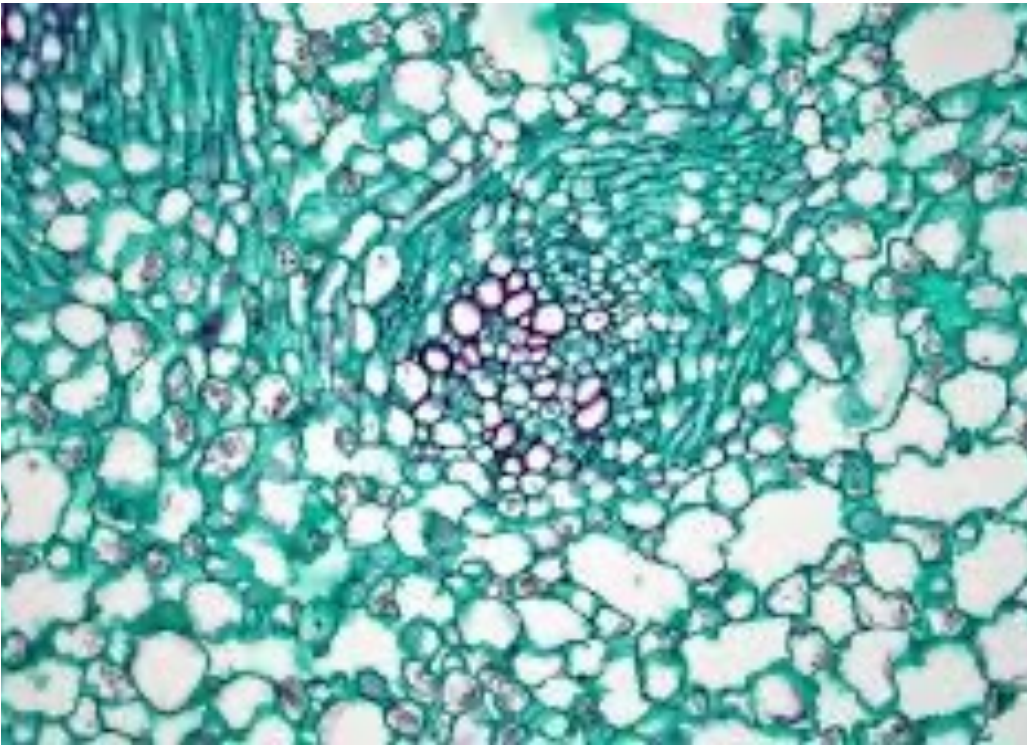


# Morning of Theoretical Physics Trinity Term 2024

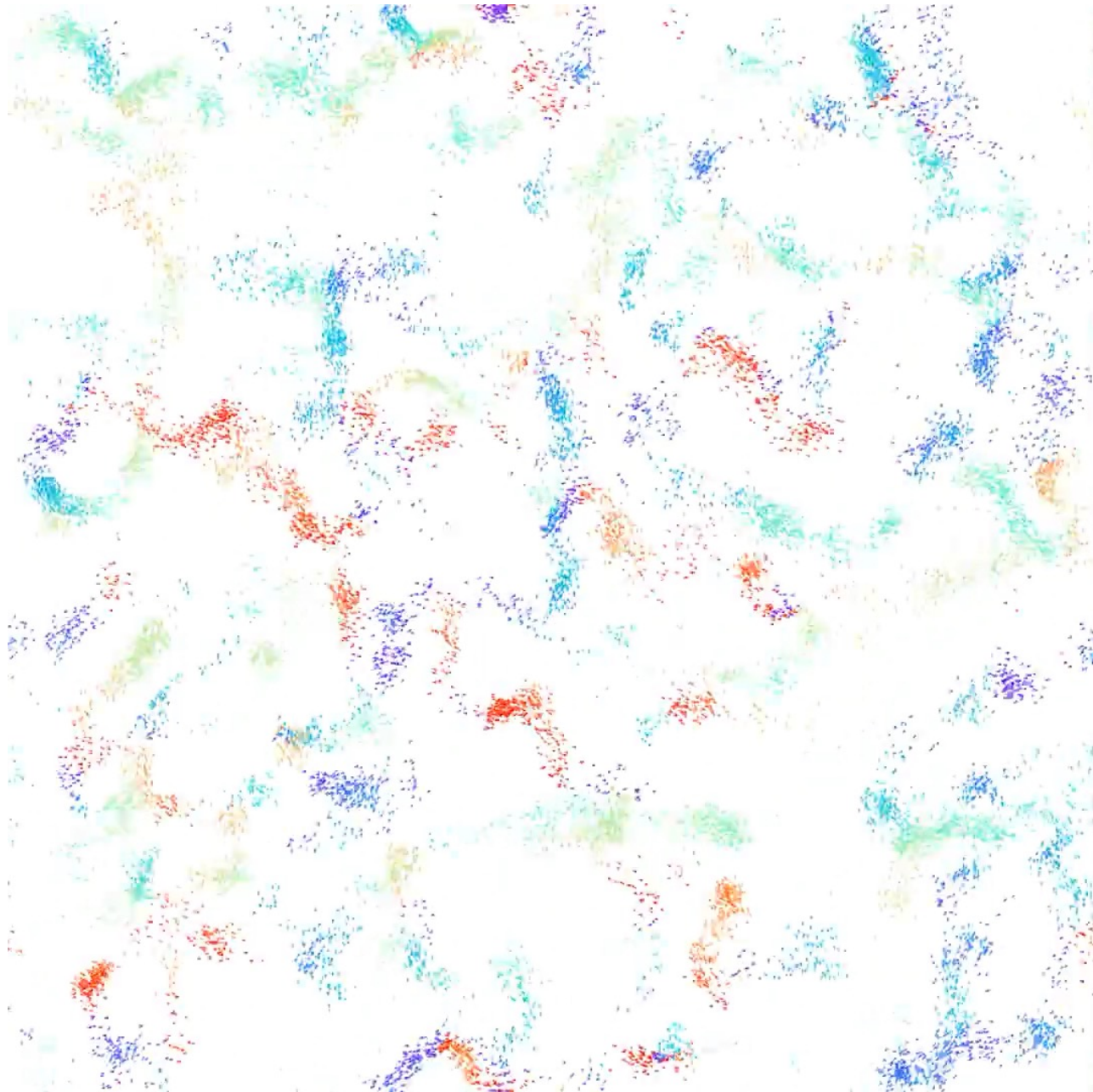
## Statistical Physics of Living Systems Julia Yeomans





- Active matter
- How do single cells move?
- How do confluent cell layers move?
- How do cells move in vivo?

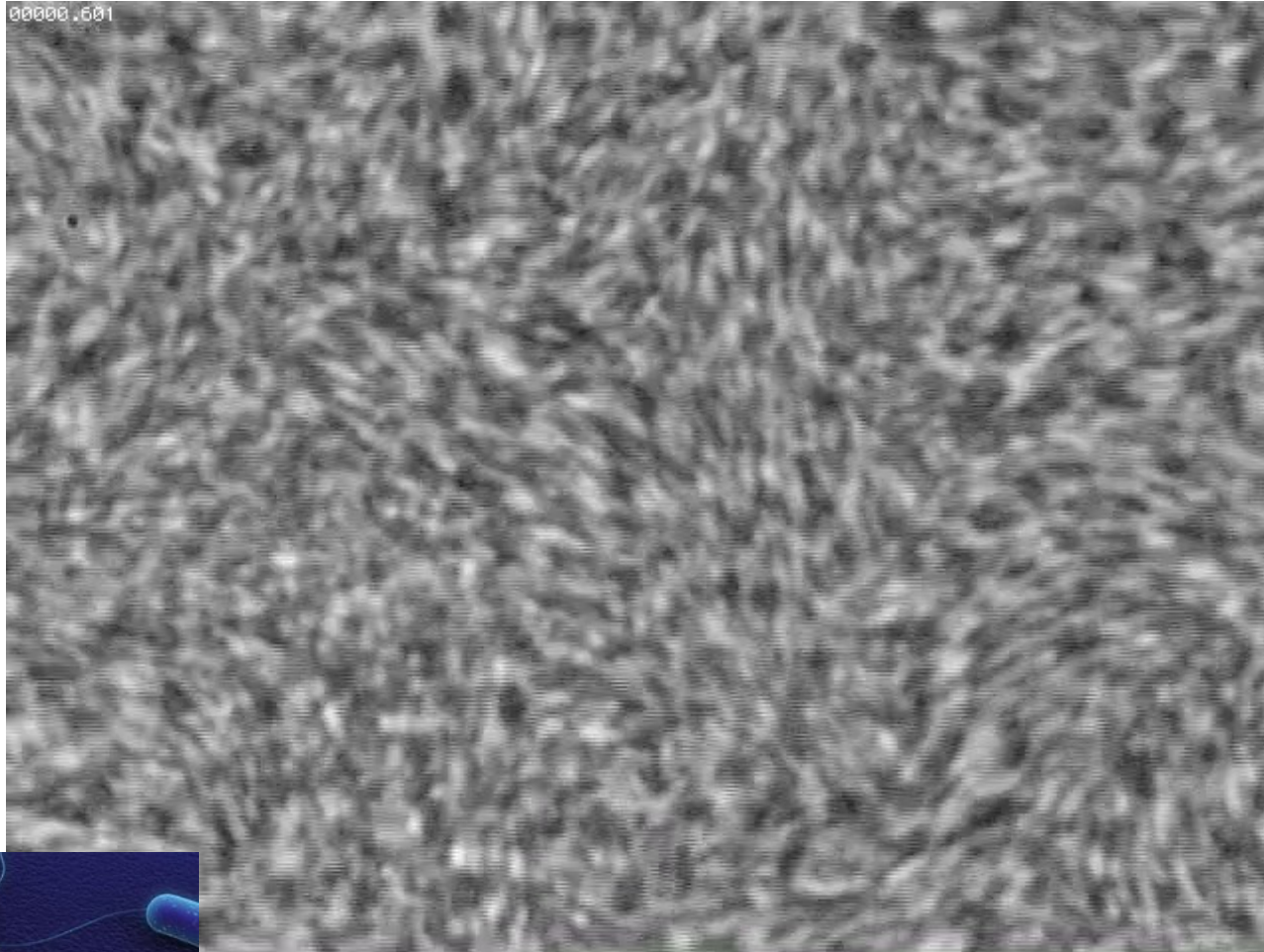
# The Vicsek model



# Flocking: starlings



# Active turbulence: bacteria

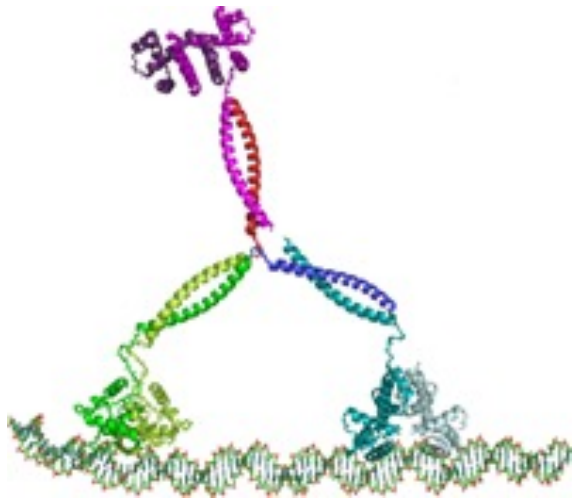


Dense suspension of microswimmers

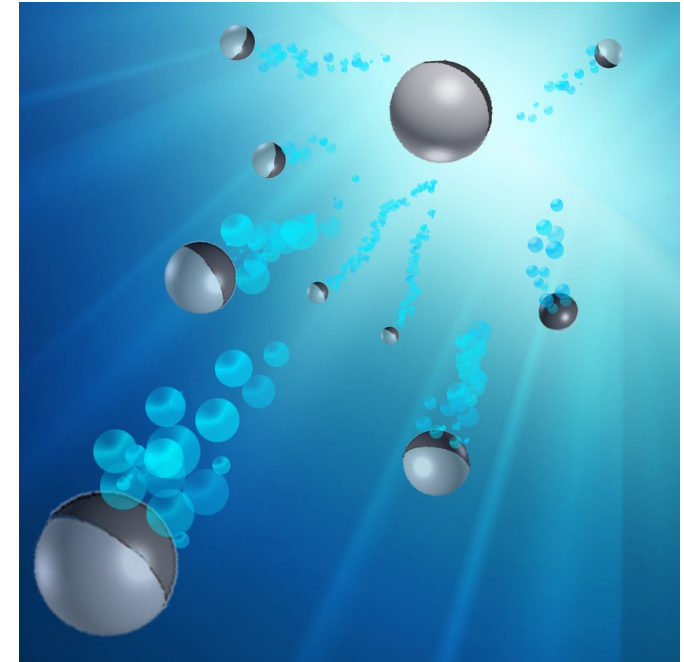
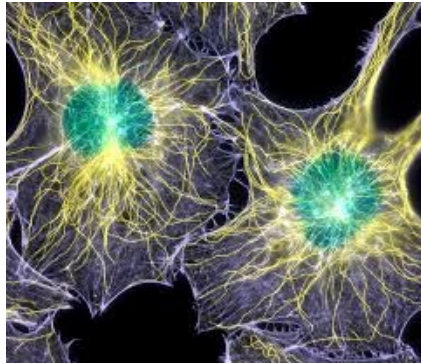
# Active matter:

takes energy from the surroundings on a single particle level and uses it to do work.

