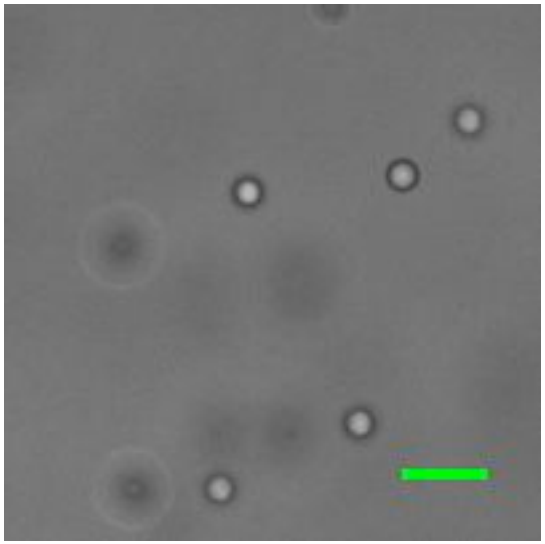
Molecular labeling:

Microtubules

XMAP215 - microtubule associated protein

DNA

Multiparticle tracking



spatial resolution: 10 nm

temporal resolution:
frame rate 1/30 sec or faster

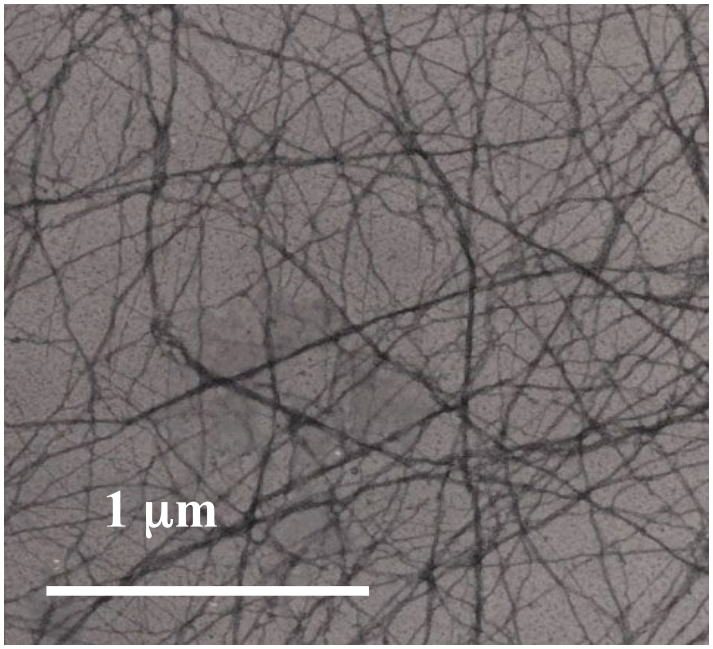
~ 100 particles in field of view (F.O.V.)

~ 3-15 minutes of video/ F.O.V.

2.5 mg/mL tubulin
3.5 μm CML beads
63X objective, bright field

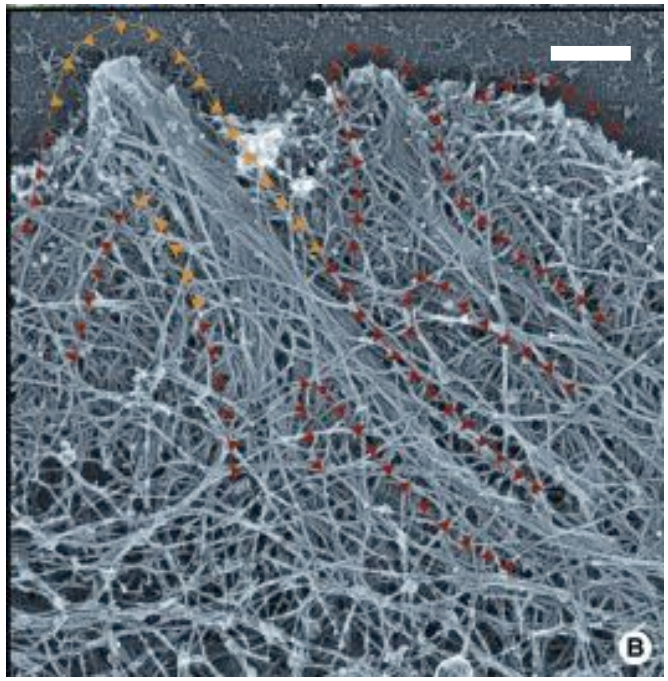
Results depend on particle size compared to mesh size

Minimal *in vitro* model for cell mechanics



in vitro
(in a glass chamber)

