School on Information, Noise, and Physics of Life

Welcome!

Добродошли!

19 - 30 September 2022
Nis, Serbia

Further information:
http://indico.ictp.it/event/9826/
smr3736@ictp.it

The Abdus Salam
International Centre for Theoretical Physics
www.ictp.it
Trieste, Italy

United Nations Educational, Scientific and Cultural Organization

IAEA
International Atomic Energy Agency

УНИВЕРЗИТЕТ У НИШУ
ПРИРОДНО-МАТЕМАТИЧКИ ФАКУЛТЕТ НИШ

MATHEMATICAL INSTITUTE OF THE SERBIAN ACADEMY OF SCIENCES AND ARTS

IYBSSD2022
International Year of Basic Sciences for Sustainable Development

Introduction to Biophysics part I

Édgar Roldán

The Abdus Salam International Centre for Theoretical Physics (Trieste, Italy)

“School of Information, Noise, and Physics of Life”

Niš (Serbia), 19-9-2022

Biophysics

Motivation, examples, focus

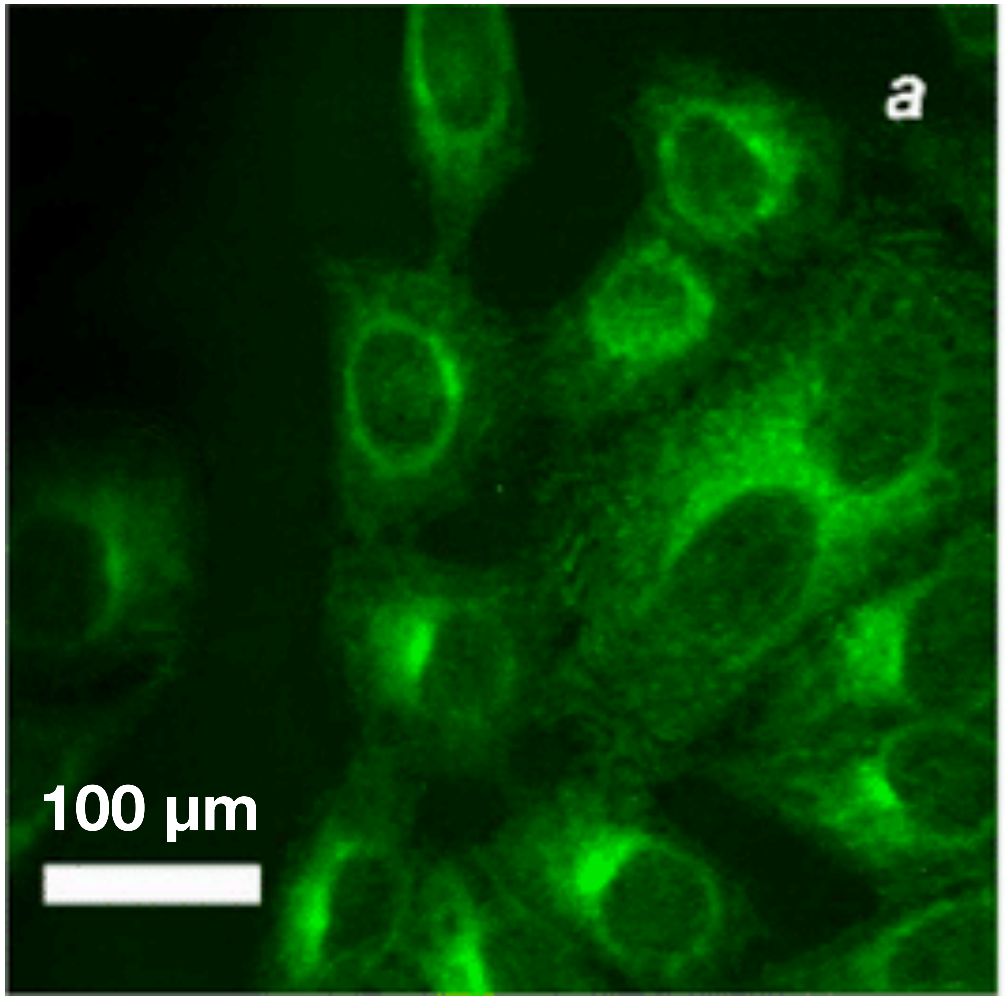
Why biophysics?

We can **SEE** cells and biomolecules under the microscope

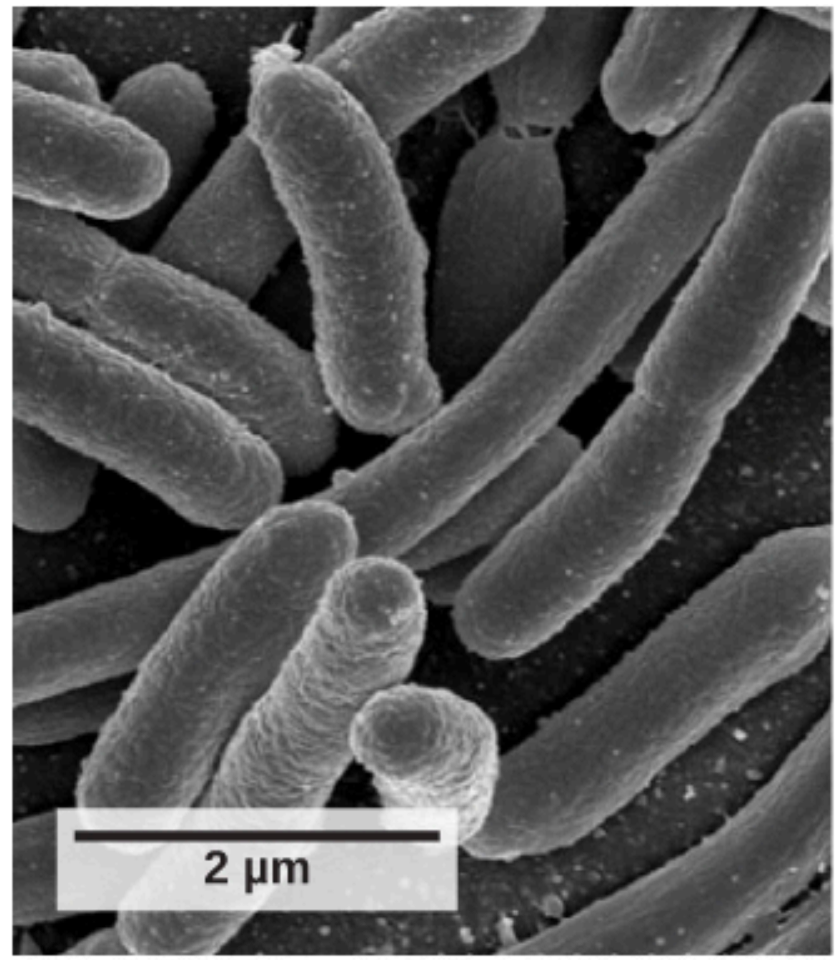
We can **MEASURE** their physical properties (forces, position, etc.)