molecular motors



cells



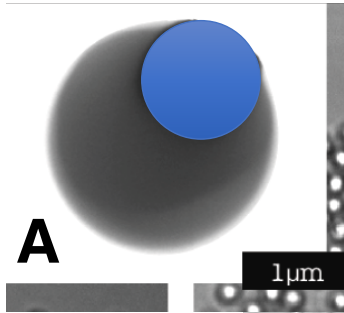
active colloids



microswimmers

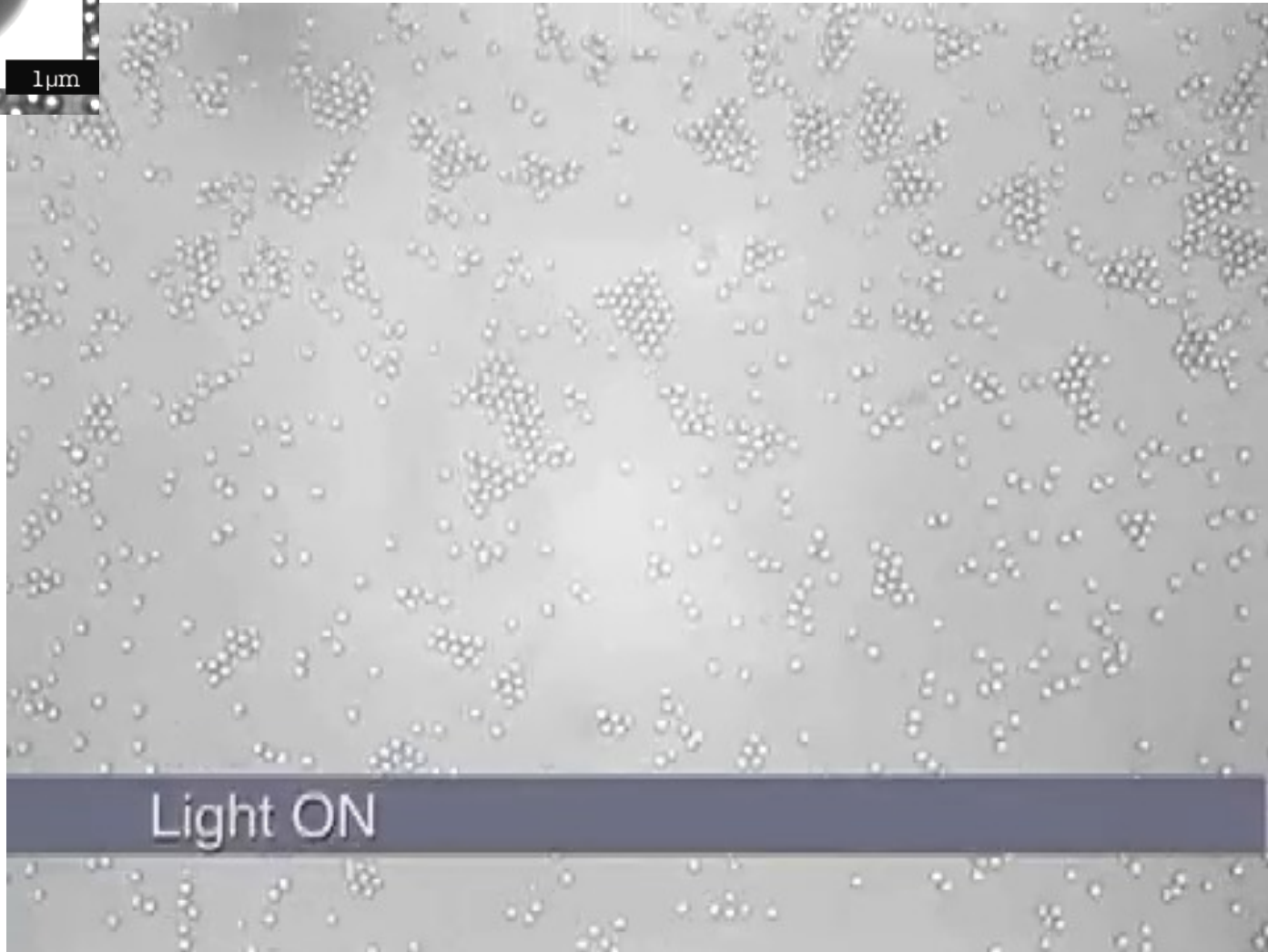
animals





hematite

hydrogen peroxide

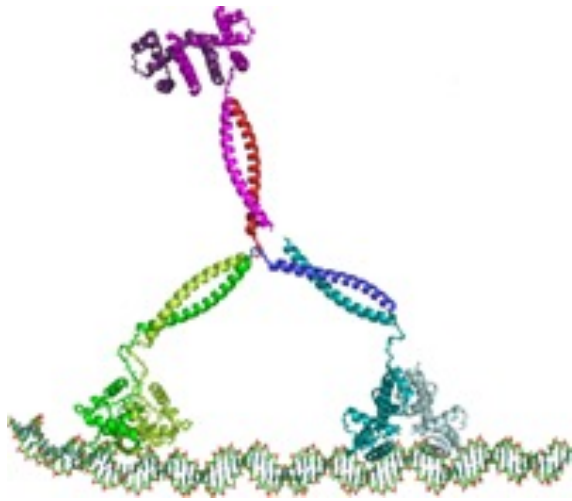


Pine group, New York

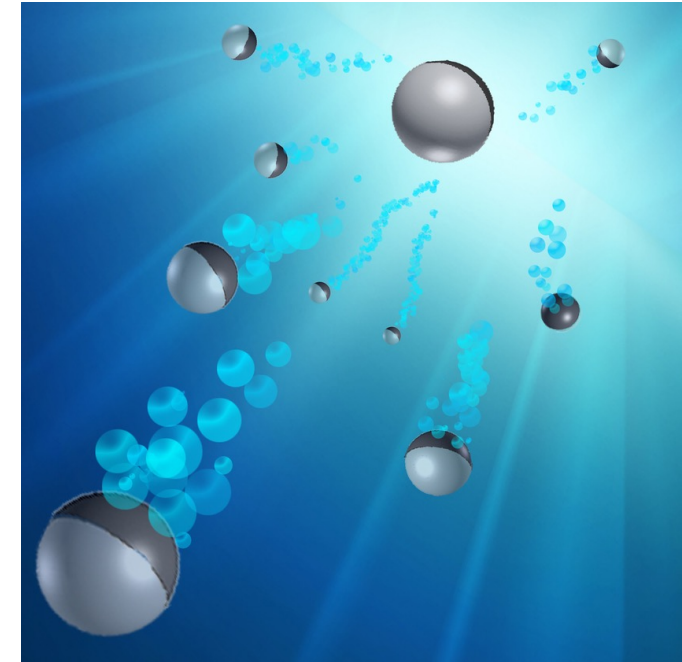
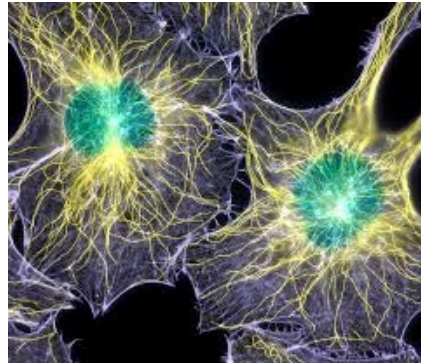
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cells



active colloids



microswimmers

animals





“Living matter evades the decay to equilibrium” Schrodinger

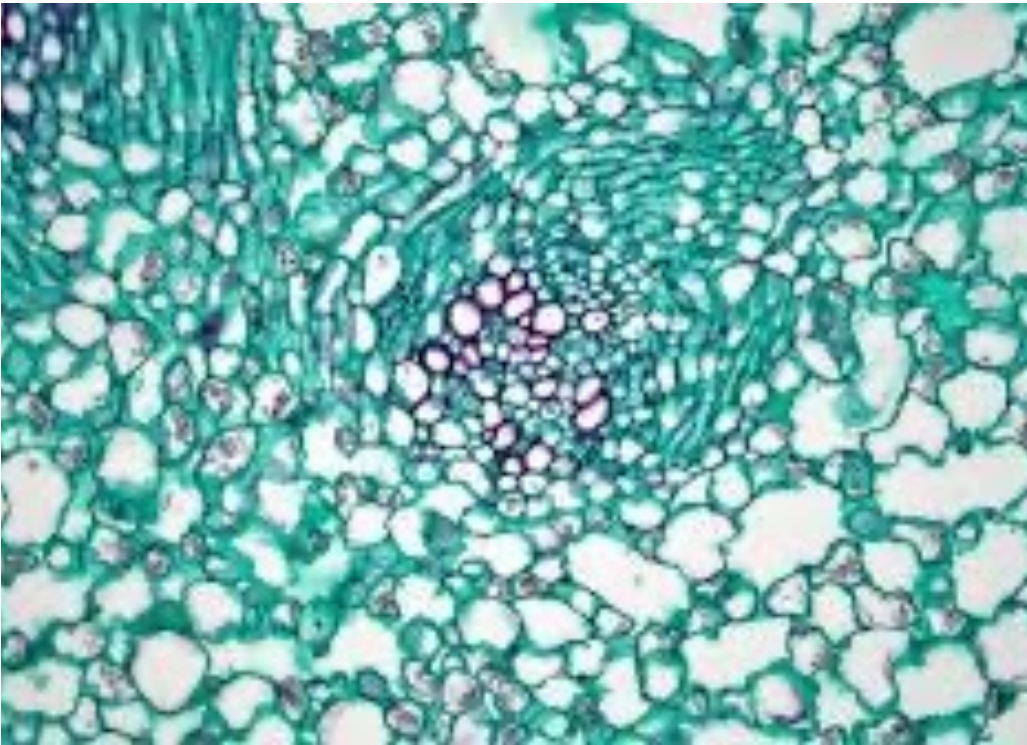
“Living matter evades the decay to equilibrium”

Schrodinger



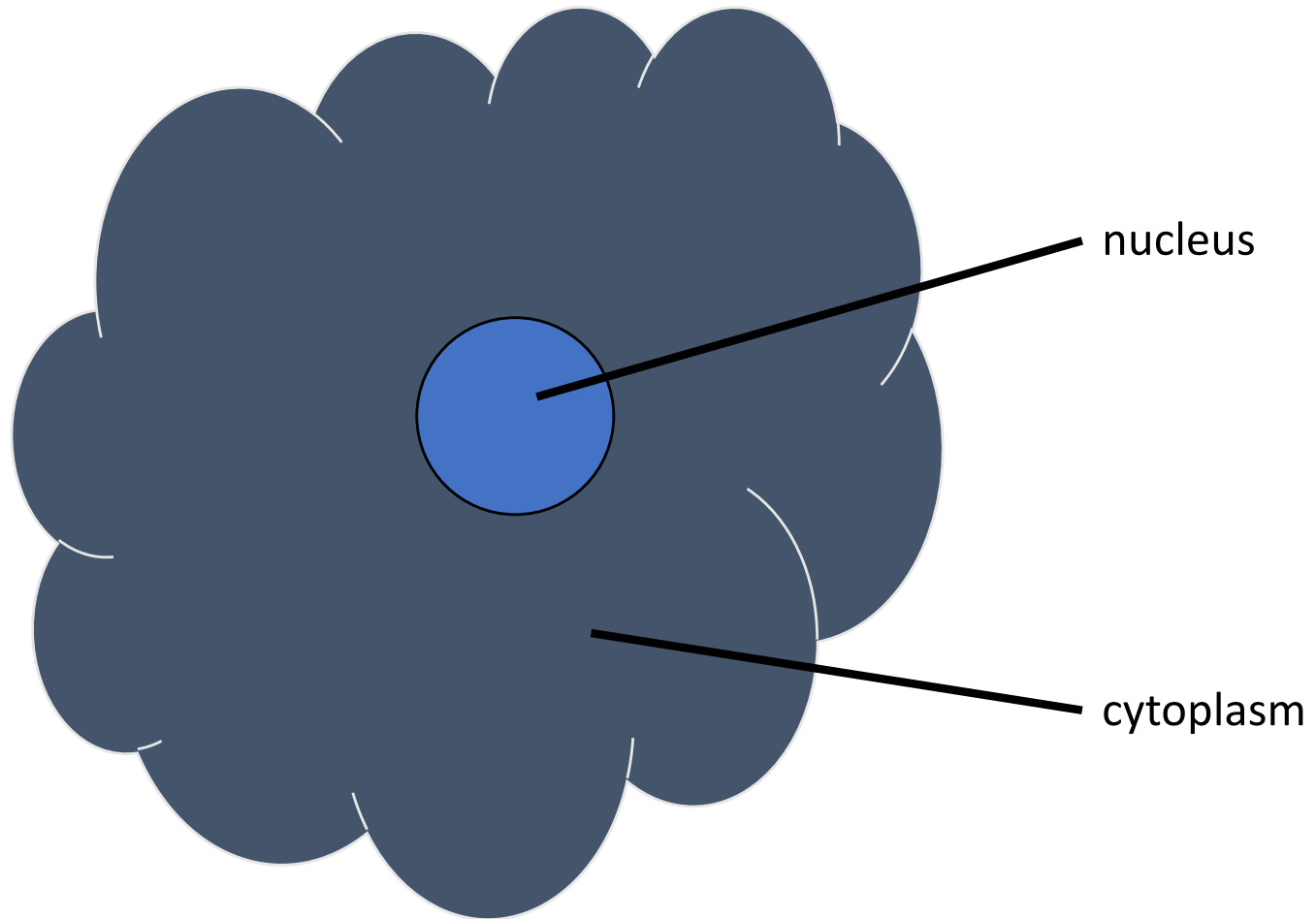
“Living matter evades the decay to equilibrium” Schrodinger



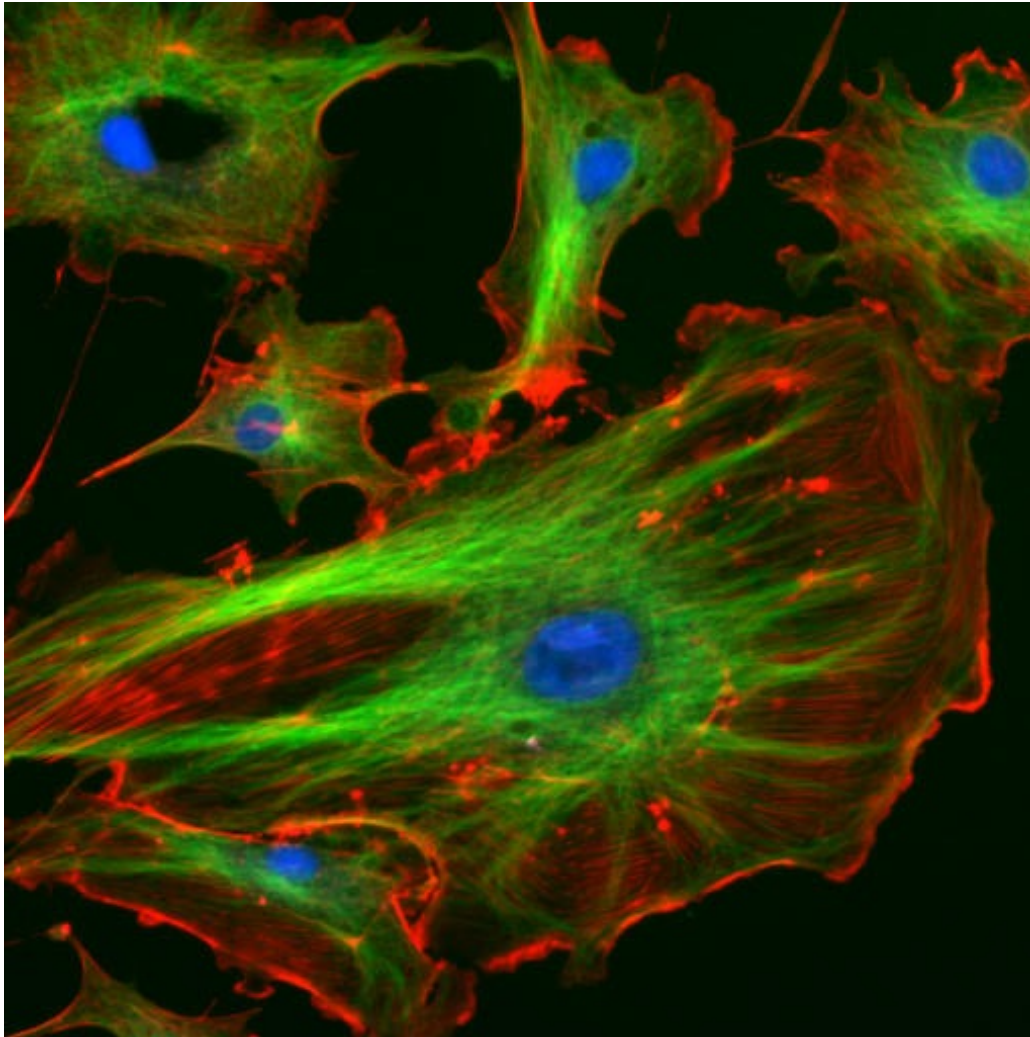


- Active matter
- How do single cells move?
- How do confluent cell layers move?
- How do cells move in vivo?