0.2 μm



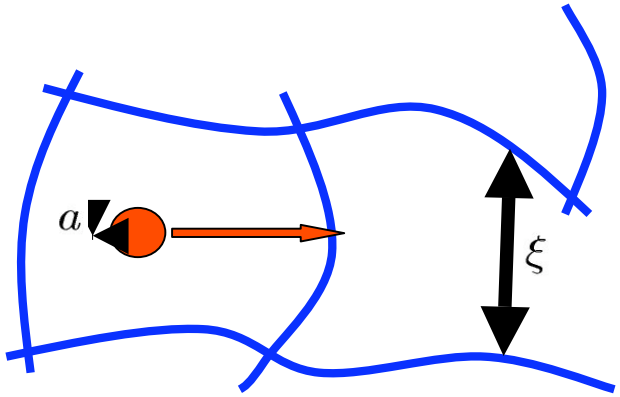
in vivo
(in cells)

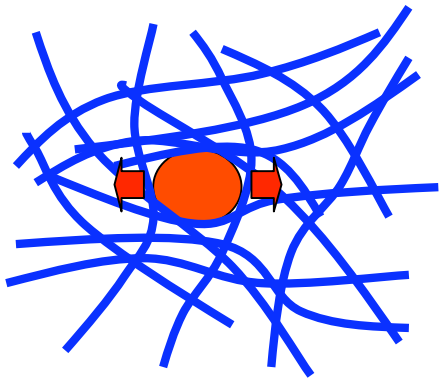
Motion of Probe Particles

Diffusion

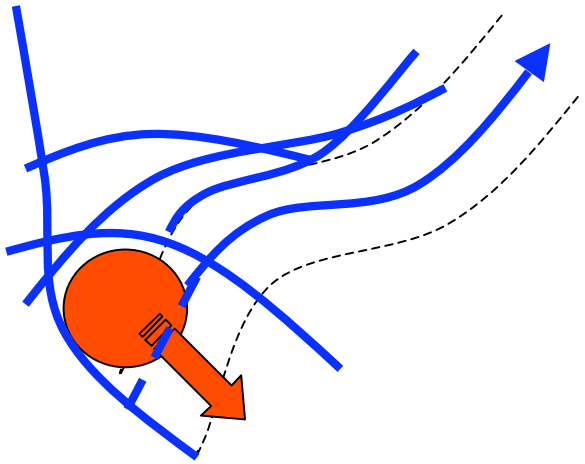
Microrheology

$a < \xi$

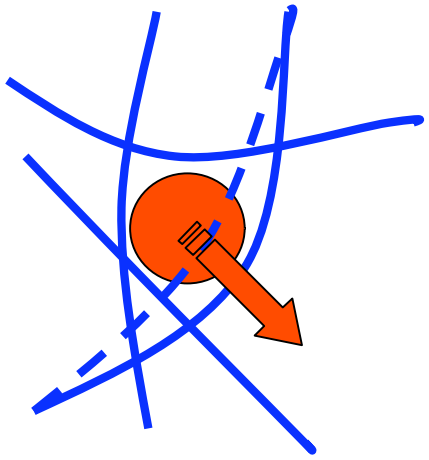




$a > \xi$



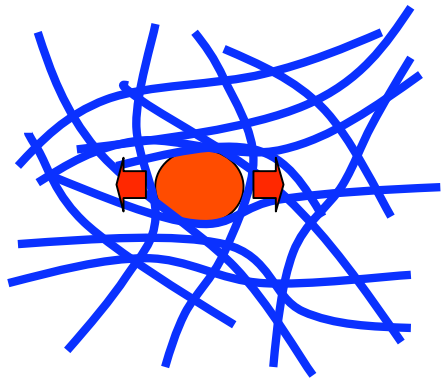
$a \sim \xi$