Cells

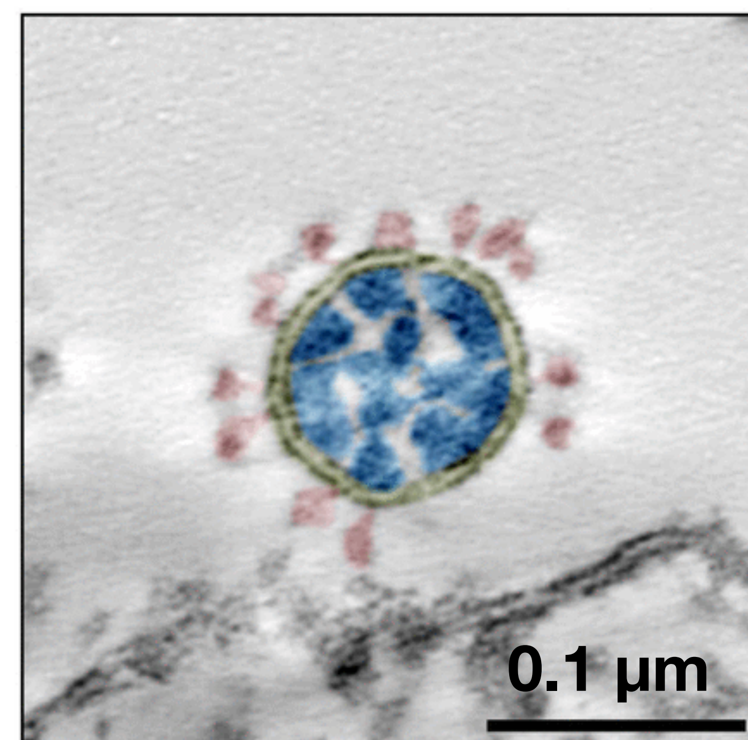
Human cells



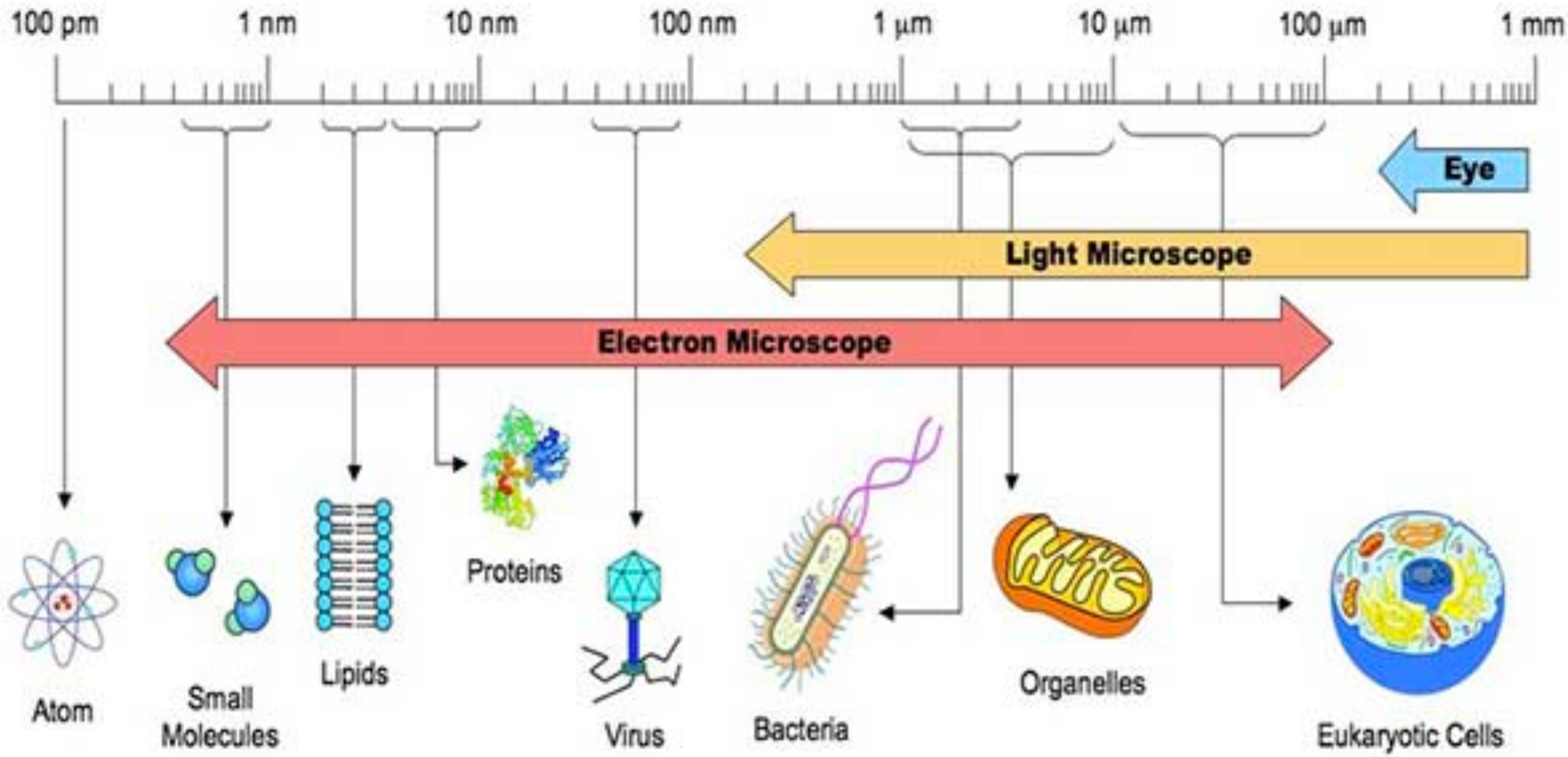
Bacteria



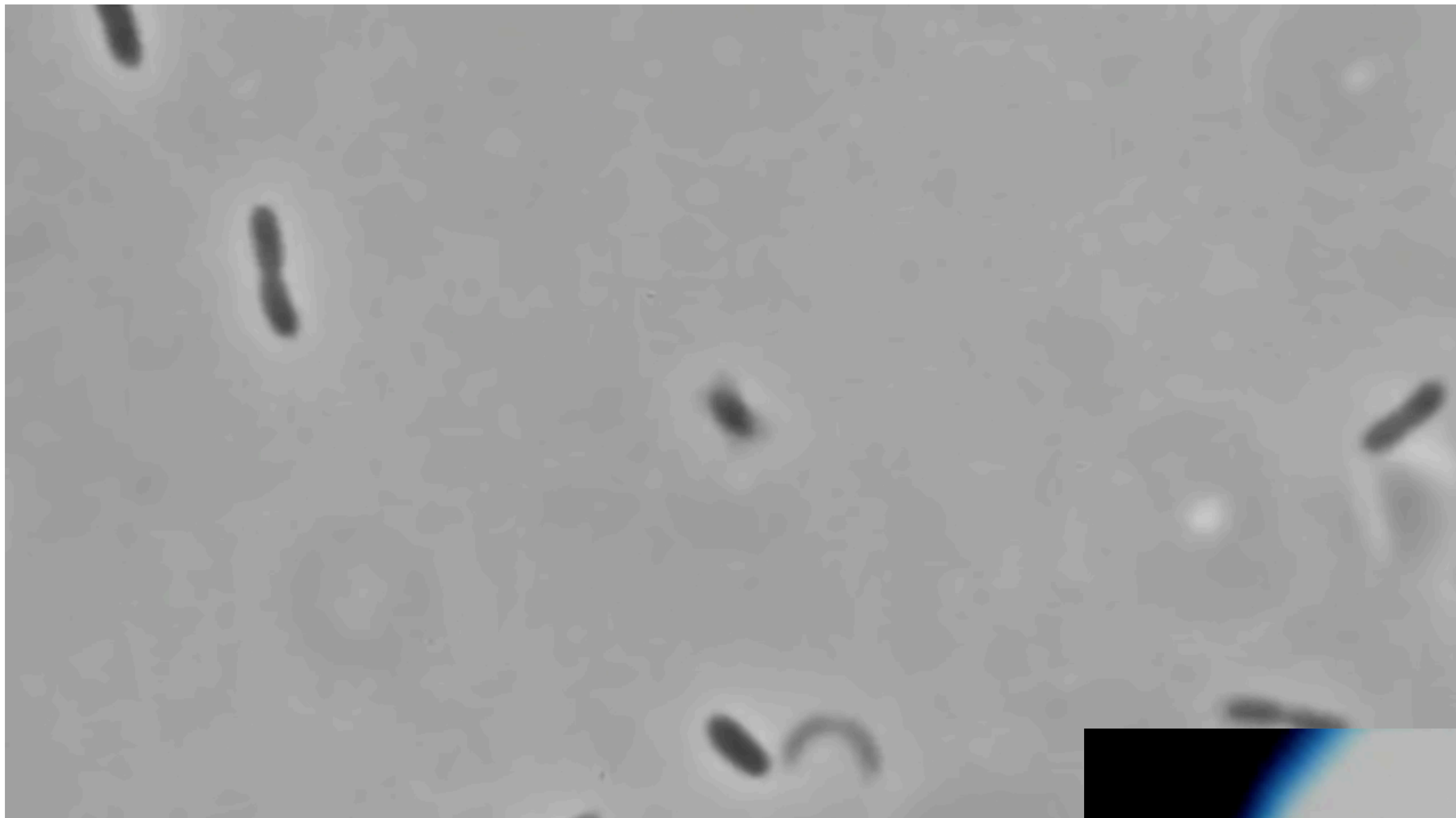
Virus



Life under the microscope



Cellular motion



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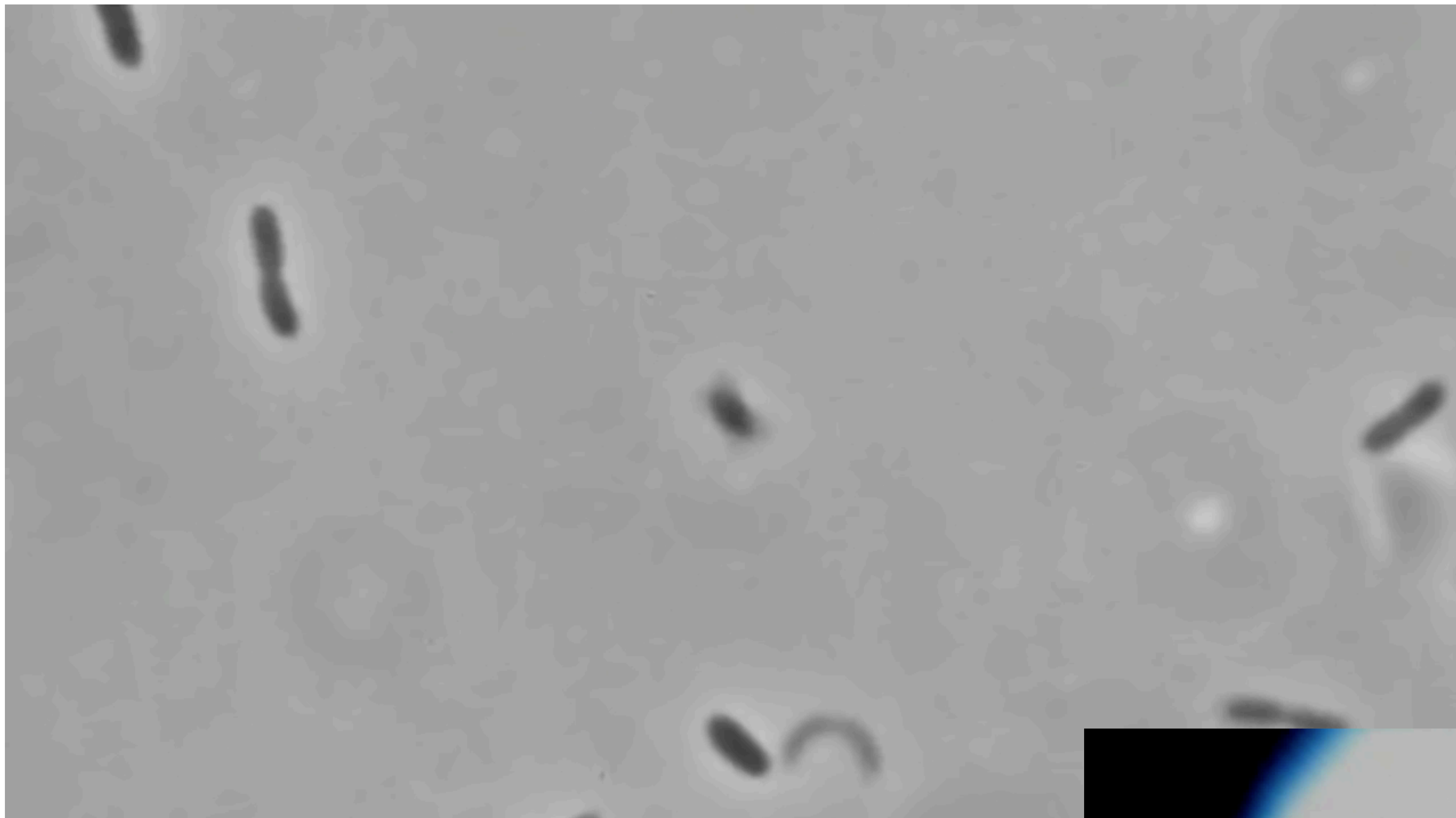