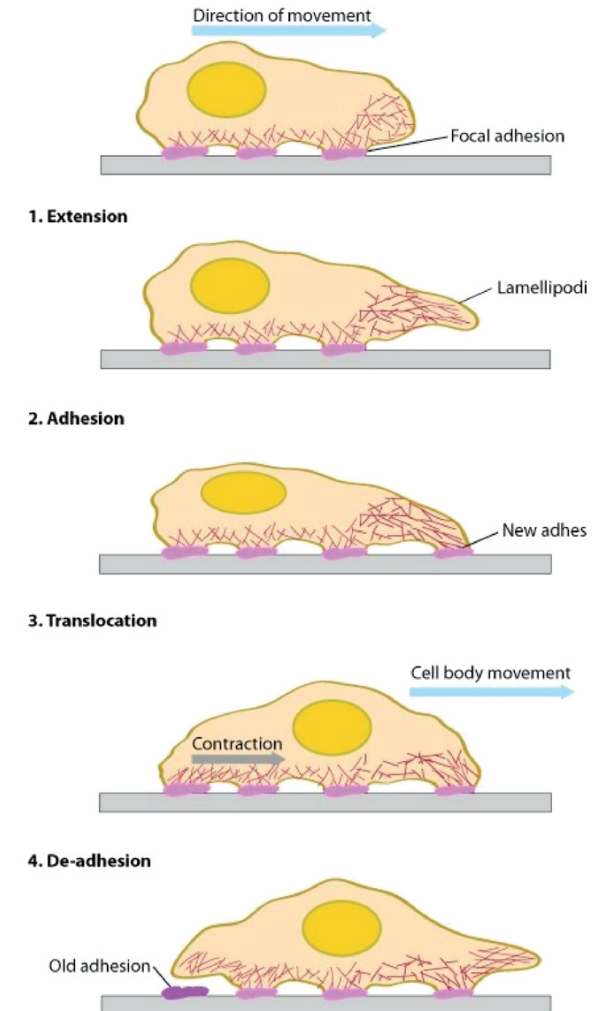
Eukaryotic cells circa the middle of the 20<sup>th</sup> century



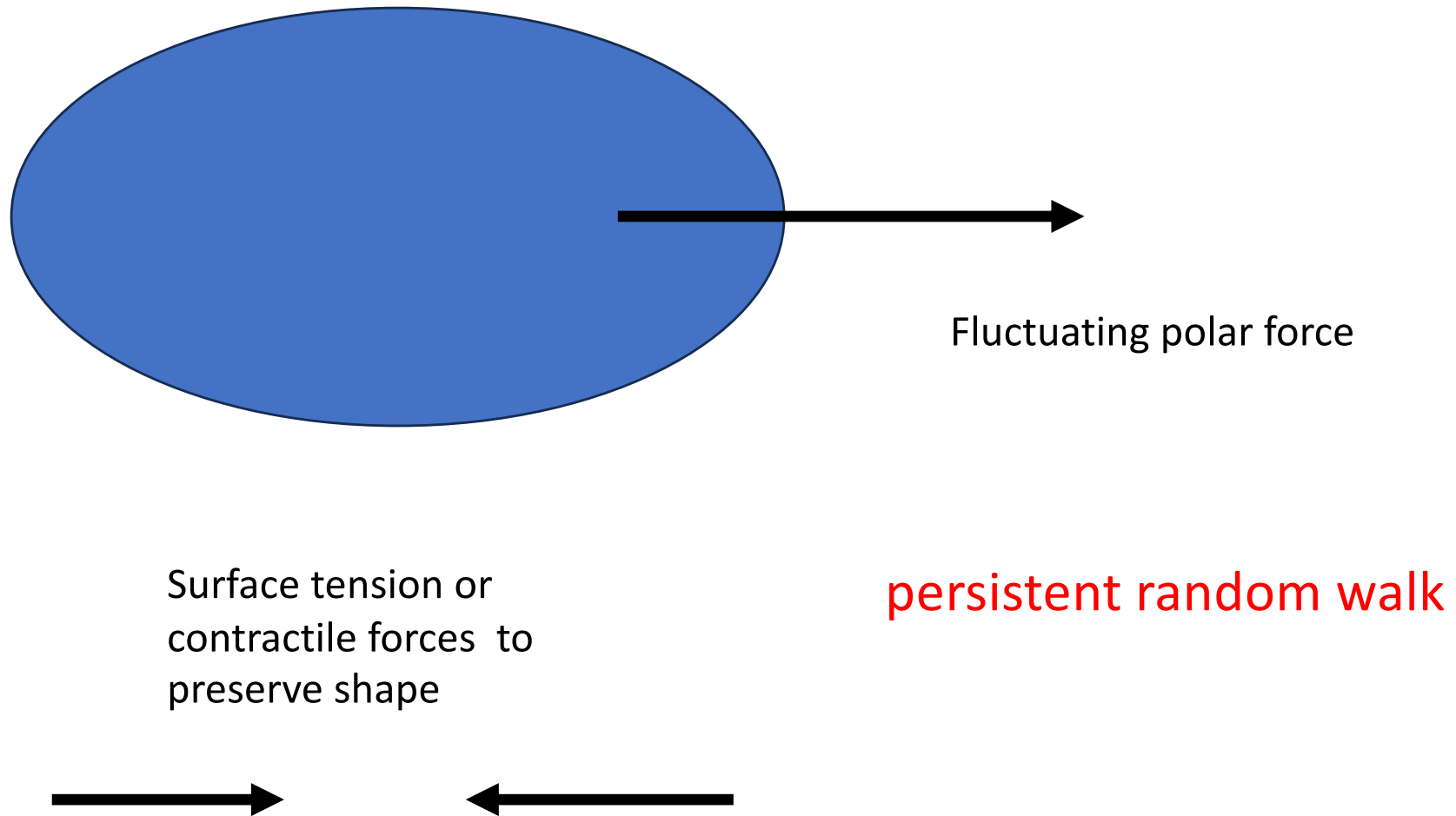
# How do individual cells move?



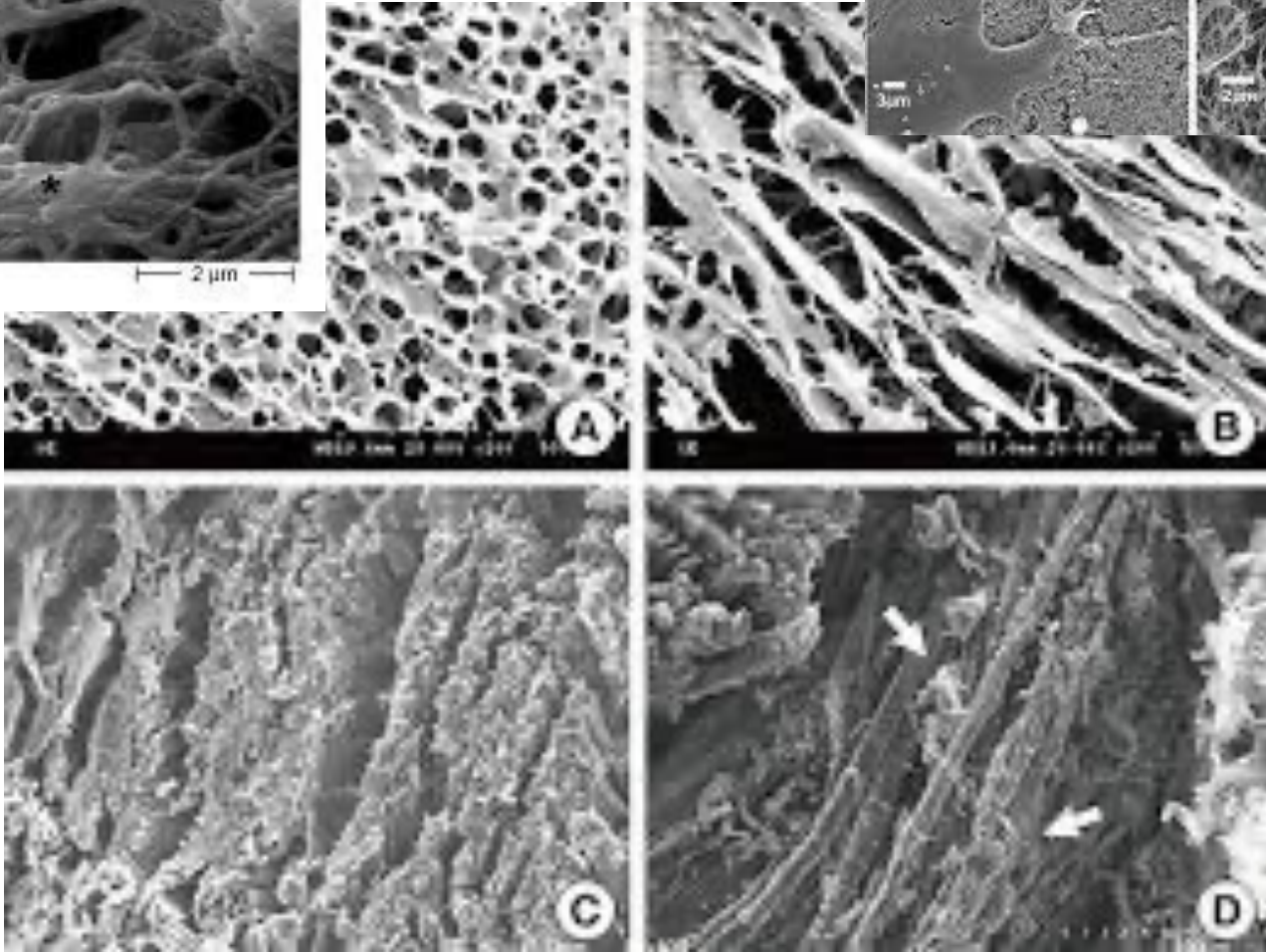
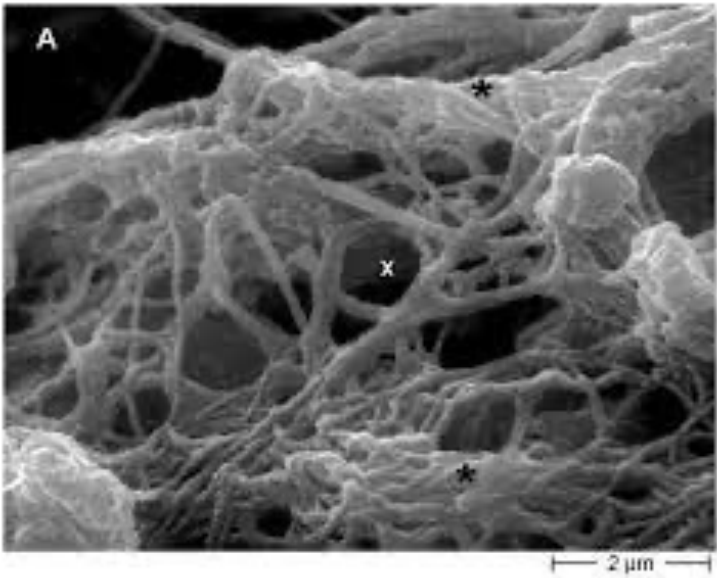
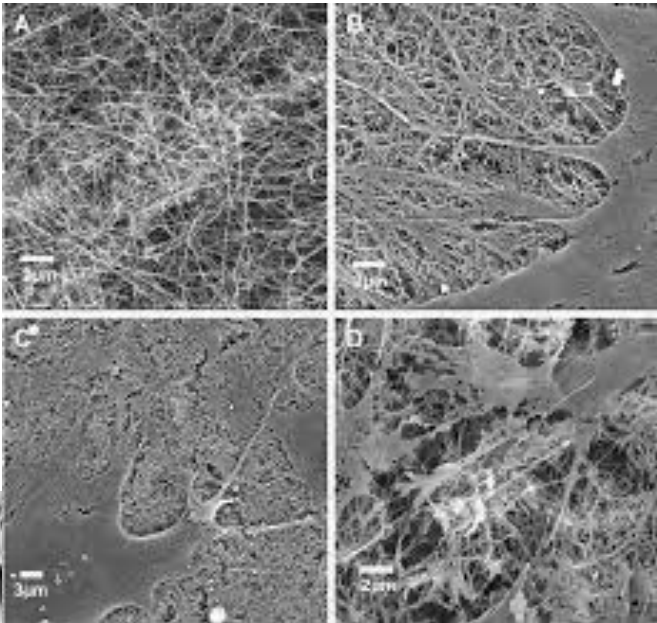
Red: focal adhesions  
Green: actin filaments  
Blue: nucleus