Jumping motion

Motion of Probe Particles

Microrheology



$a > \xi$

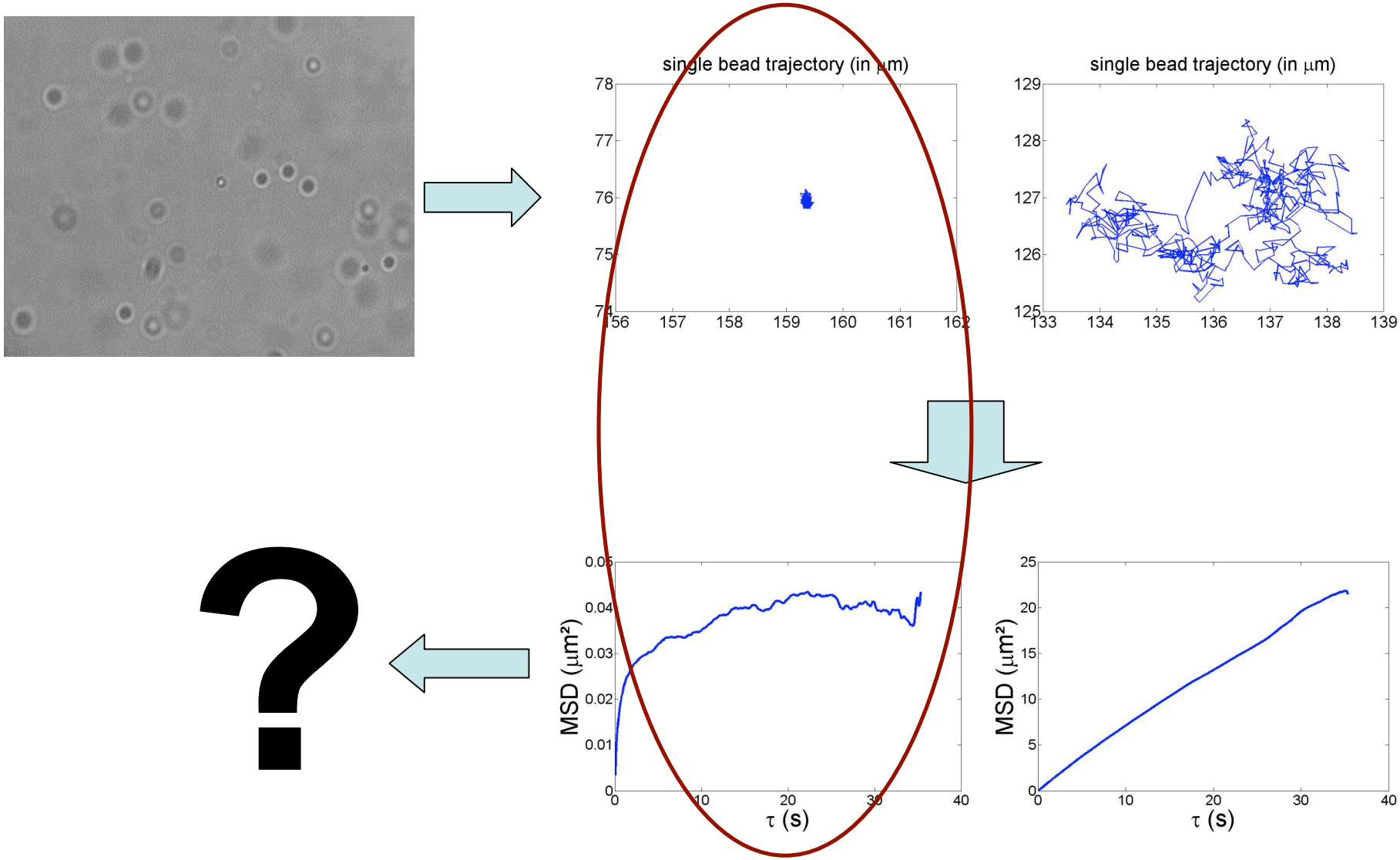
The *in vitro* System

- Tubulin at ~2.5 mg/ml
- A fraction is labeled with cy-3
- MAPS are present
- GTP at ~1mM
- Add ~10% DMSO for nucleation
- No taxol or other drug is added
- Incubation at 36°C for 30 min