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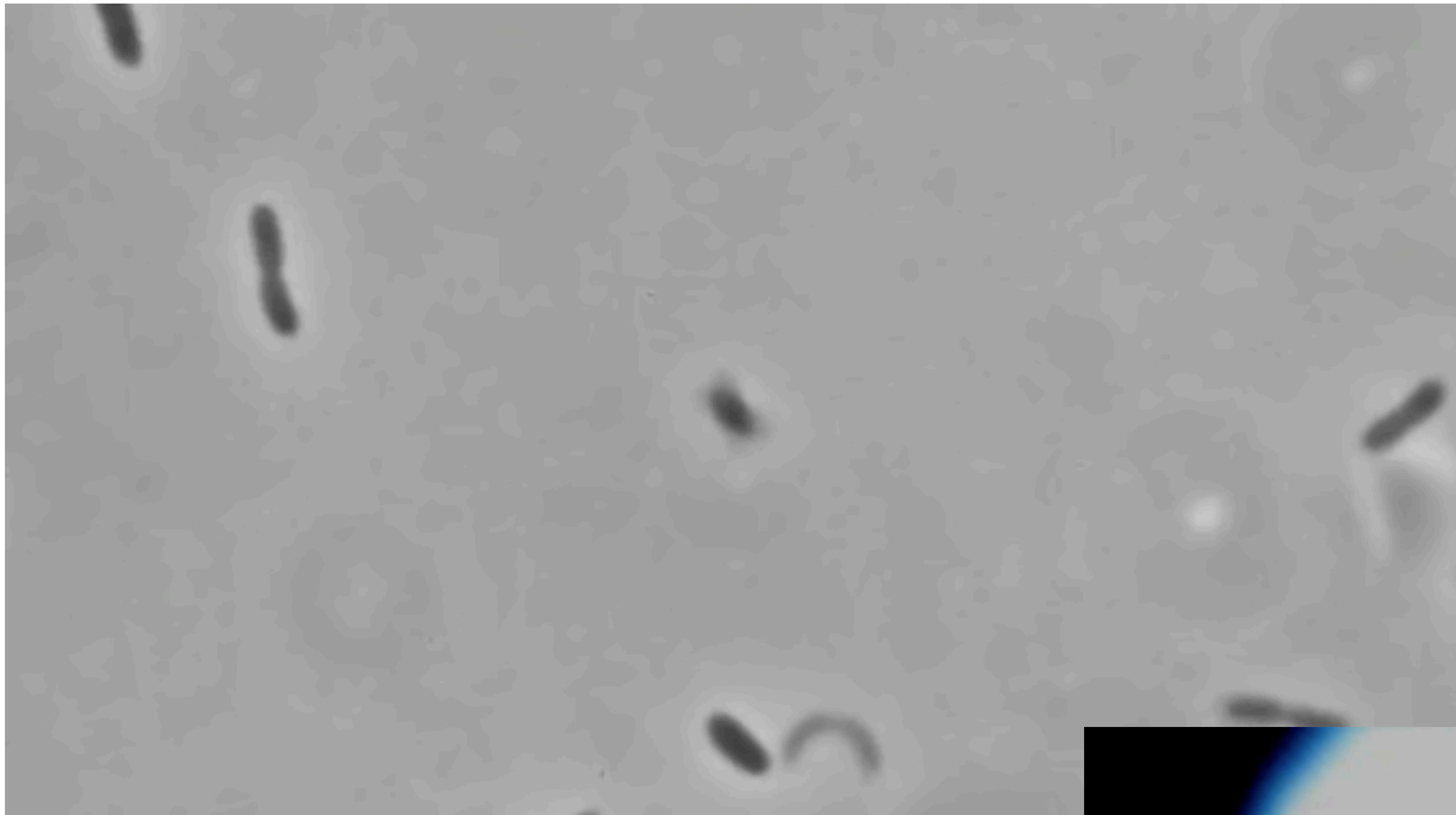
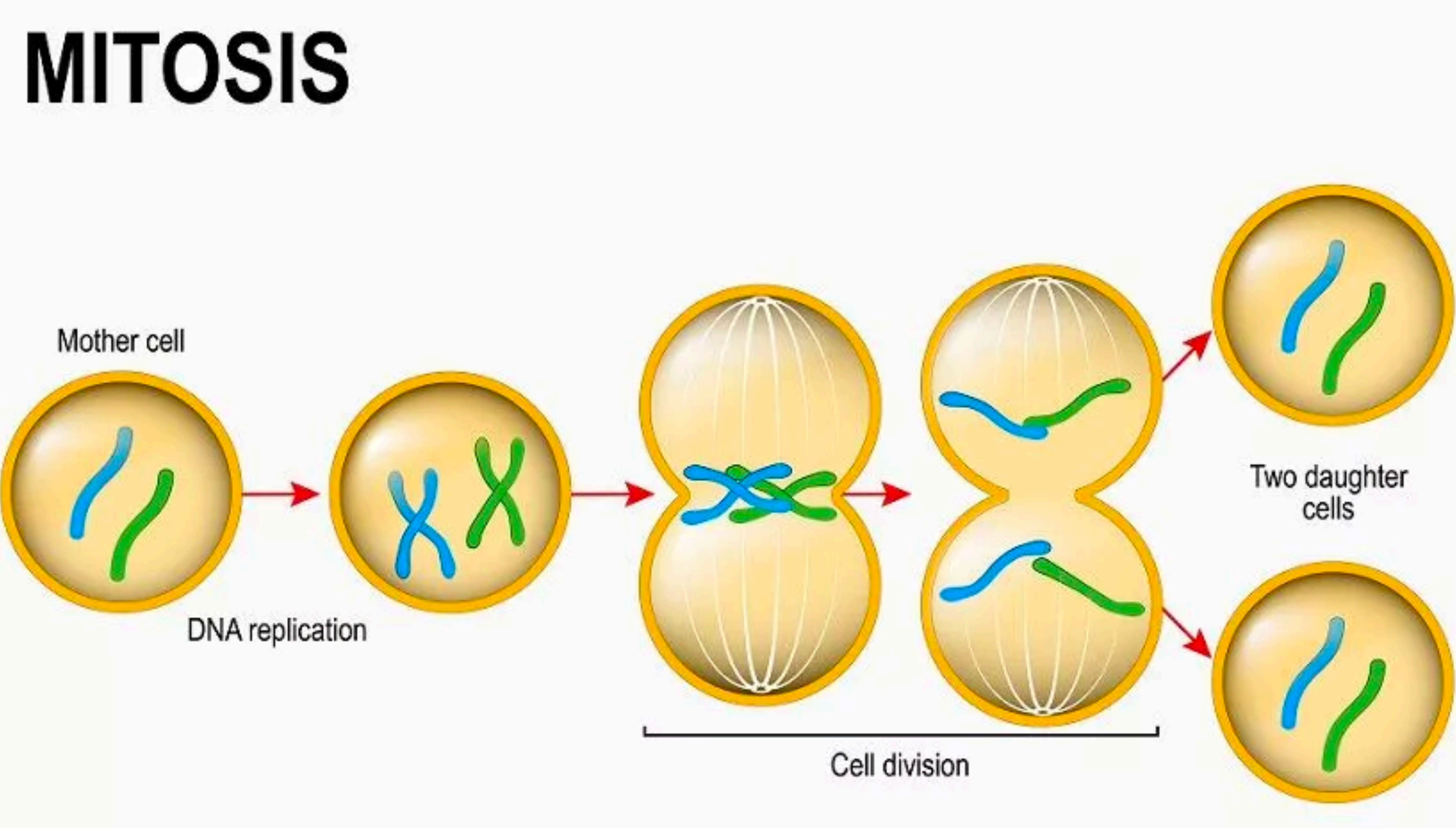