# How do individual cells move?



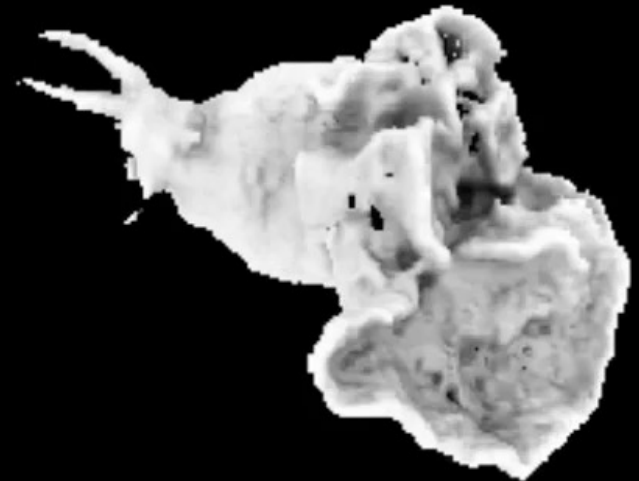
# Extra-cellular matrix



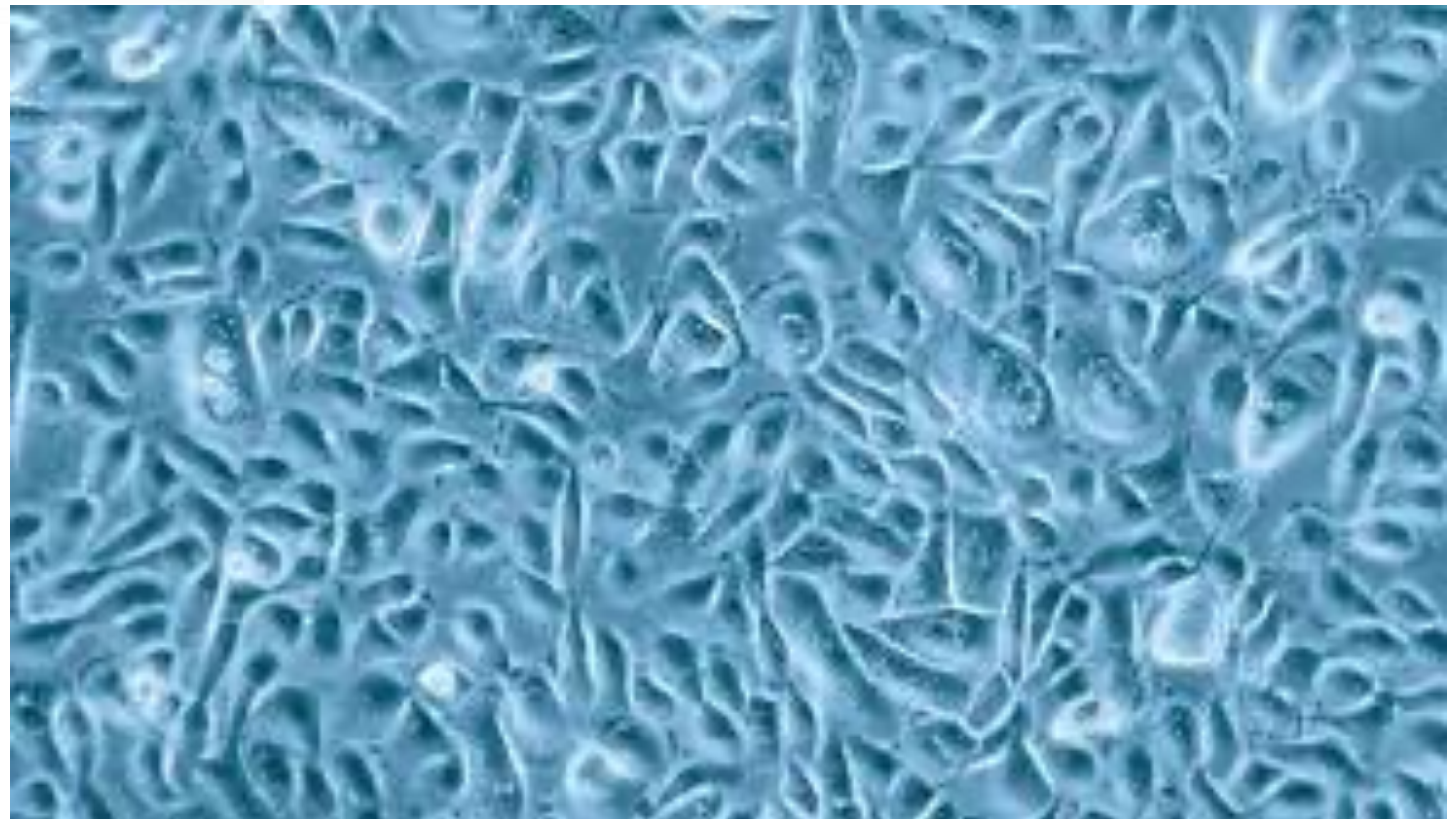
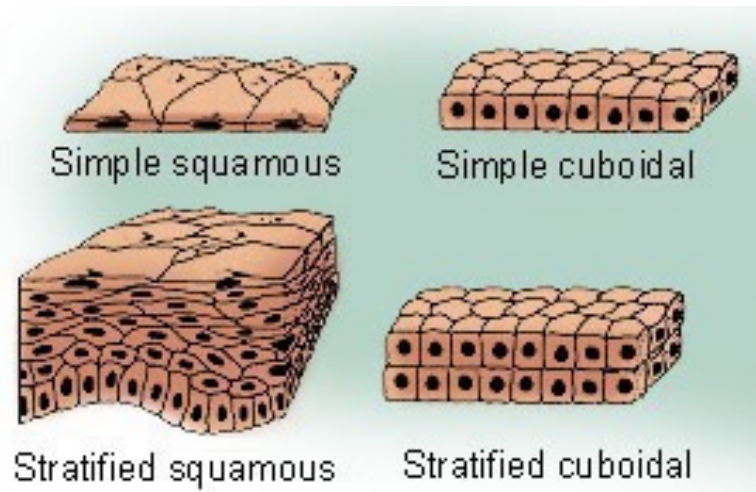


# White blood cells moving through an extra-cellular matrix

UCSF scientists are using new **3D microscopes** to discover how white blood cells move.

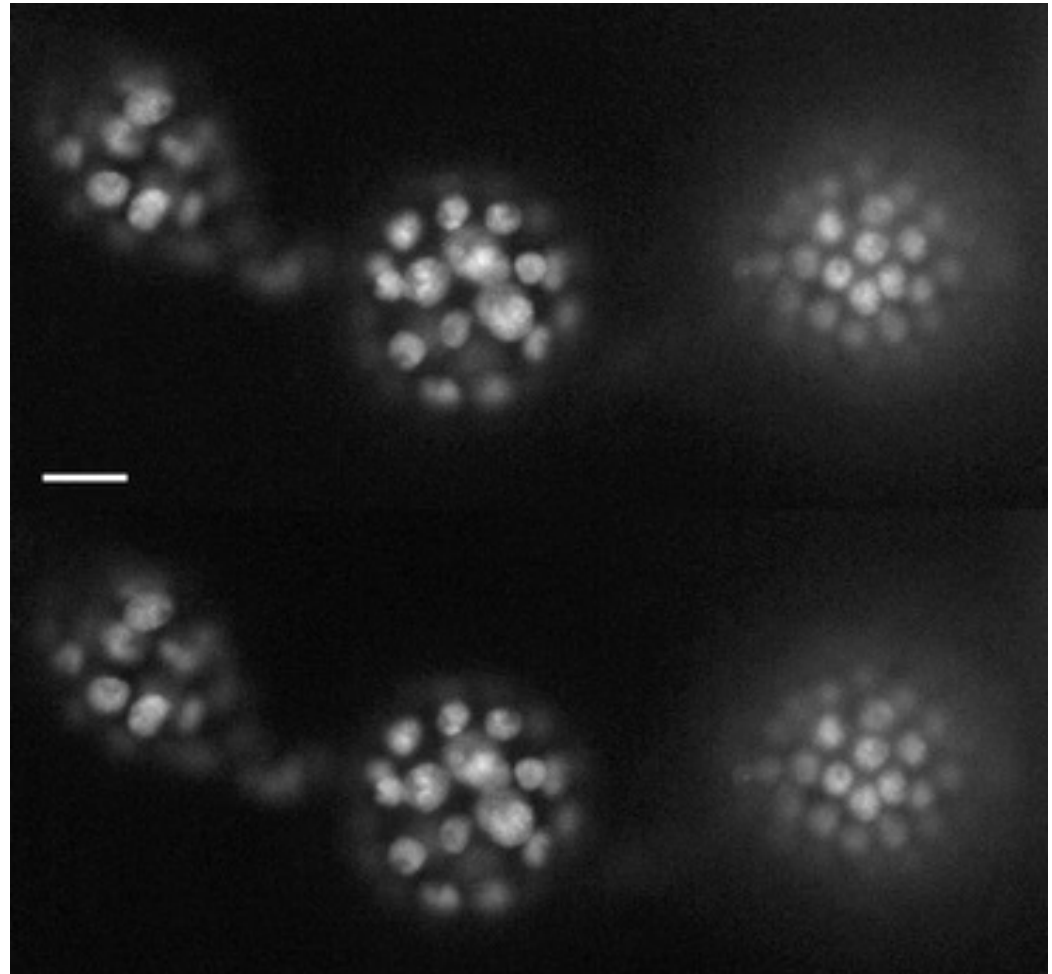
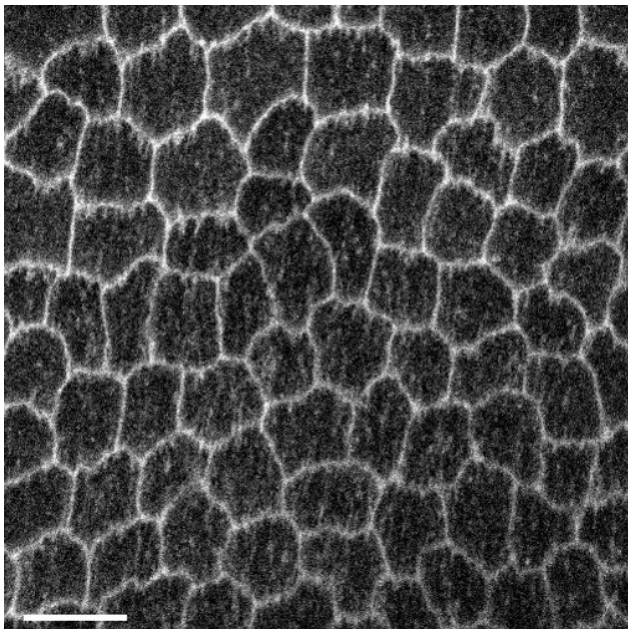
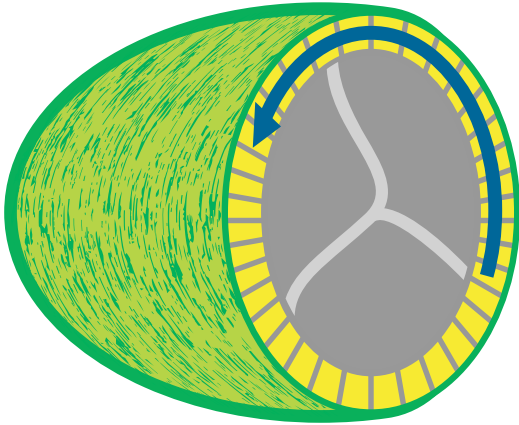