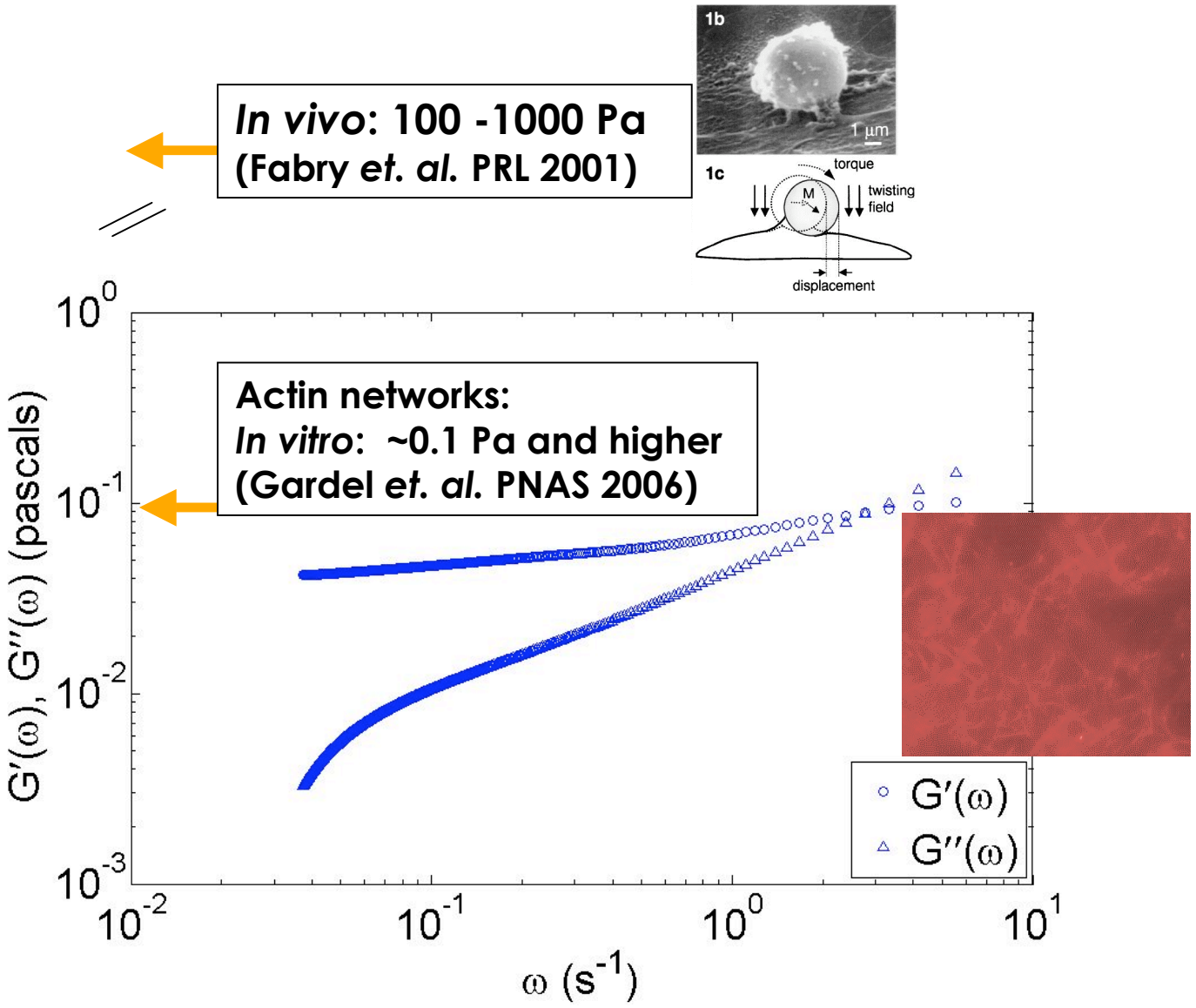
- Polystyrene beads coated with PLL-g-PEG