Cell division



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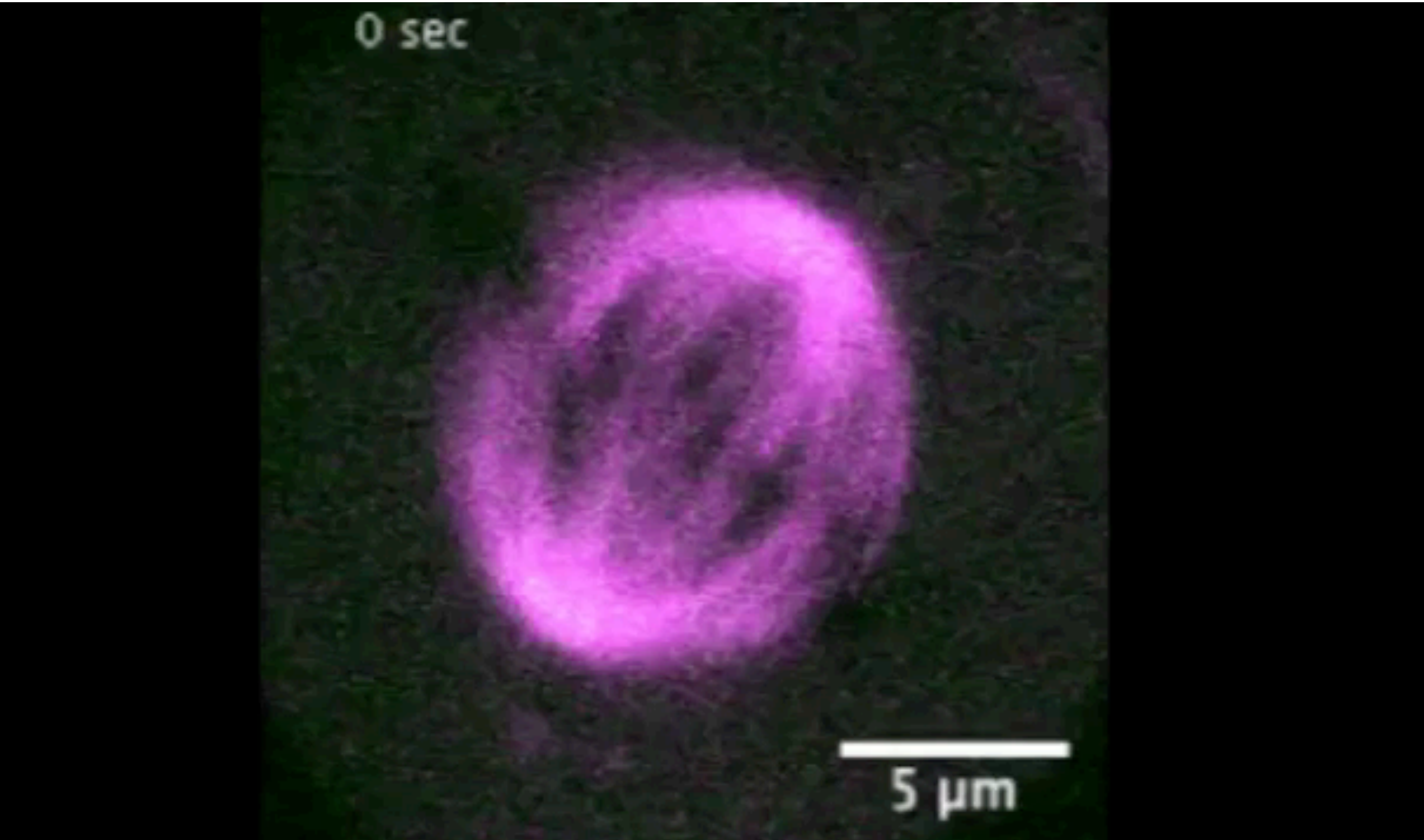


Iva Tolic lab (Ruder Boskovic Institute, Zagreb, Croatia)

Life at the microscale

Macroscopic scale ("macroscale")

Deterministic Hamiltonian dynamics

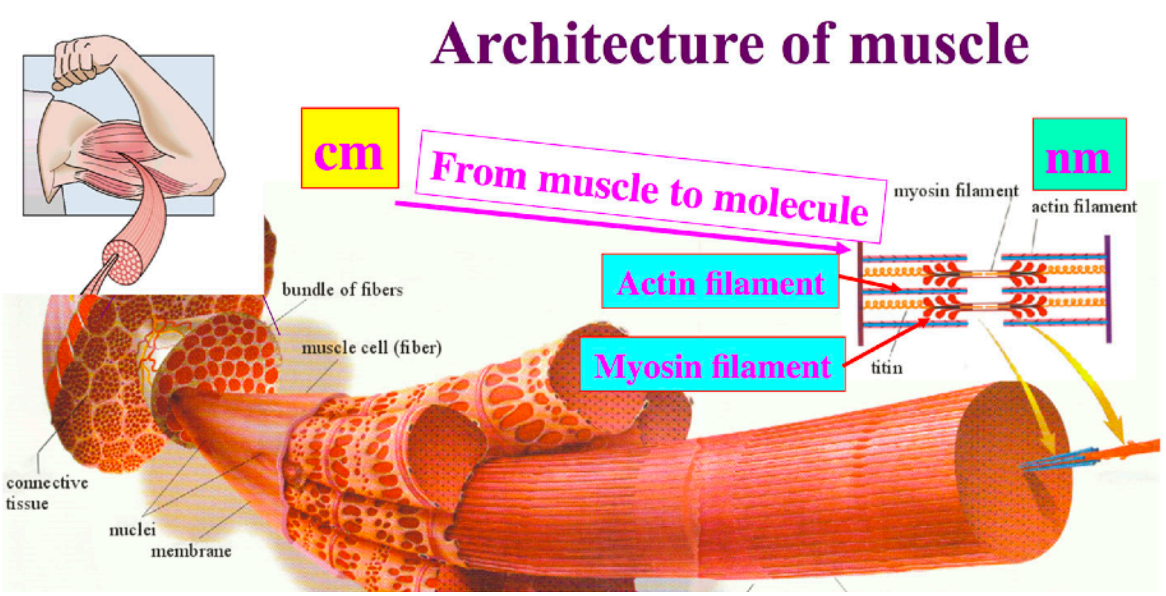
Classical mechanics: Newton's laws

Life at the microscale

Macroscopic scale ("macroscale")

Deterministic Hamiltonian dynamics

Classical mechanics: Newton's laws



Mesoscopic scale ("mesoscale")

Stochastic dynamics

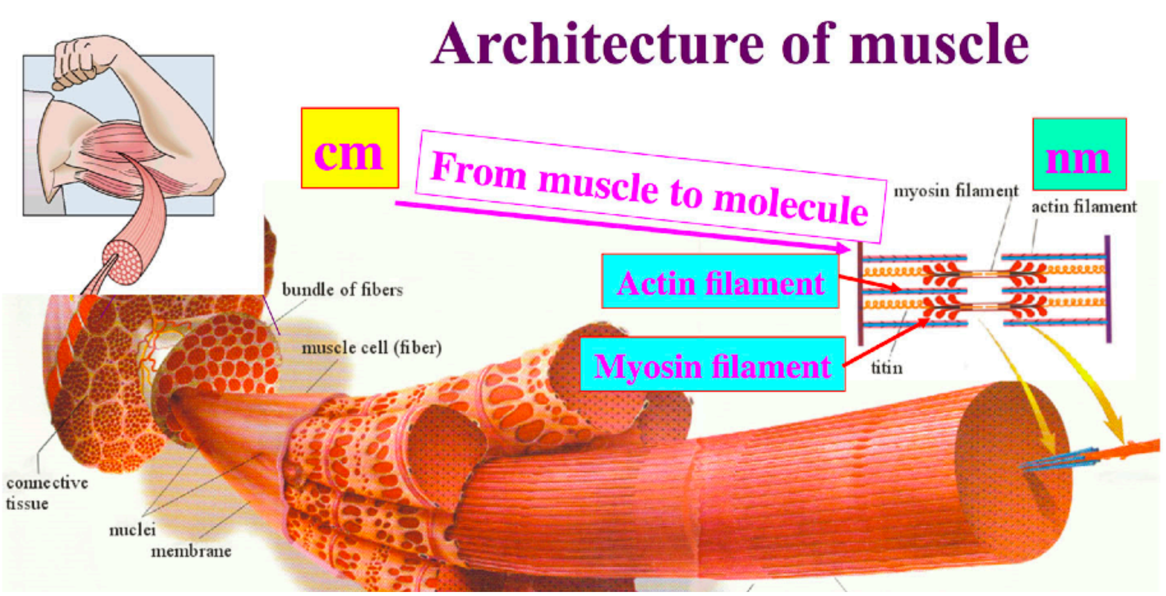
Noise and fluctuations

Life at the microscale

Macroscopic scale ("macroscale")