# Epithelial cells

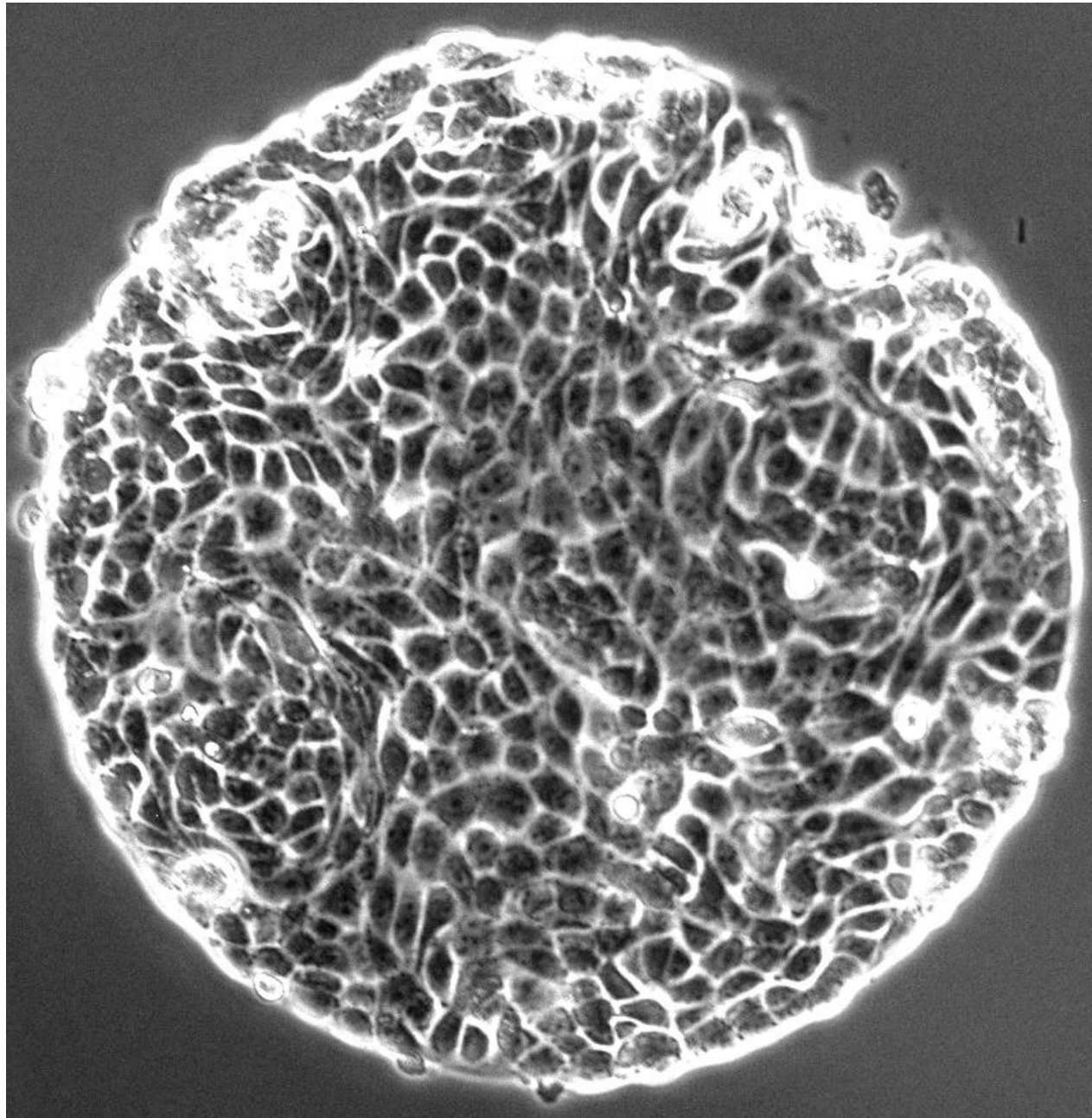


# How do layers of cells move? Flocking

Egg chamber rotation

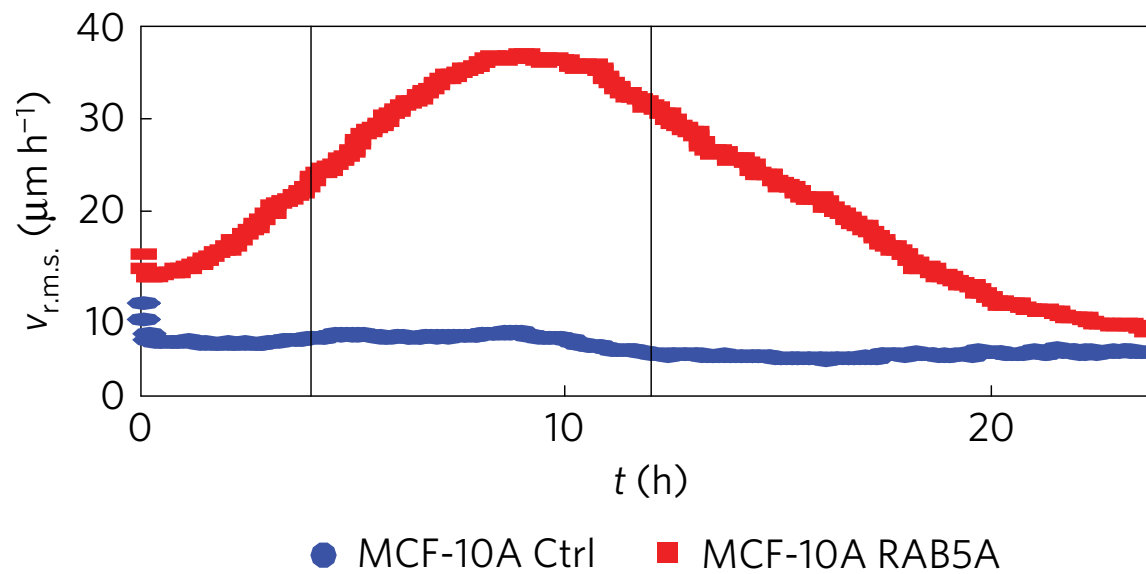
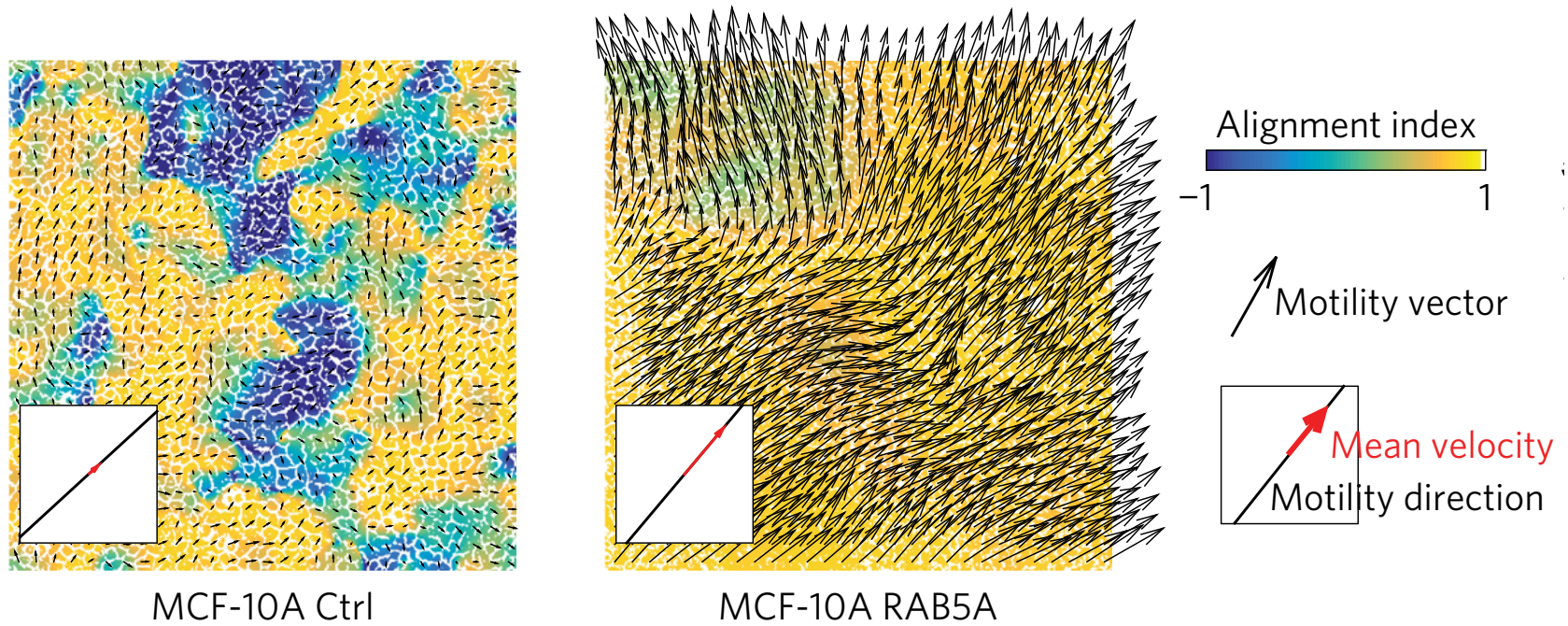


# How do layers of cells move Active turbulence

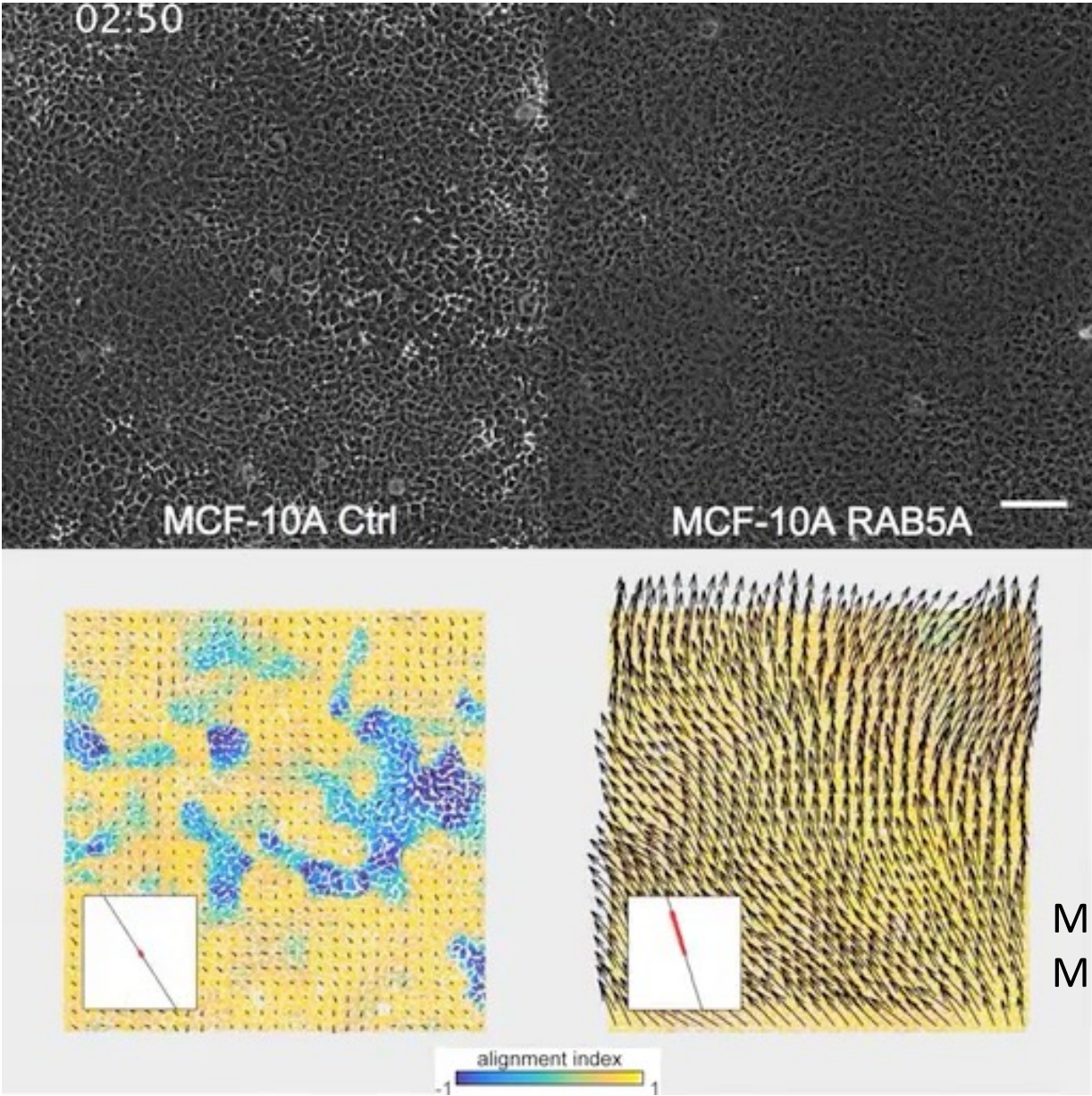


Malinverno et al Nature Materials 16 (2017)

**a**

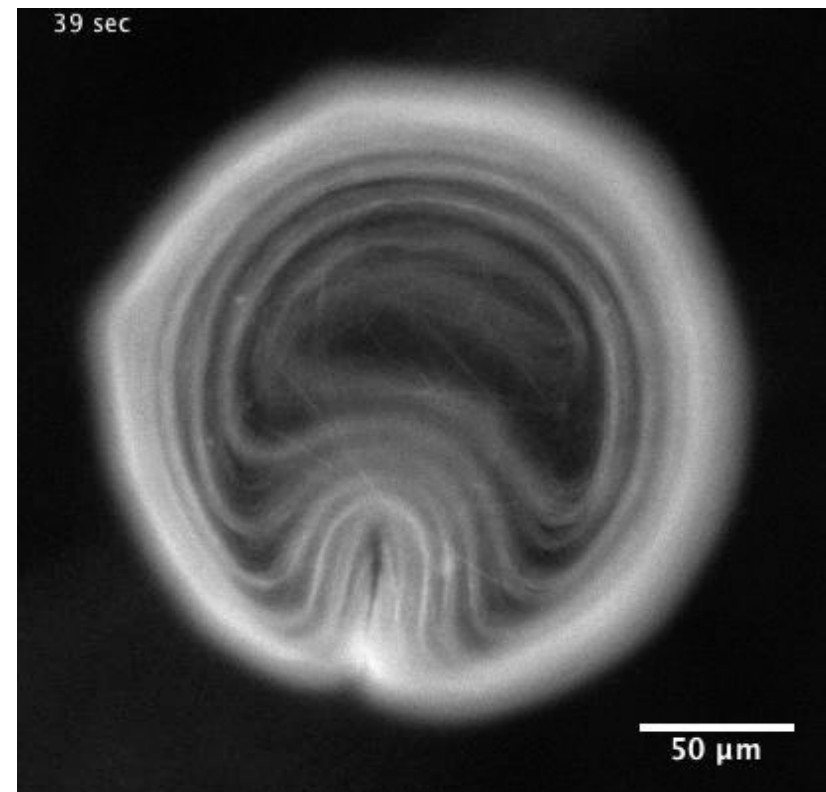
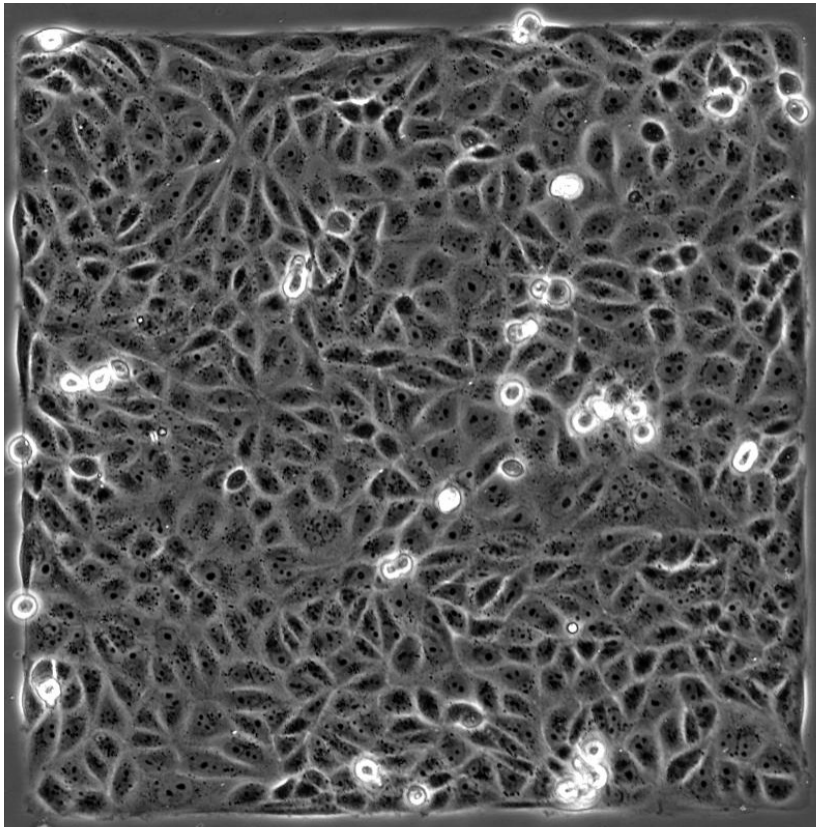