15 µm

The analysis procedure

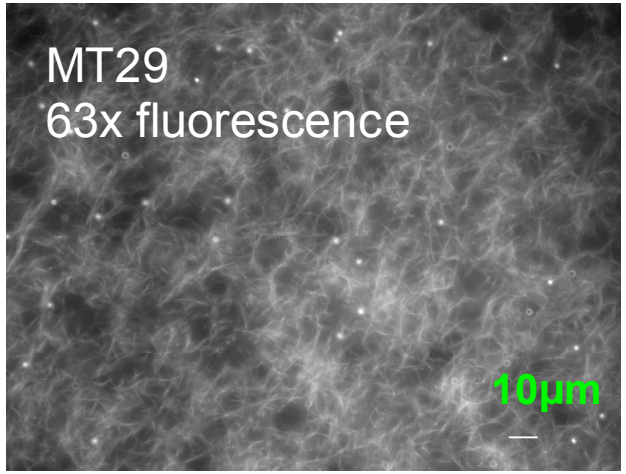


Results: 1 μm beads

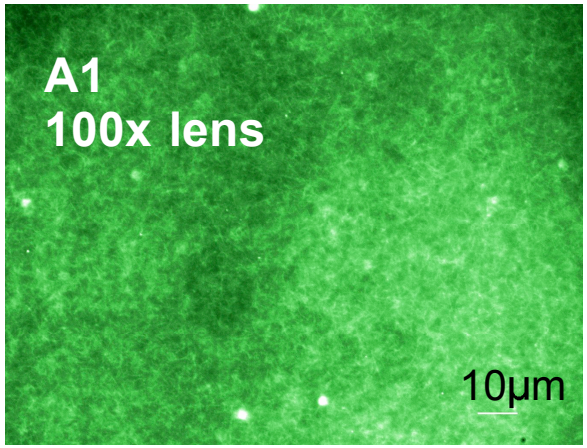


More complex *in vitro* System: Composite networks

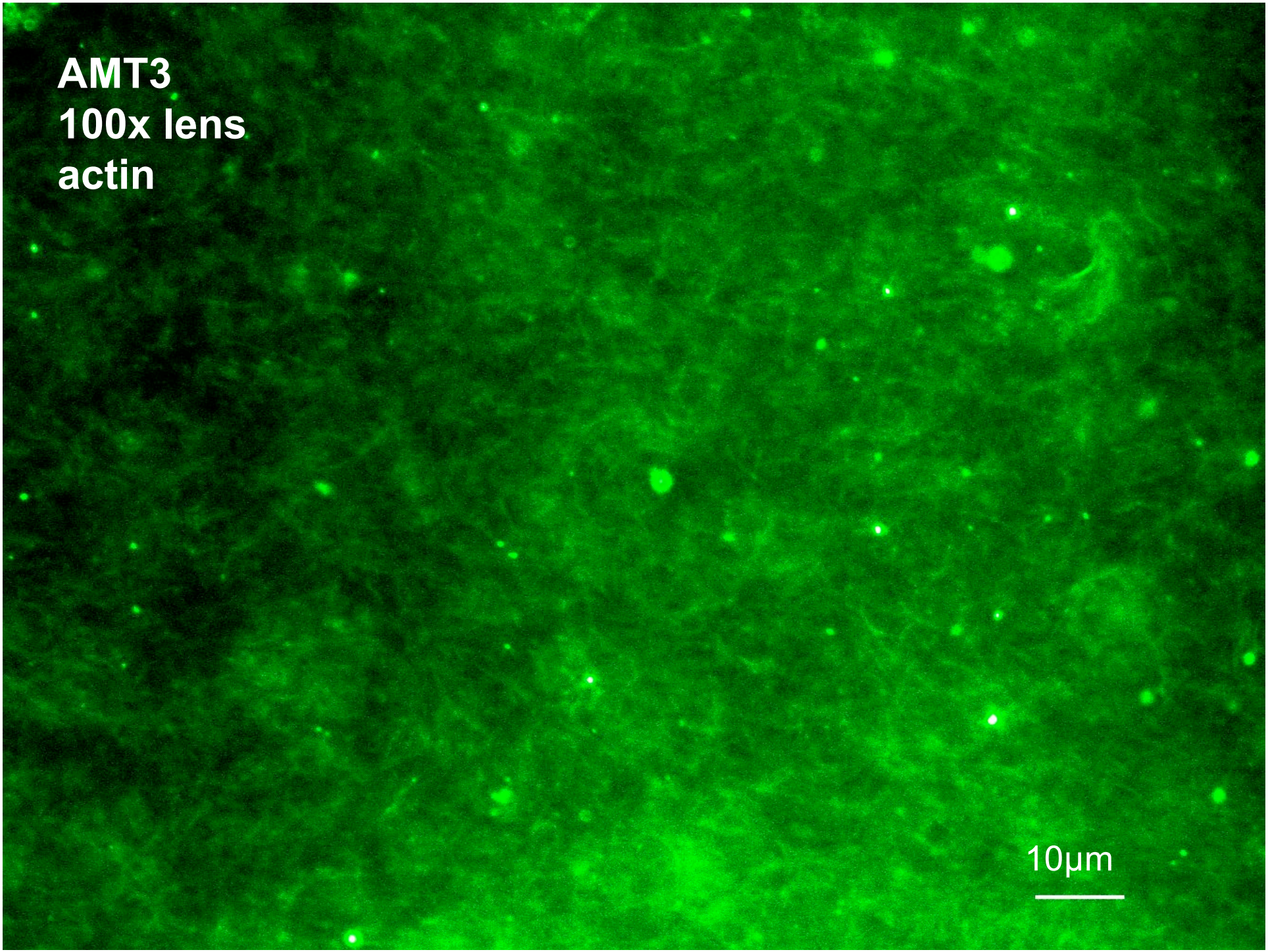