Deterministic Hamiltonian dynamics

Classical mechanics: Newton's laws



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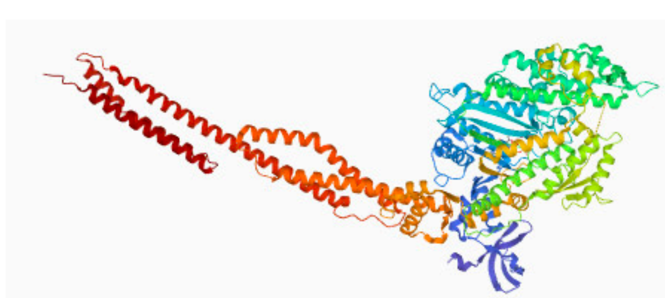

Atomic scale

Molecular dynamics simulations
Quantum dynamics

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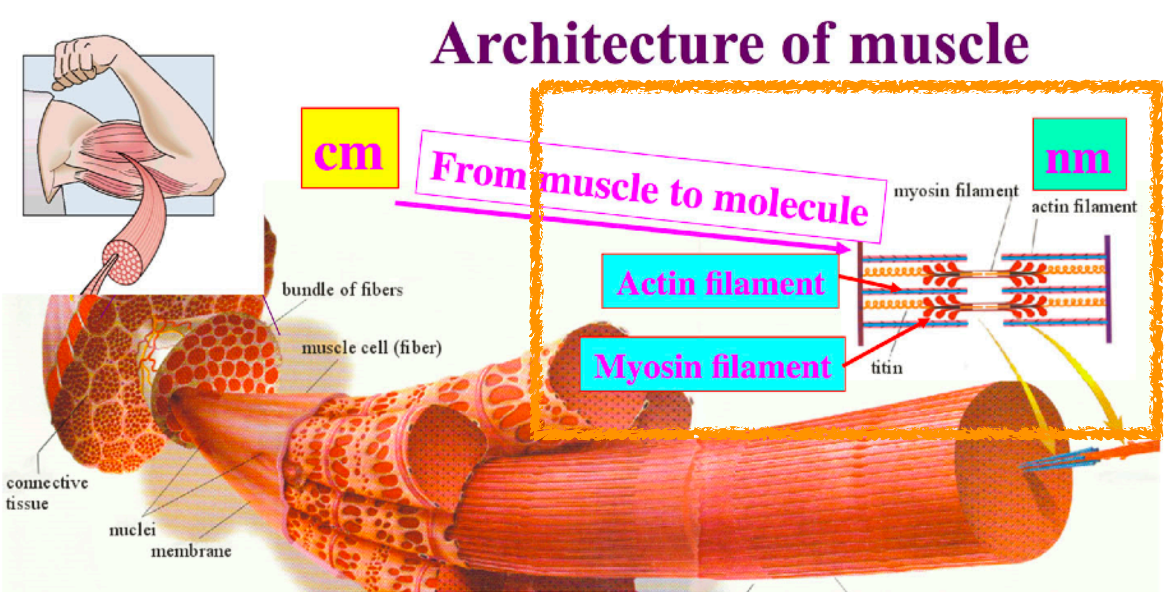

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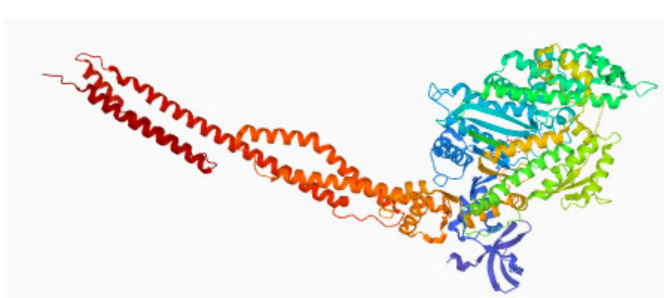

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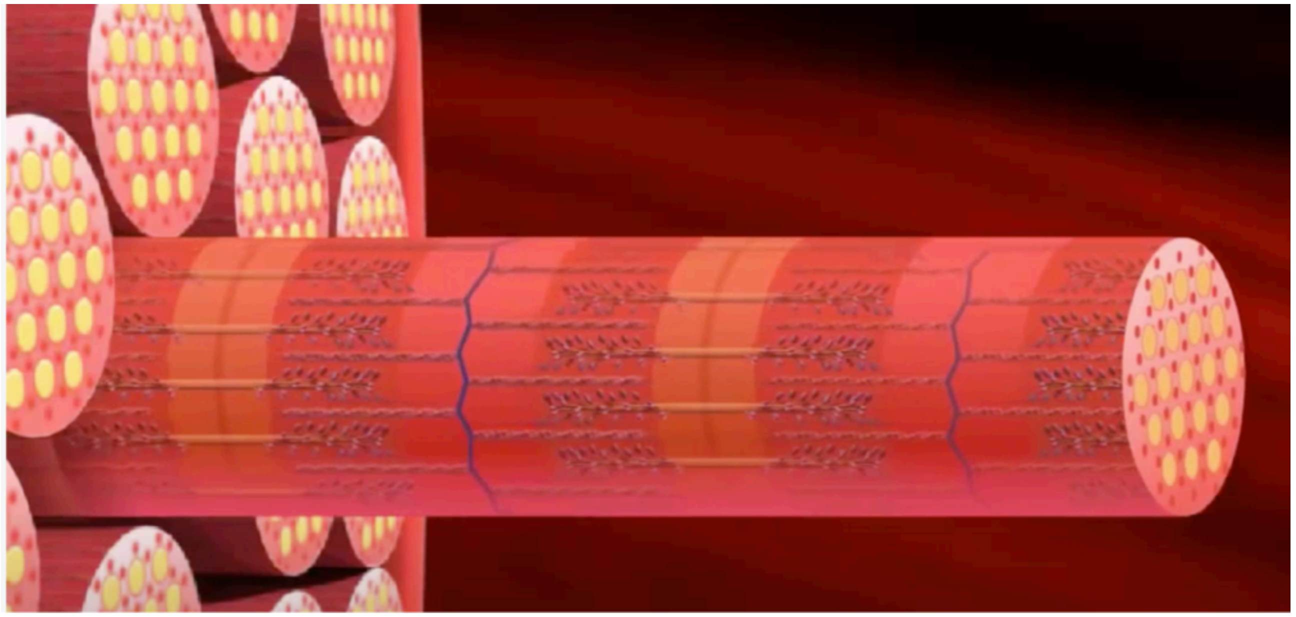
Muscle contraction at the microscale



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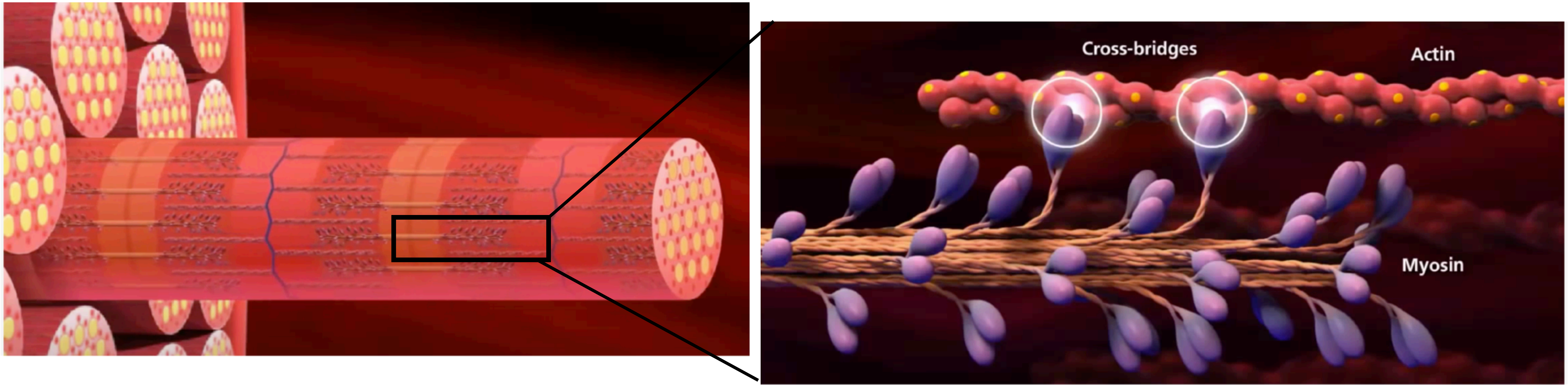

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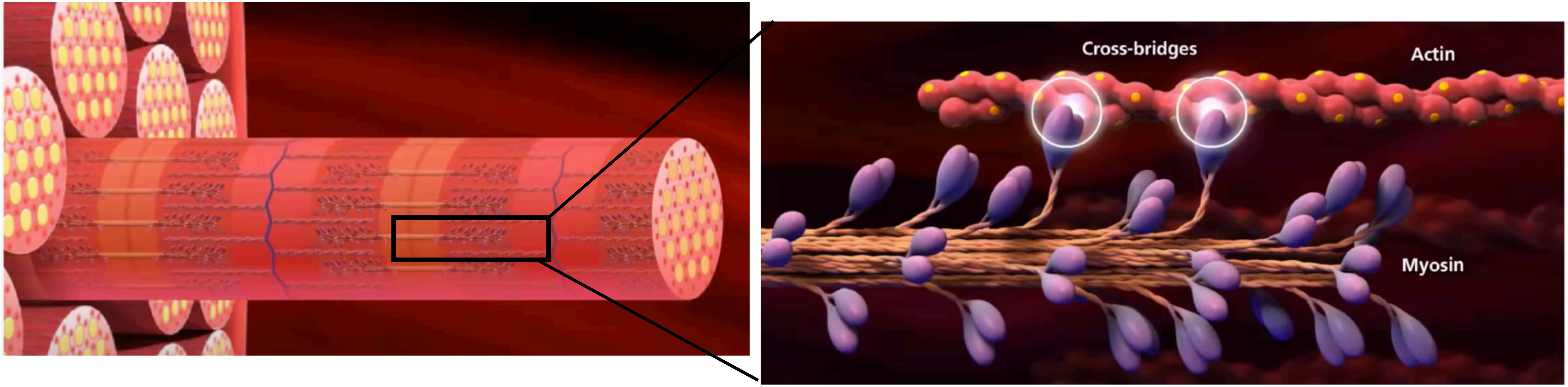