# Transition from active turbulence to flocking



Malinverno et al Nature Materials 16 (2017)

# Confined active matter



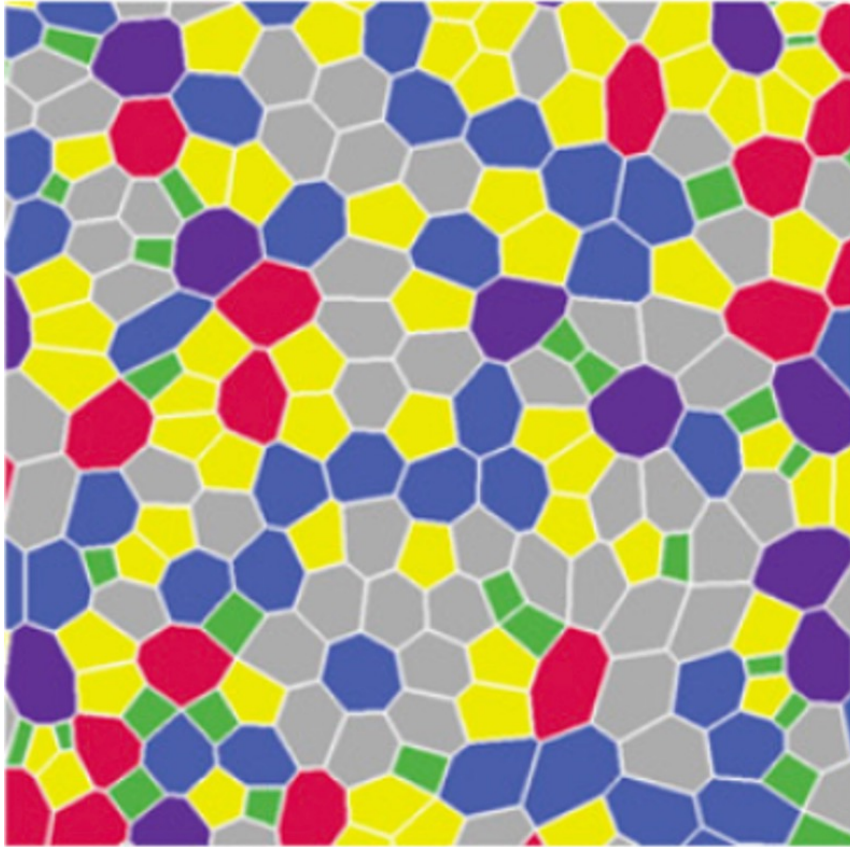
Opathalage et al PNAS 116, 4788 (2019)

How do epithelial cells move?

1. Jamming
2. Flocking
3. Active turbulence
4. Coherent flow in confinement



# Vertex model



Farhadifar *et al.* Curr. Biol. (2007)

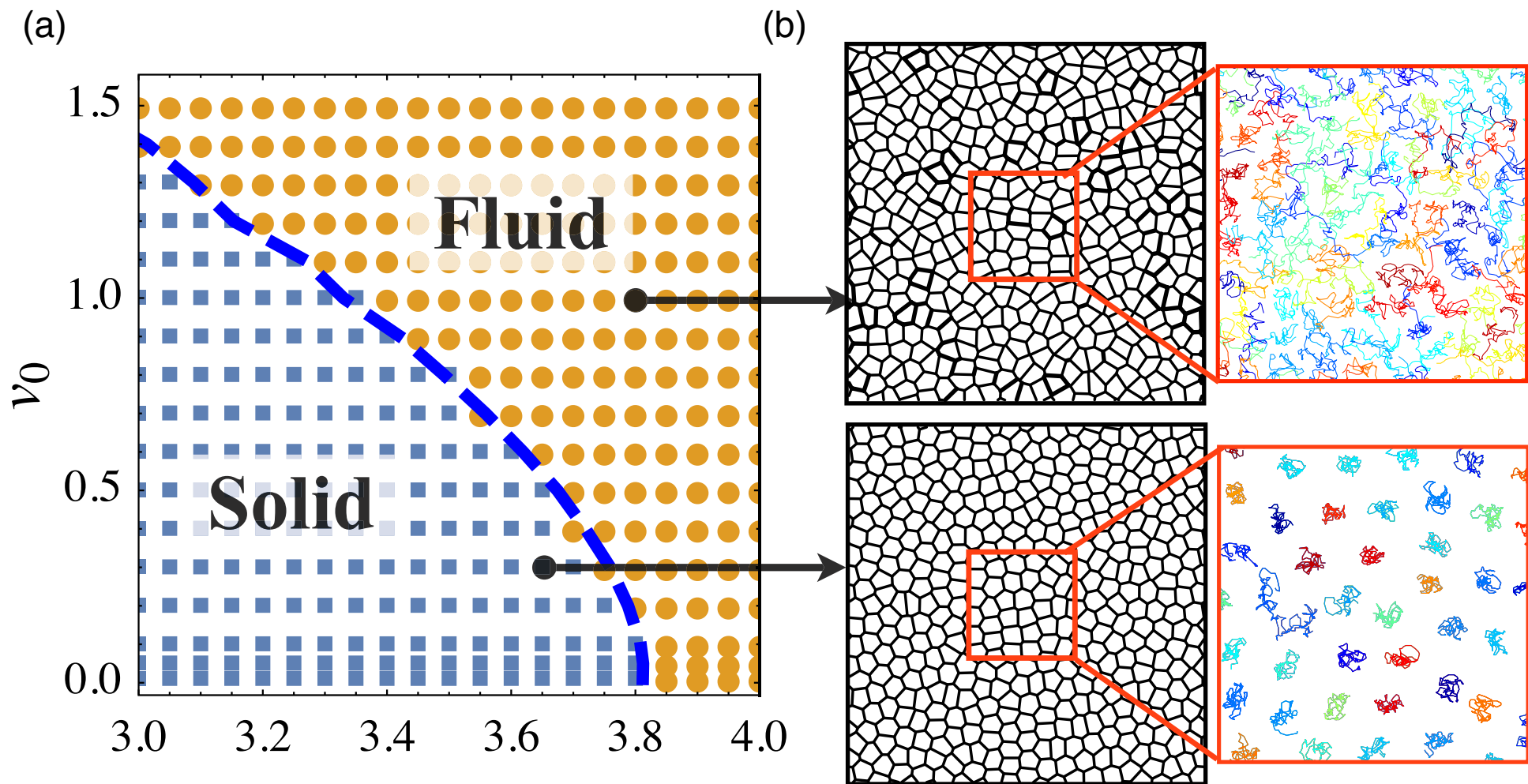


Jan Rozman

$$E_{\text{VM}} = \sum_c \left[ \frac{1}{2} k_A (A_c - A_0)^2 + \frac{1}{2} k_P (P_c - P_0)^2 \right]$$

area term                  perimeter term

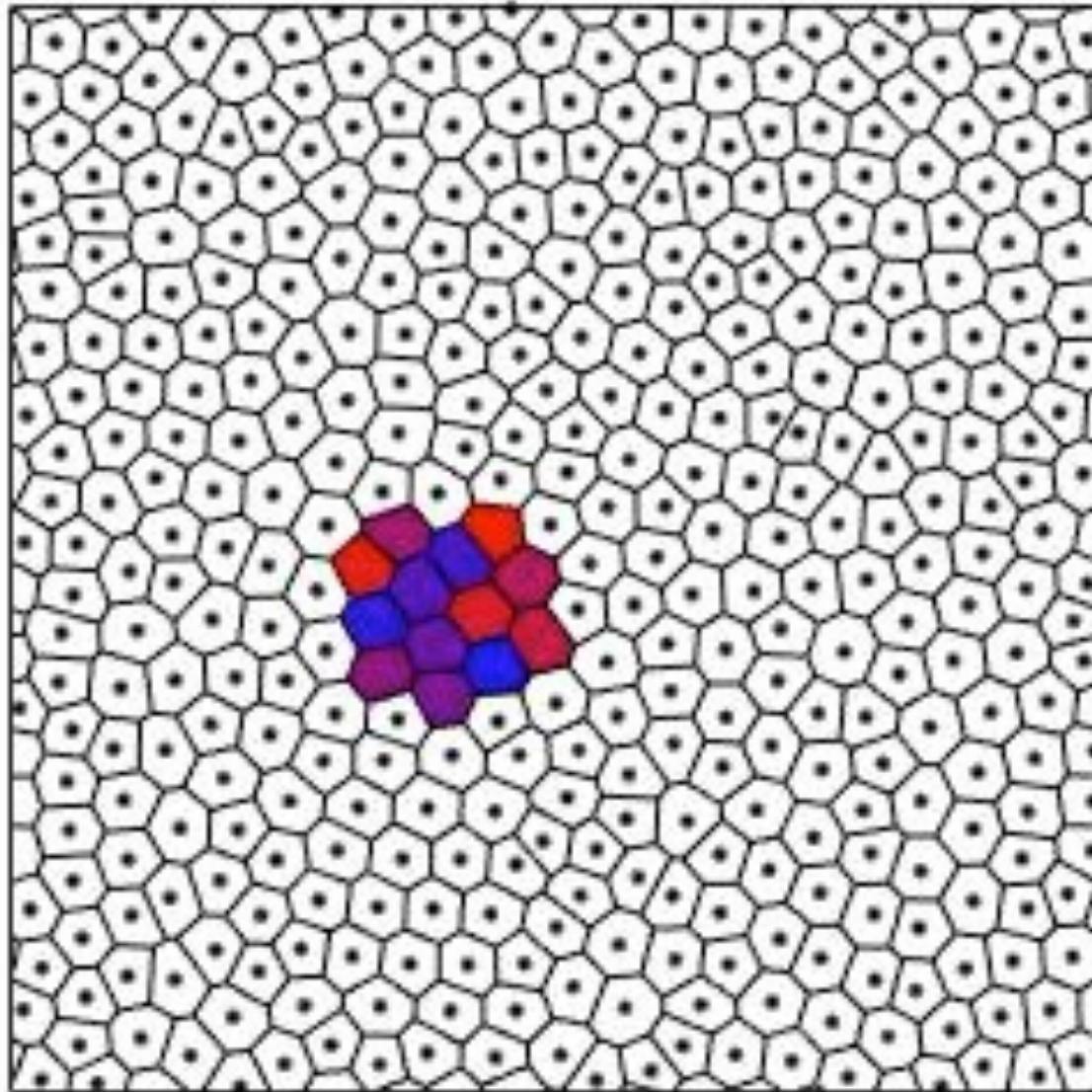
# Vertex model: jamming



$$p_0 = P_0 / \sqrt{A_0}$$

Bi, Yang, Marchetti & Manning, 2016

## Vertex model: flocking



# Contact inhibition of locomotion (Abercrombie, 1953)

If two cells come into contact they tend to move away from each other – cells prefer to move into free space colony expansion / wound healing

Polarisation tends to point away from the direction of greatest cell-cell overlap