Microtubule network

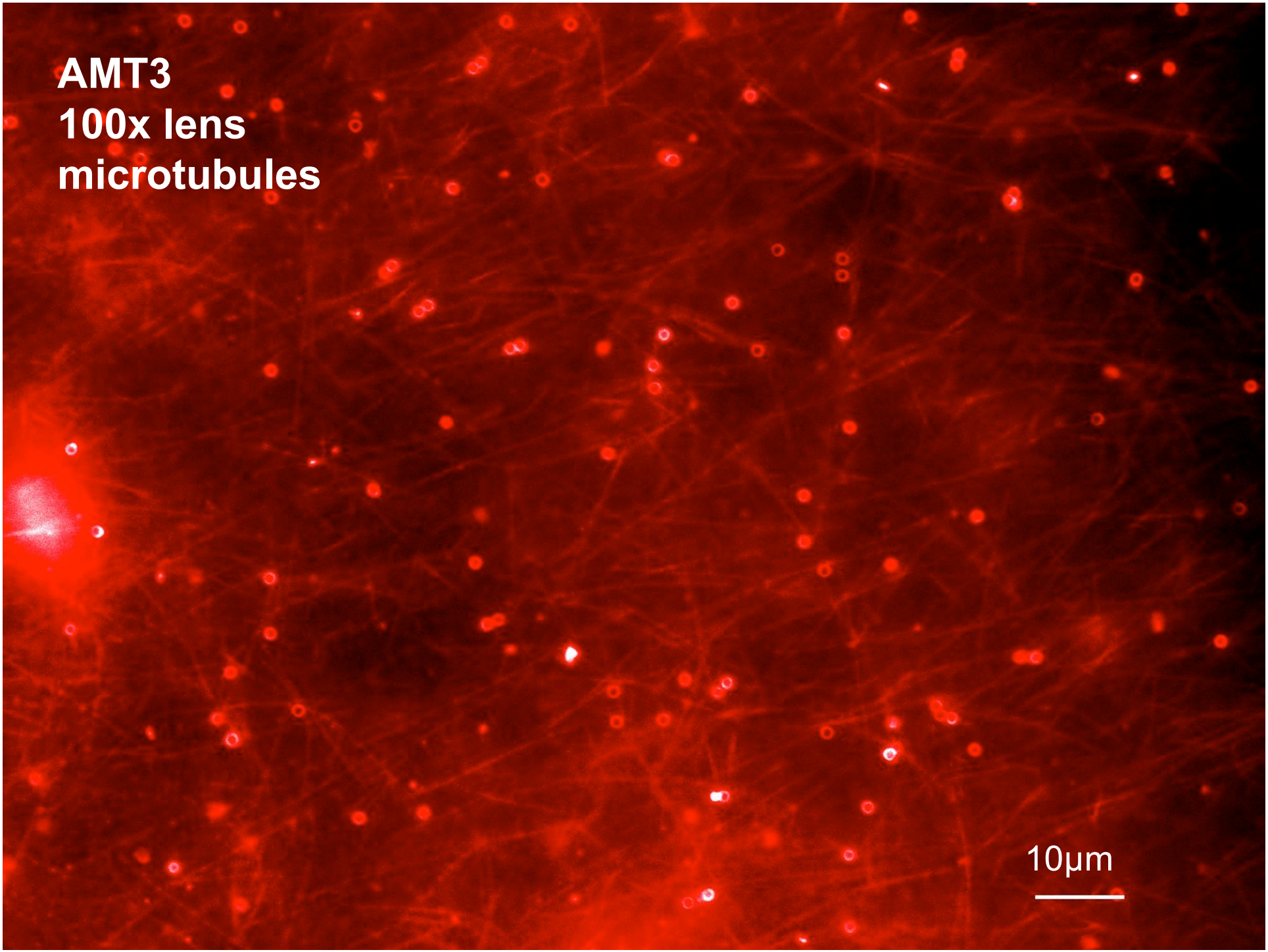


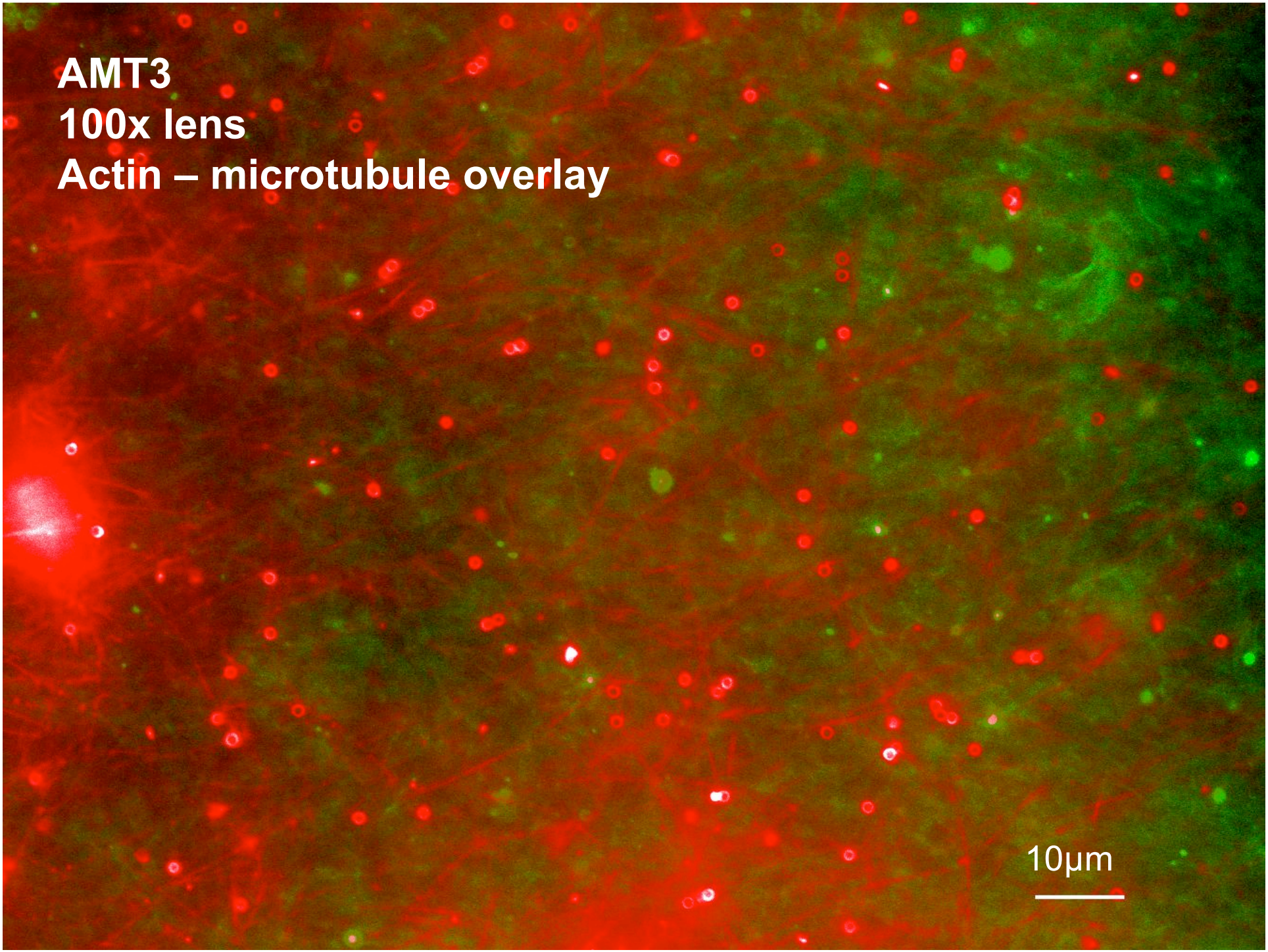
Actin network

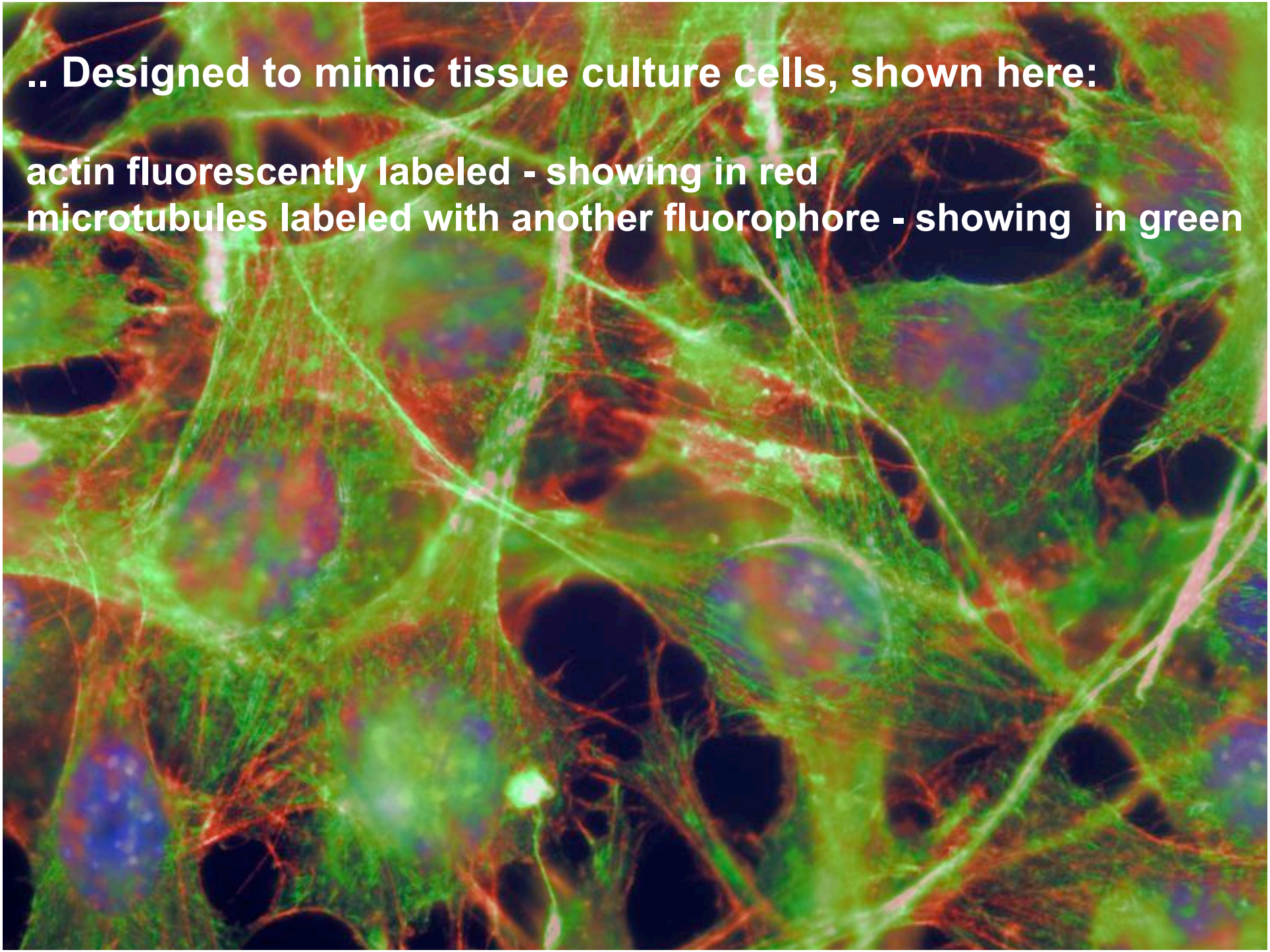


Final concentrations:
Microtubules: 1.28 mg/mL