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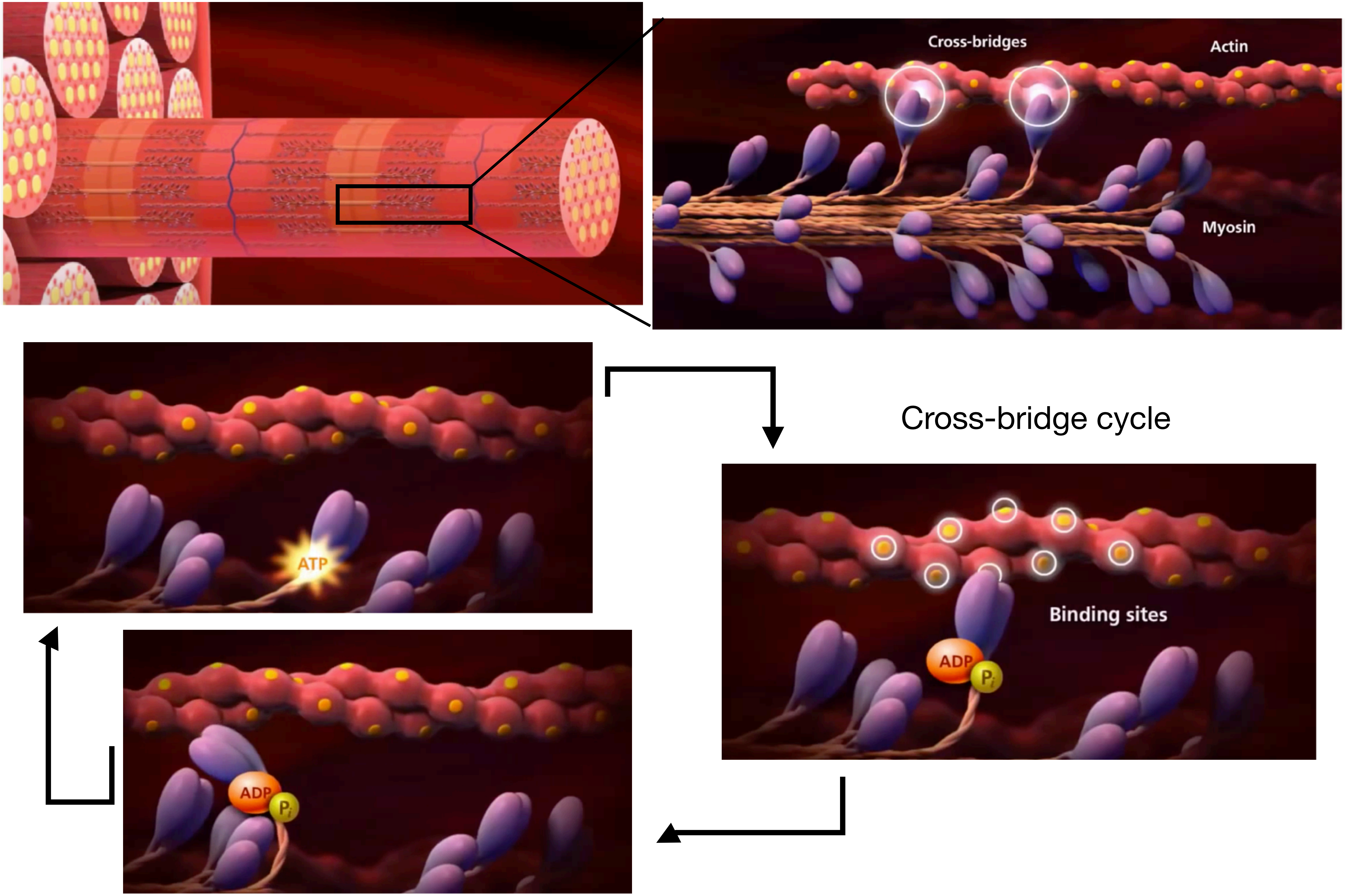
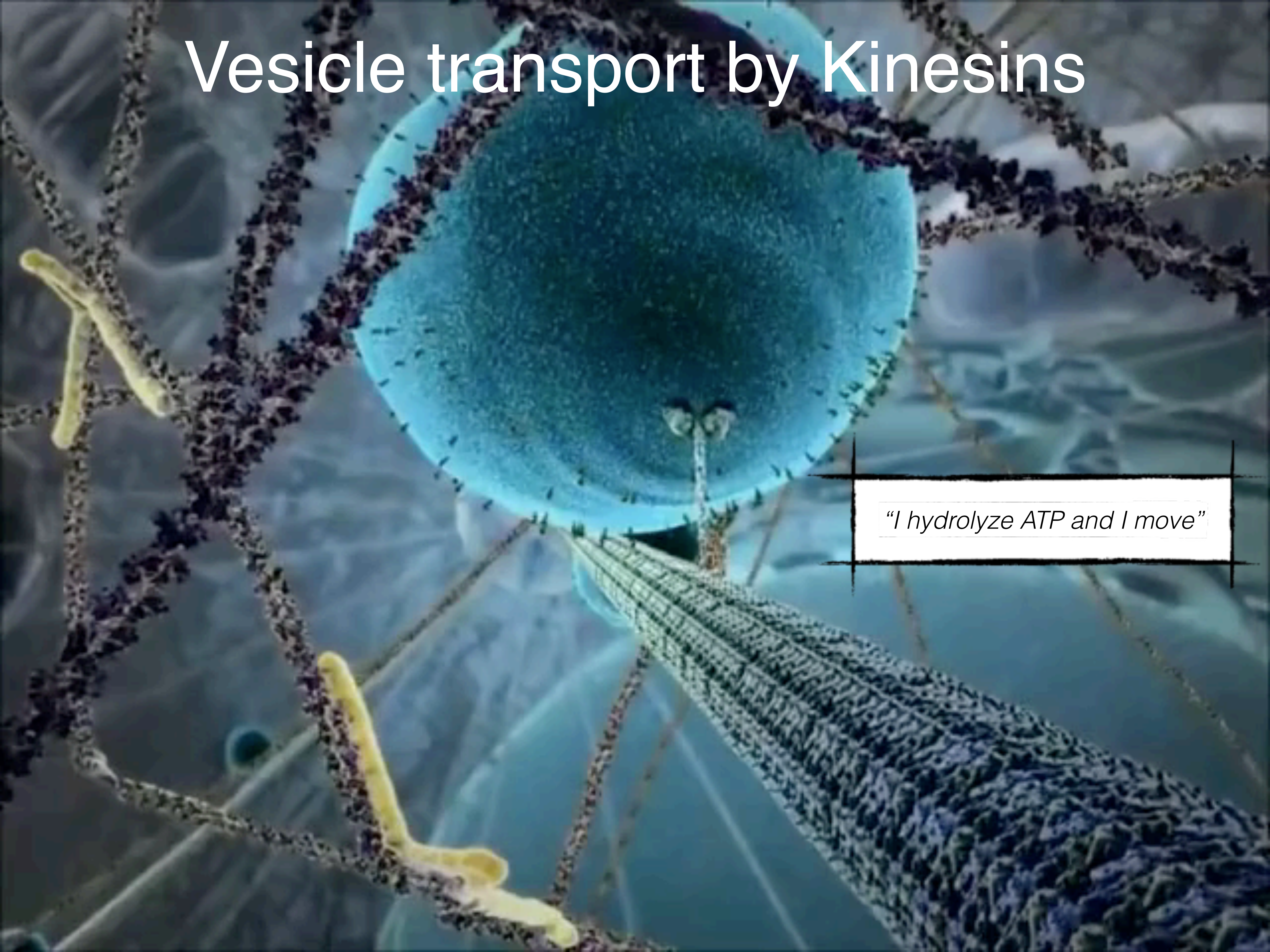