Cells within a colony are much less likely to form lamellopodia

Strength of the polarization decreases with increasing cell-cell overlap

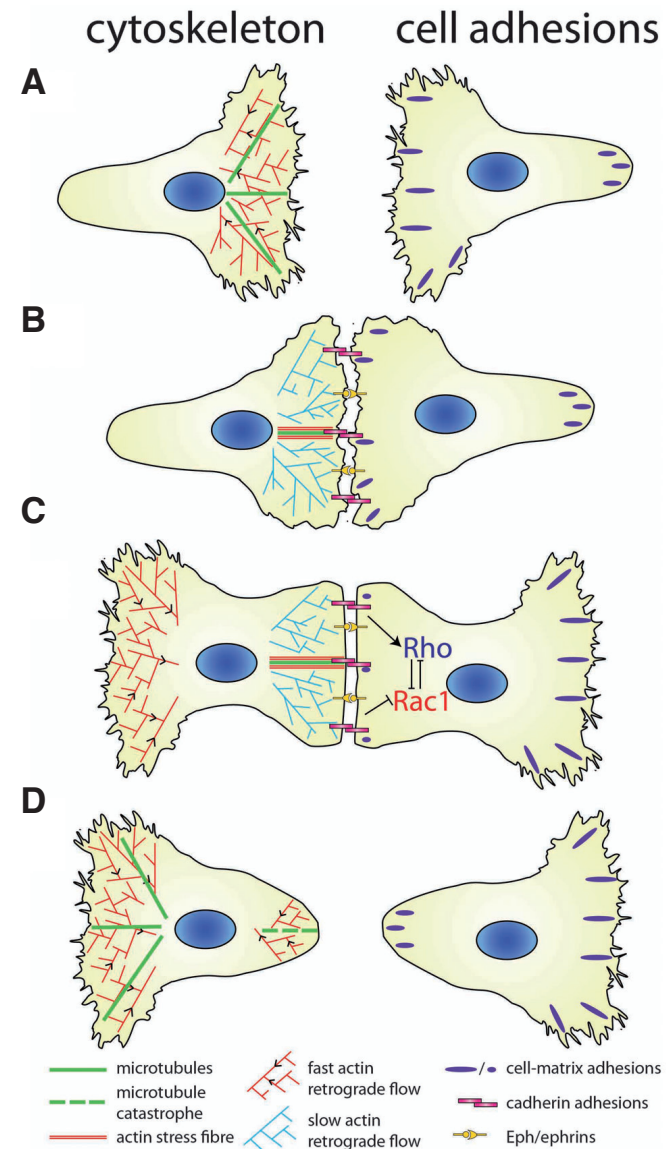
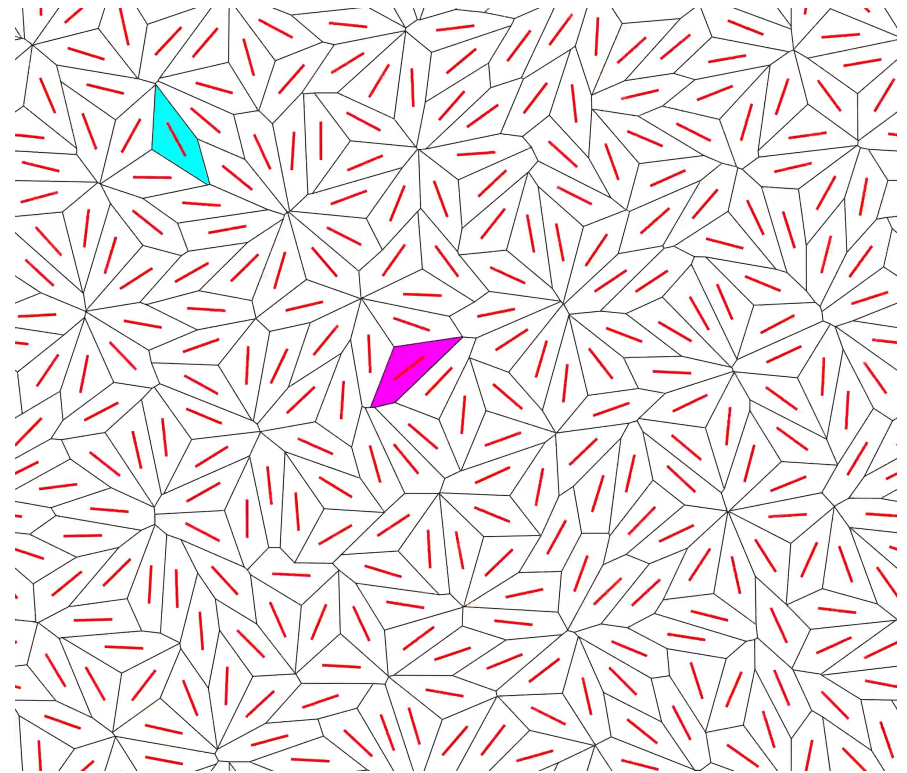
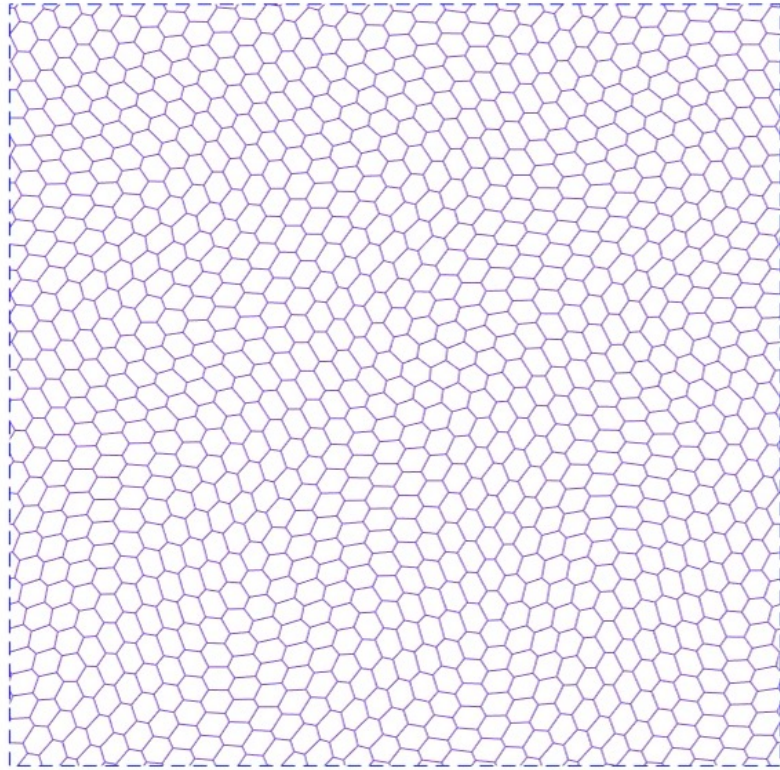
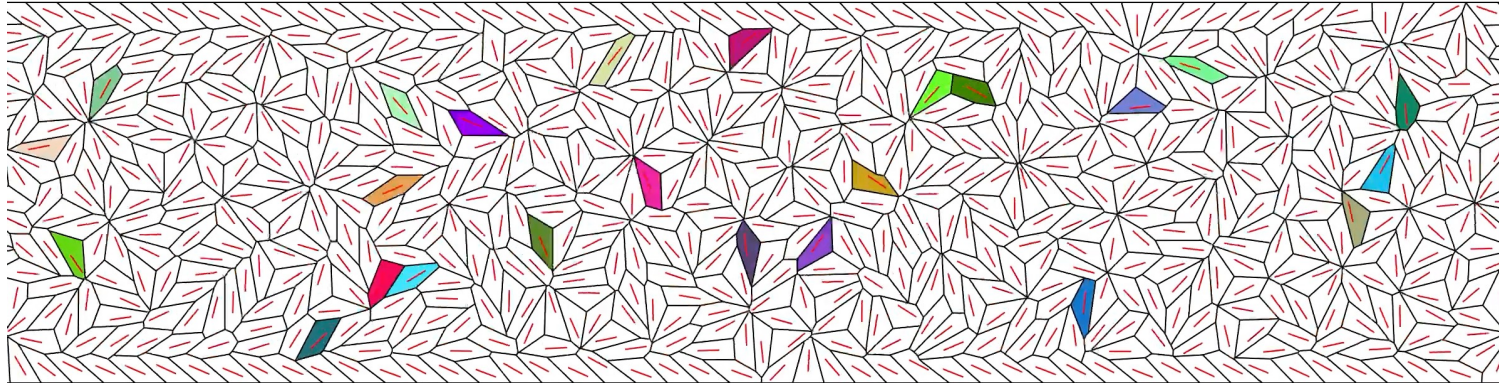


Fig from Int. J. Dev. Biol. 62: 5-13 (2018)

# Vertex model: active turbulence



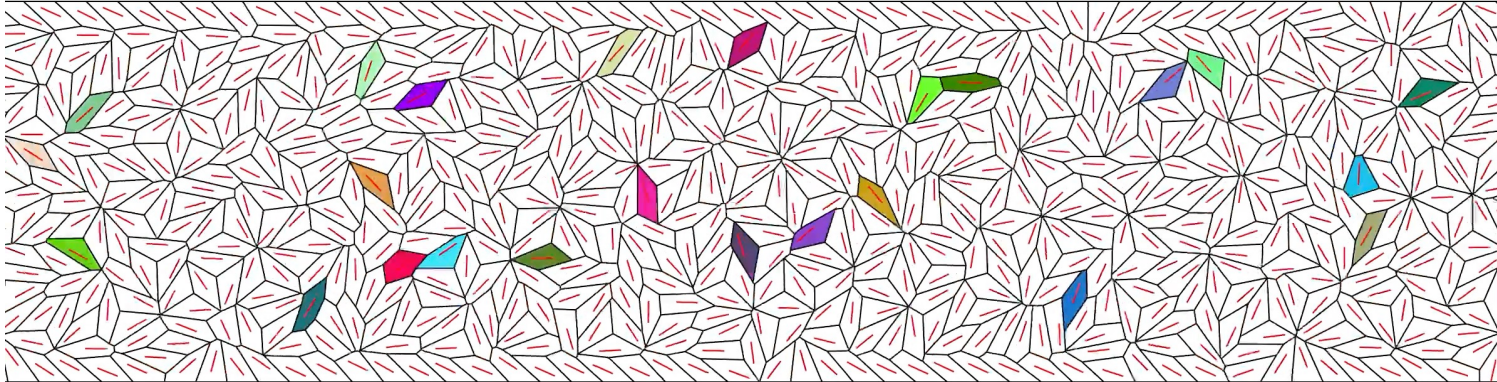
# Vertex model: confined flows



Dissipation by substrate friction

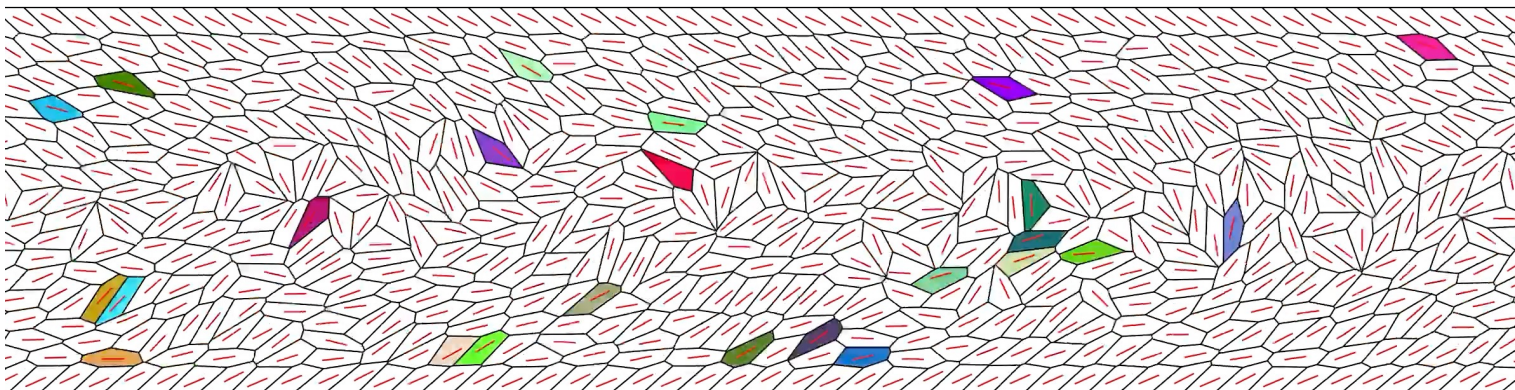
$$\eta \dot{\mathbf{r}}_i = \mathbf{f}_i$$

# Vertex model: confined flows



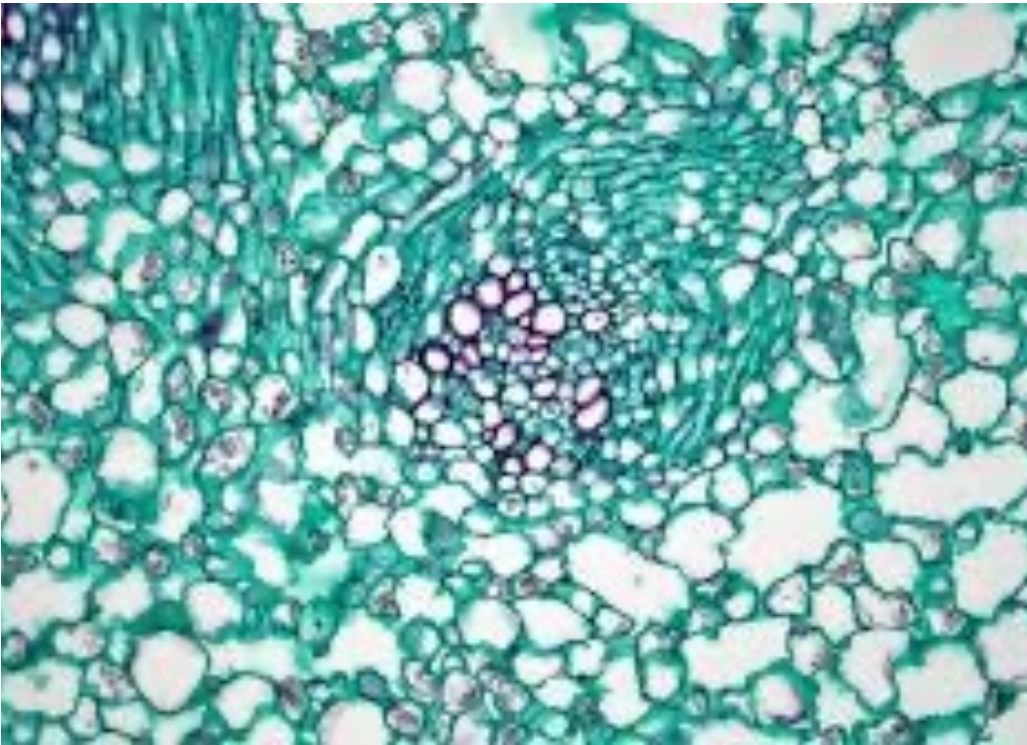
Dissipation by substrate friction

$$\eta \dot{\mathbf{r}}_i = \mathbf{f}_i$$



Dissipation by viscosity

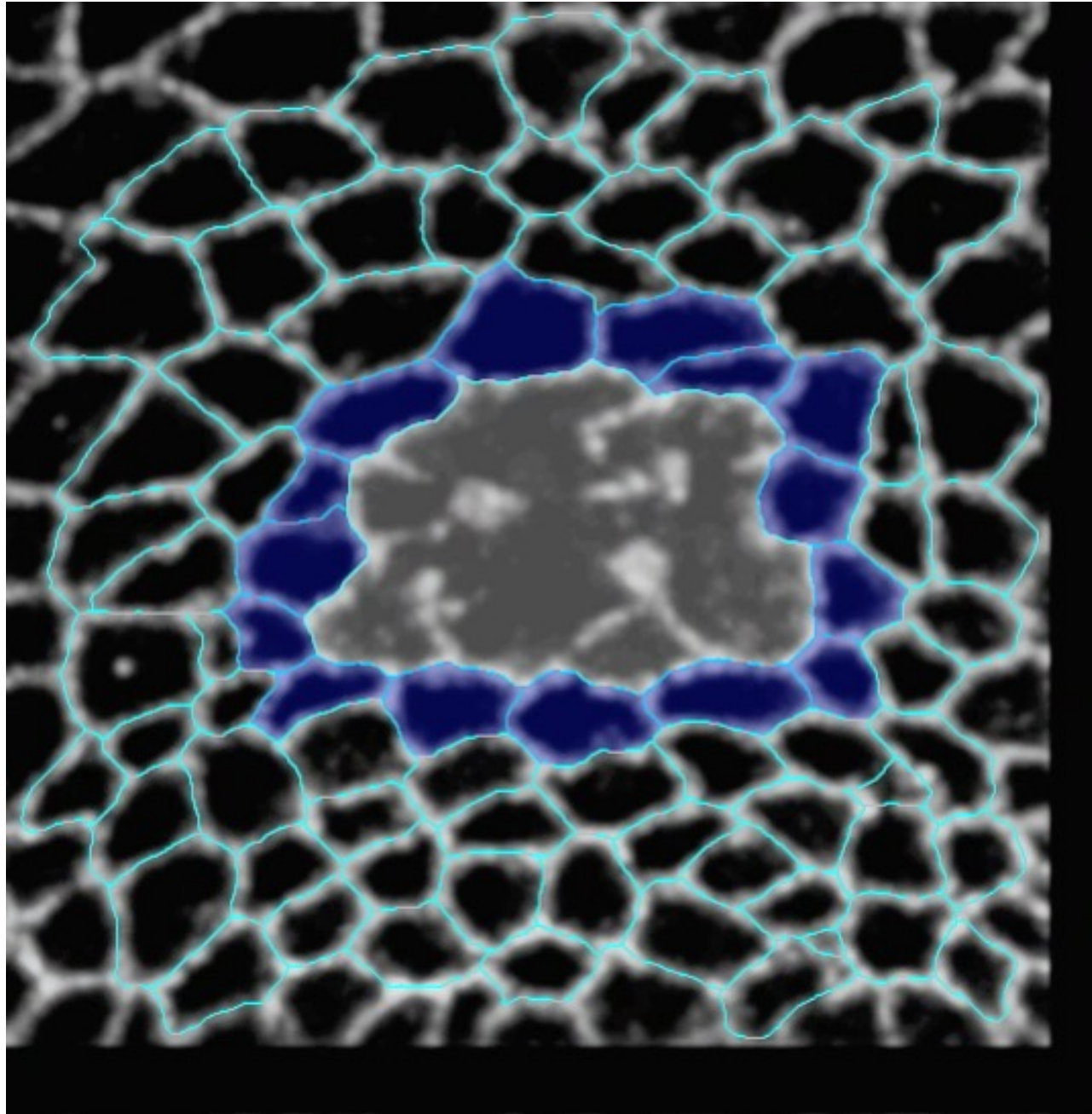
$$\eta \dot{\mathbf{r}}_i + \xi \sum_{S_i} (\dot{\mathbf{r}}_i - \dot{\mathbf{r}}_j) = \mathbf{f}_i$$