Actin: 0.71 mg/mL

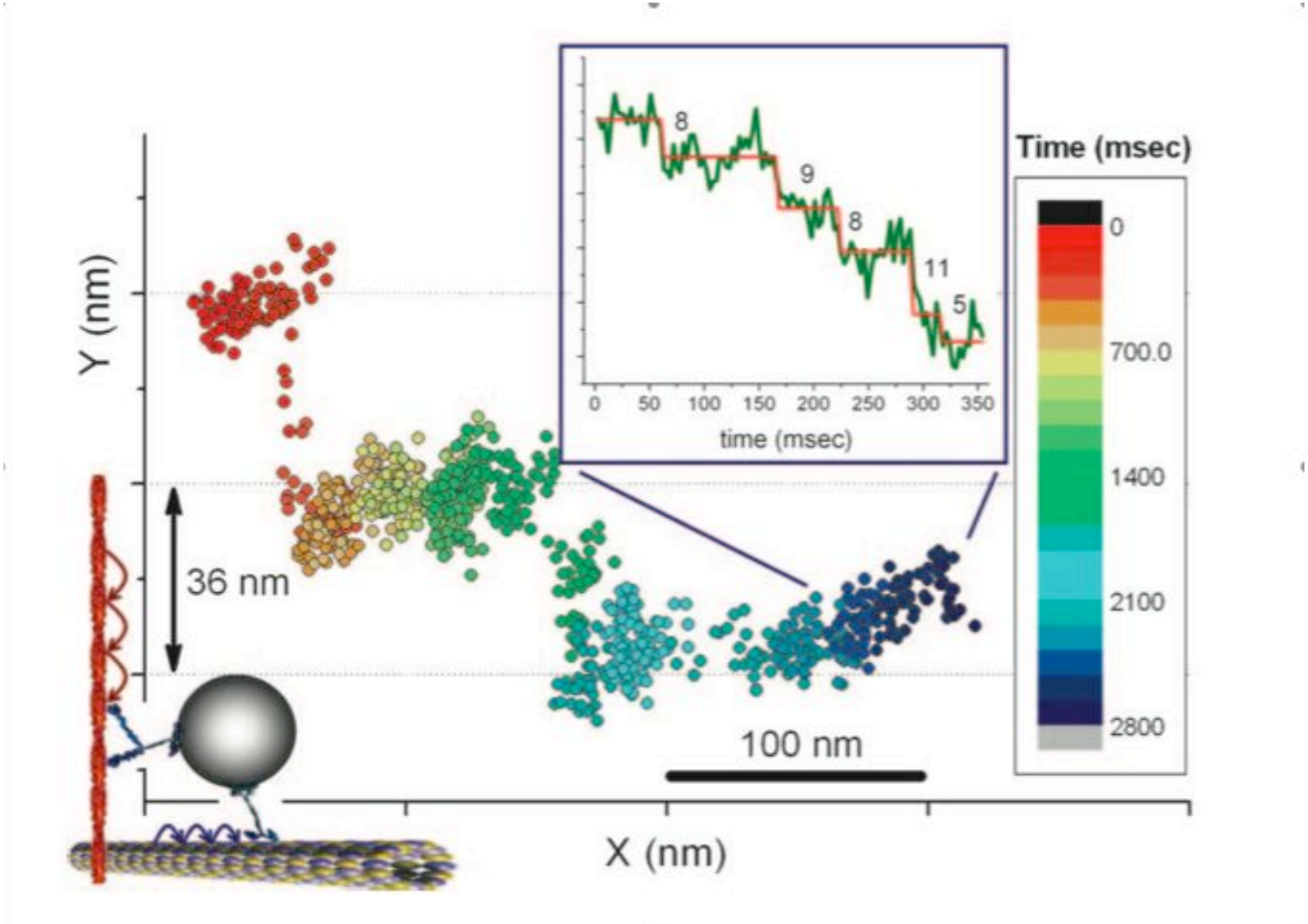

AMT3
100x lens
actin
10µm


AMT3
100x lens
microtubules
10µm


AMT3
100x lens
Actin – microtubule overlay
10µm


.. Designed to mimic tissue culture cells, shown here:
actin fluorescently labeled - showing in red
microtubules labeled with another fluorophore - showing in green

Future directions: motor proteins



Myosin V and kinesin Selvin *et al*, March 2007