Vesicle transport by Kinesins



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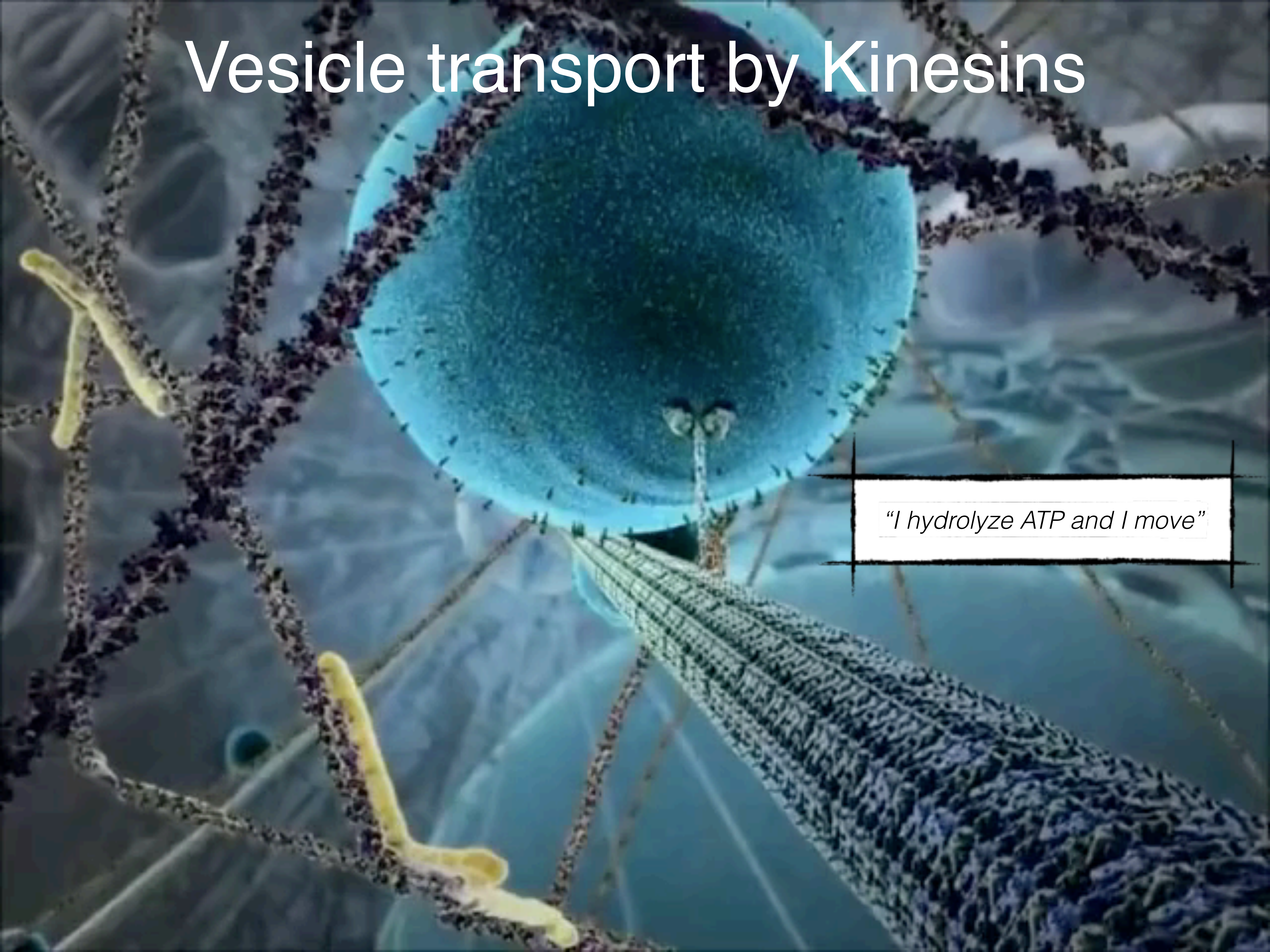

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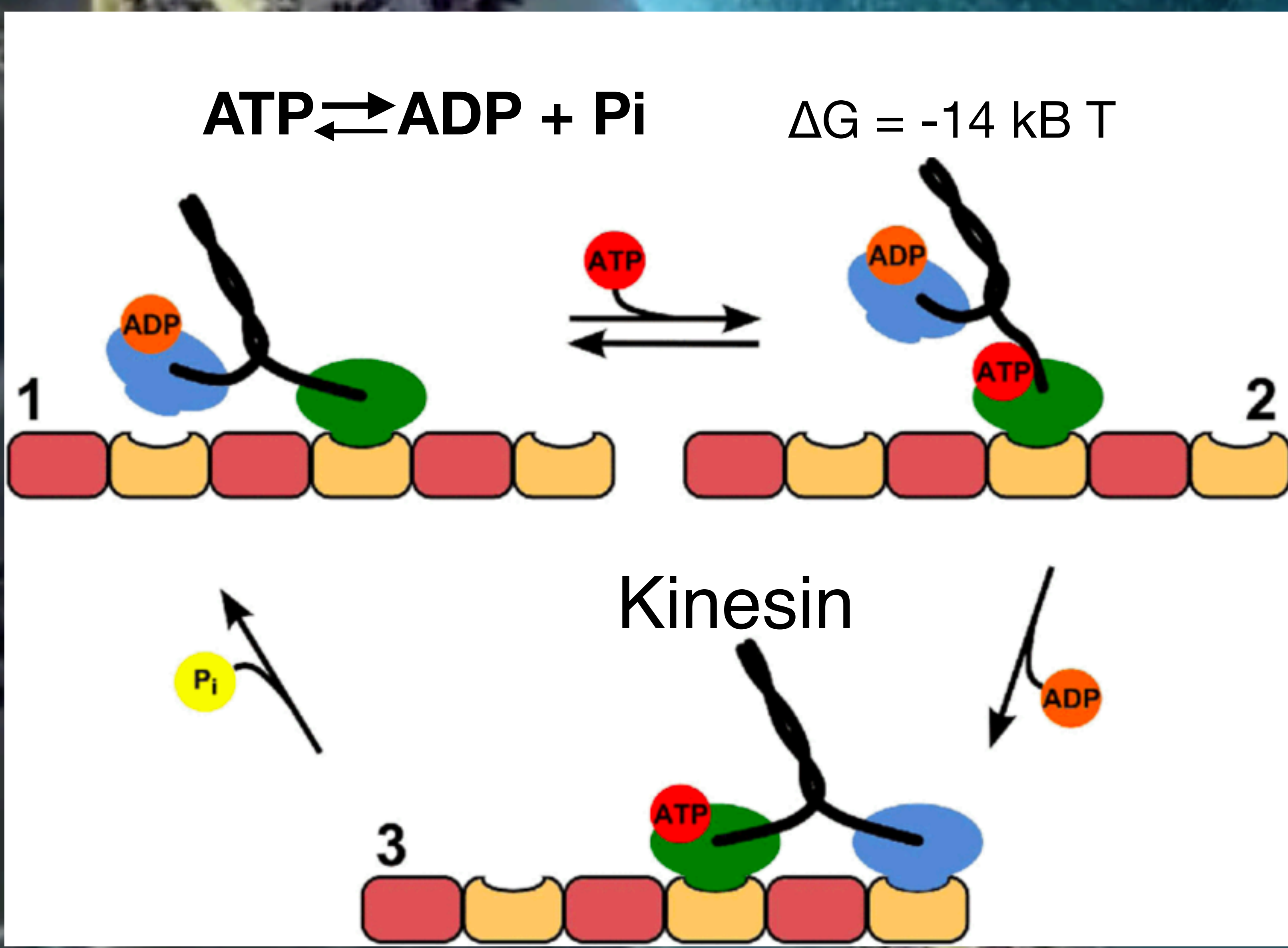


"I hydrolyze ATP and I move"

The mesoscale

Orders of magnitude

Nanometers (10^{-9} m)

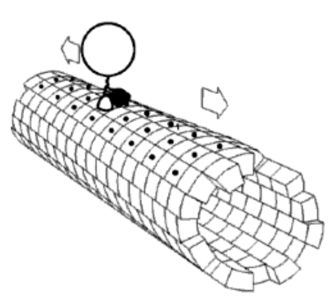
Microsecnds (10^{-6} s)

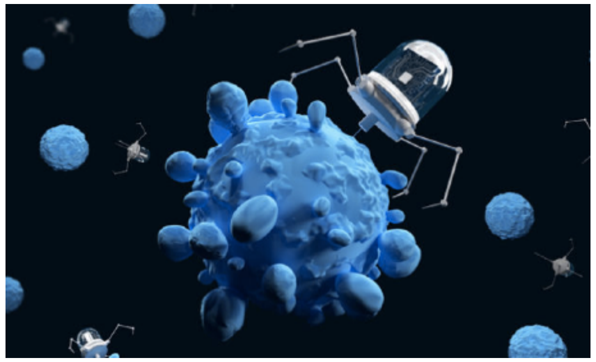
ZeptoJoules (10^{-21} J)