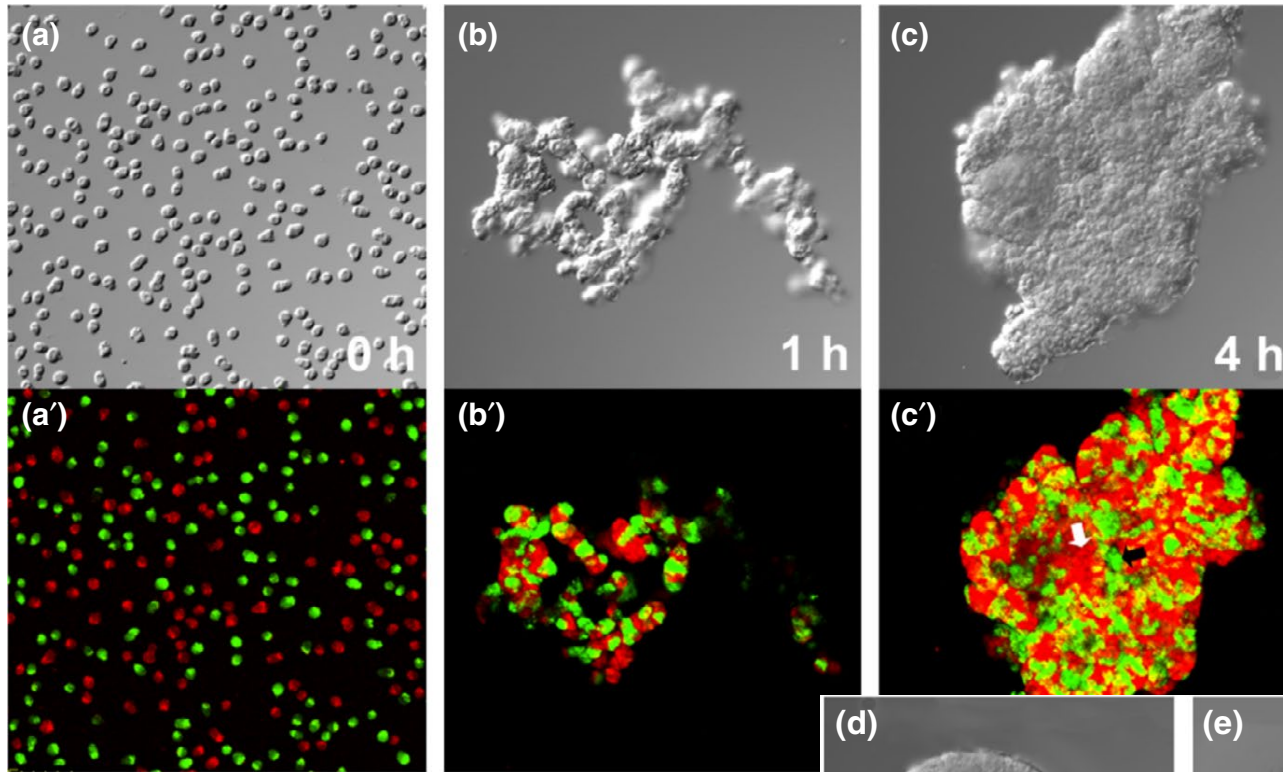


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# Wound healing

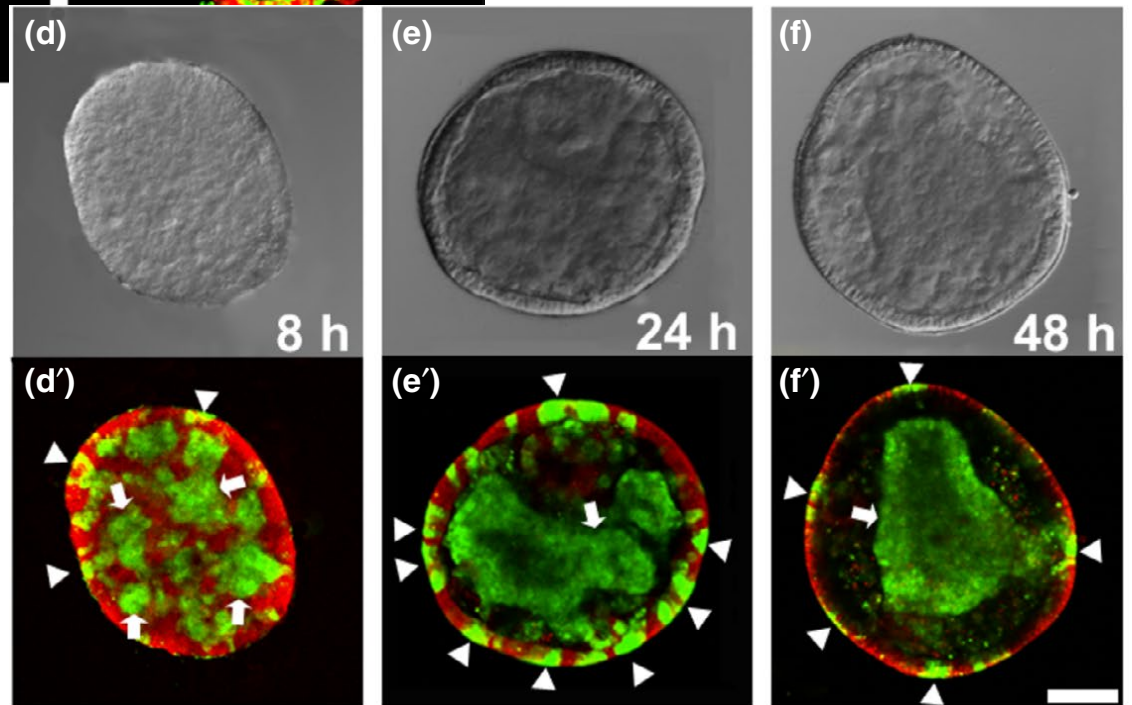




Cell sorting

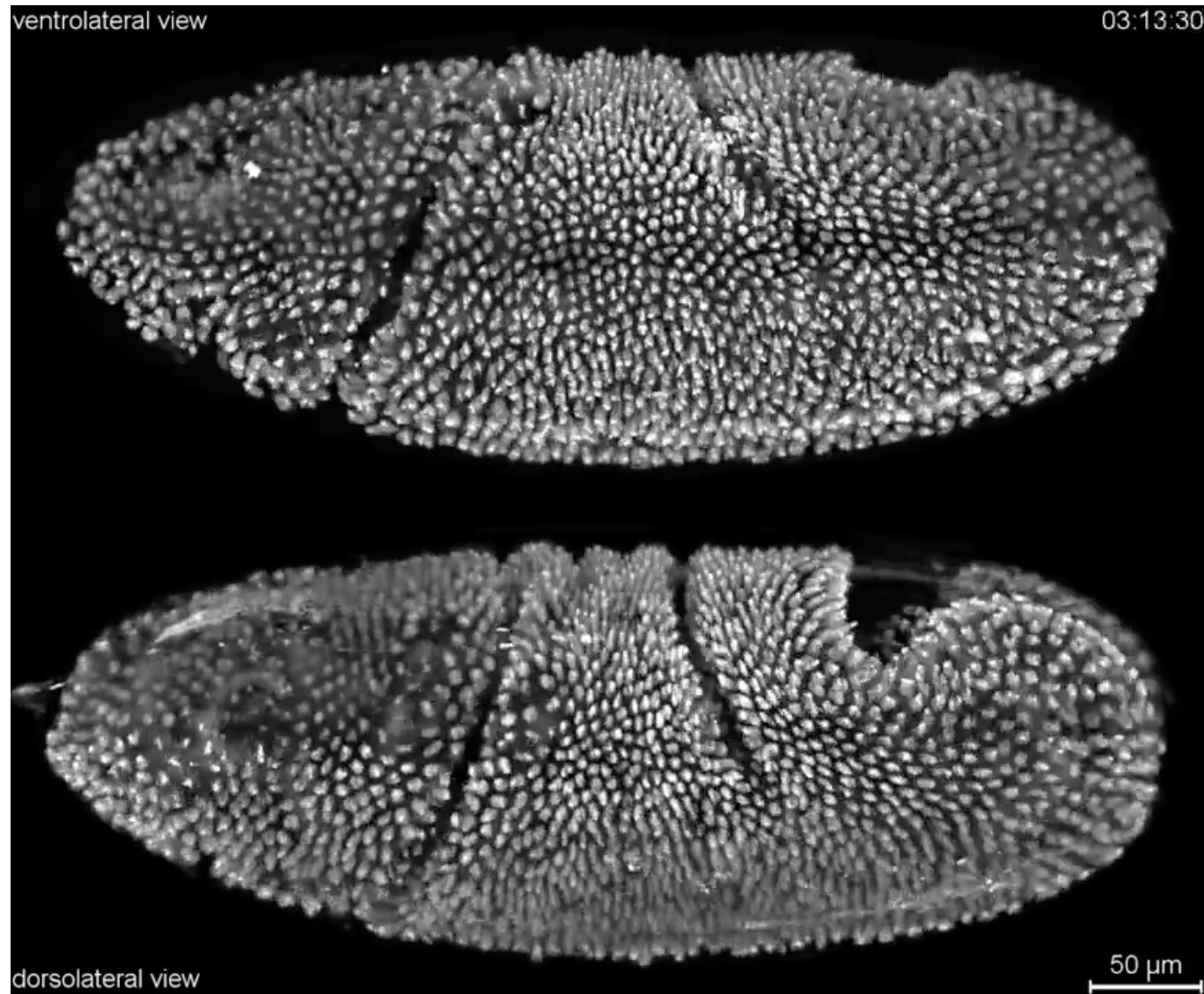
starfish embryo

green: endoderm, red: ectoderm

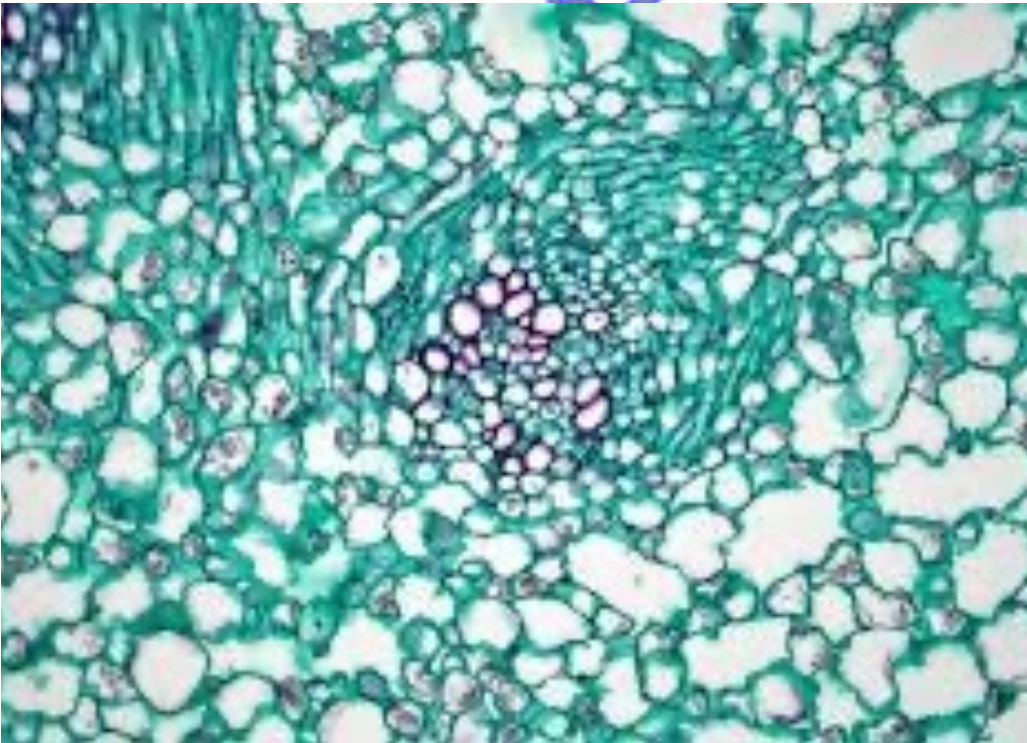


Suzuki, Omori, Kuraishi, Kaneko,  
Development, Growth & Differentiation 2021

# Drosophila development



Tomer et al, Nature Methods 2012  
light sheet microscopy



- Active matter
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- How do cells move in vivo?





# Movie S2a

*In toto* live imaging of mouse development  
from gastrulation to early organogenesis