Two-side challenge: natural and artificial

Understand nature: molecular motors

Build artificial nanomachines





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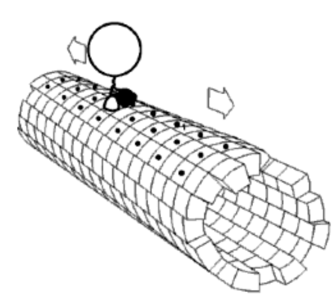
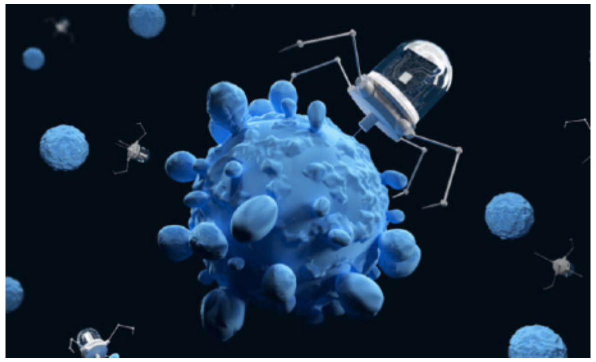
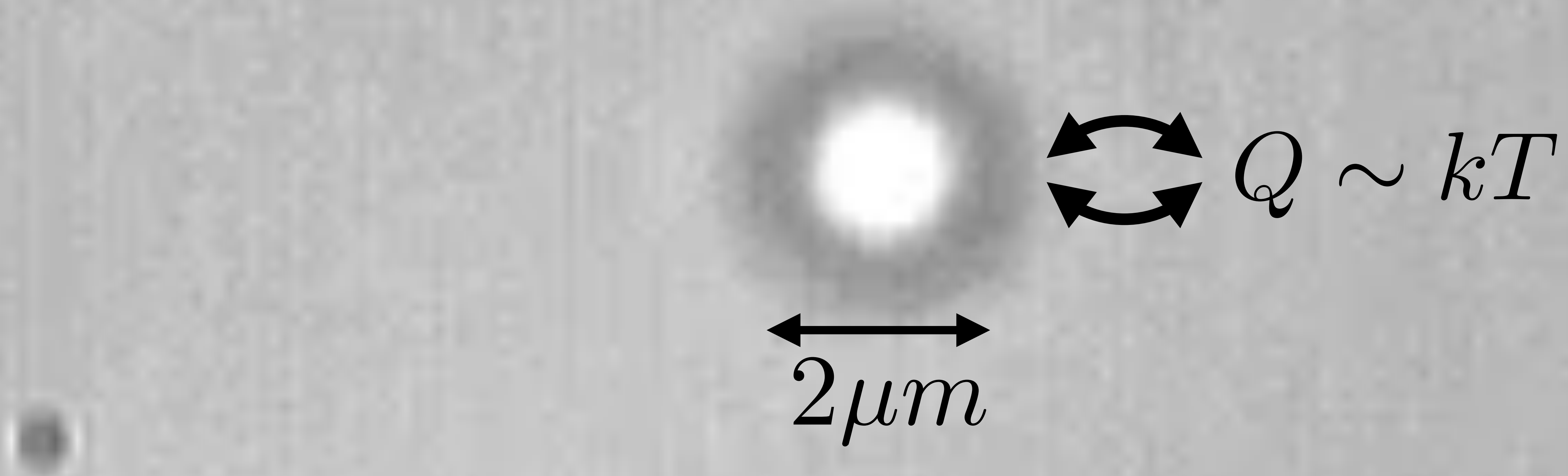




Fluctuations are intrinsic to any small system



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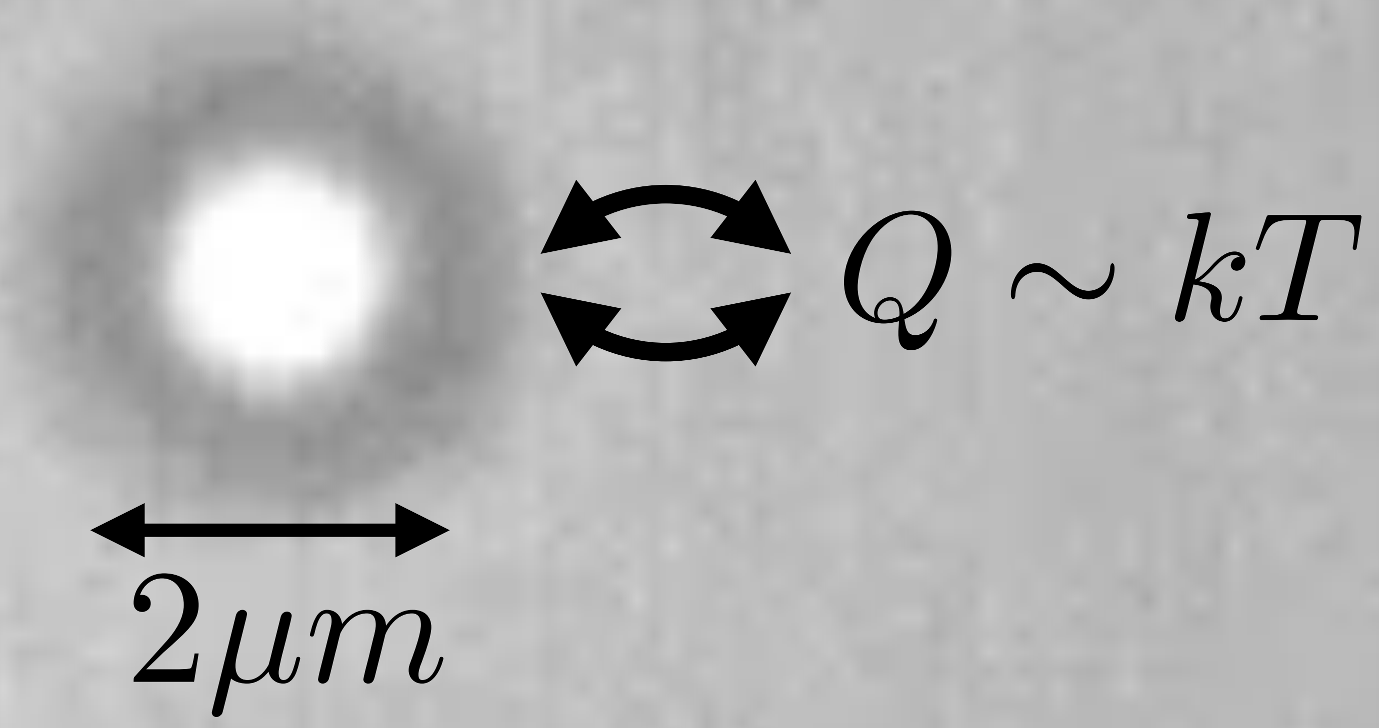

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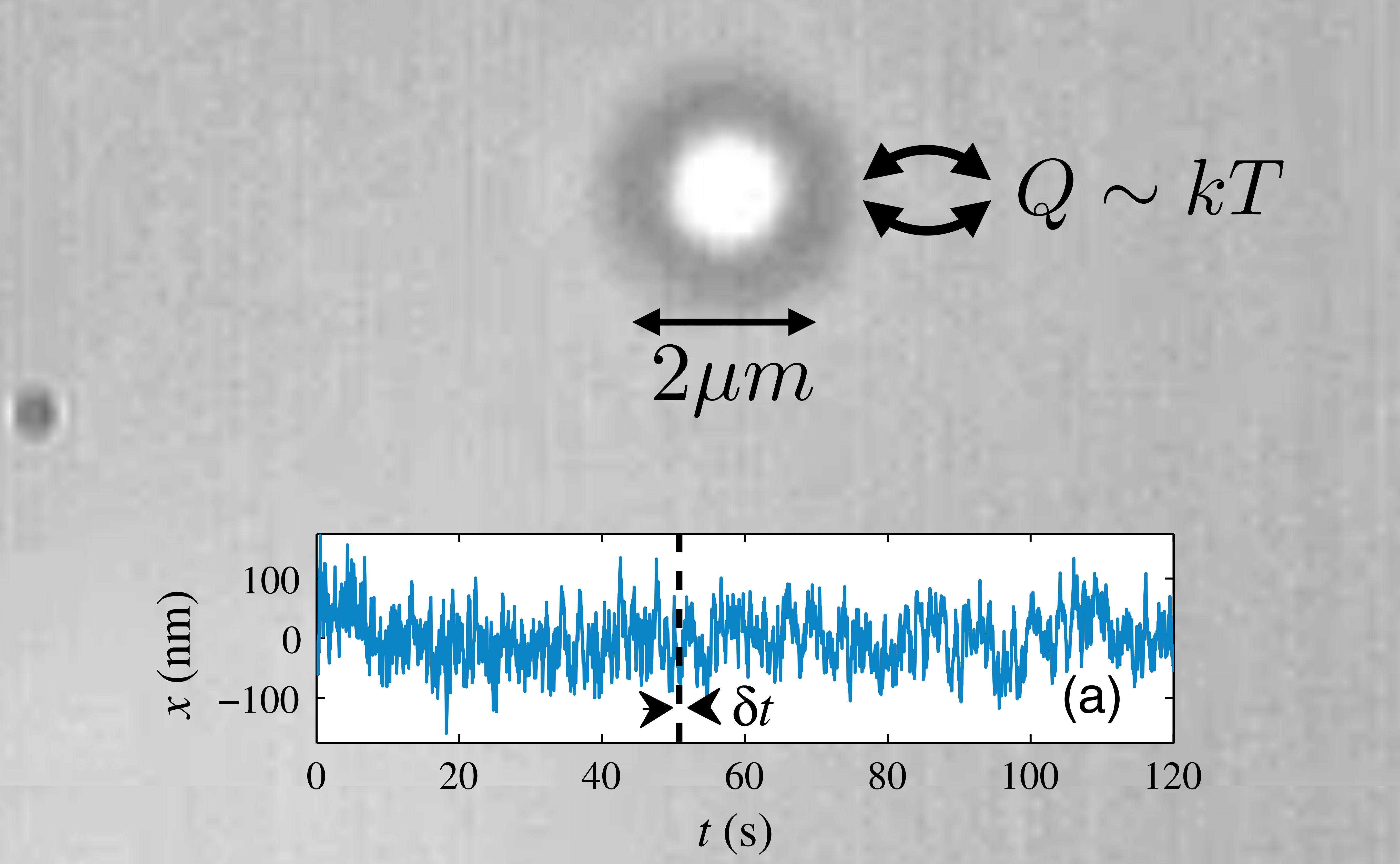
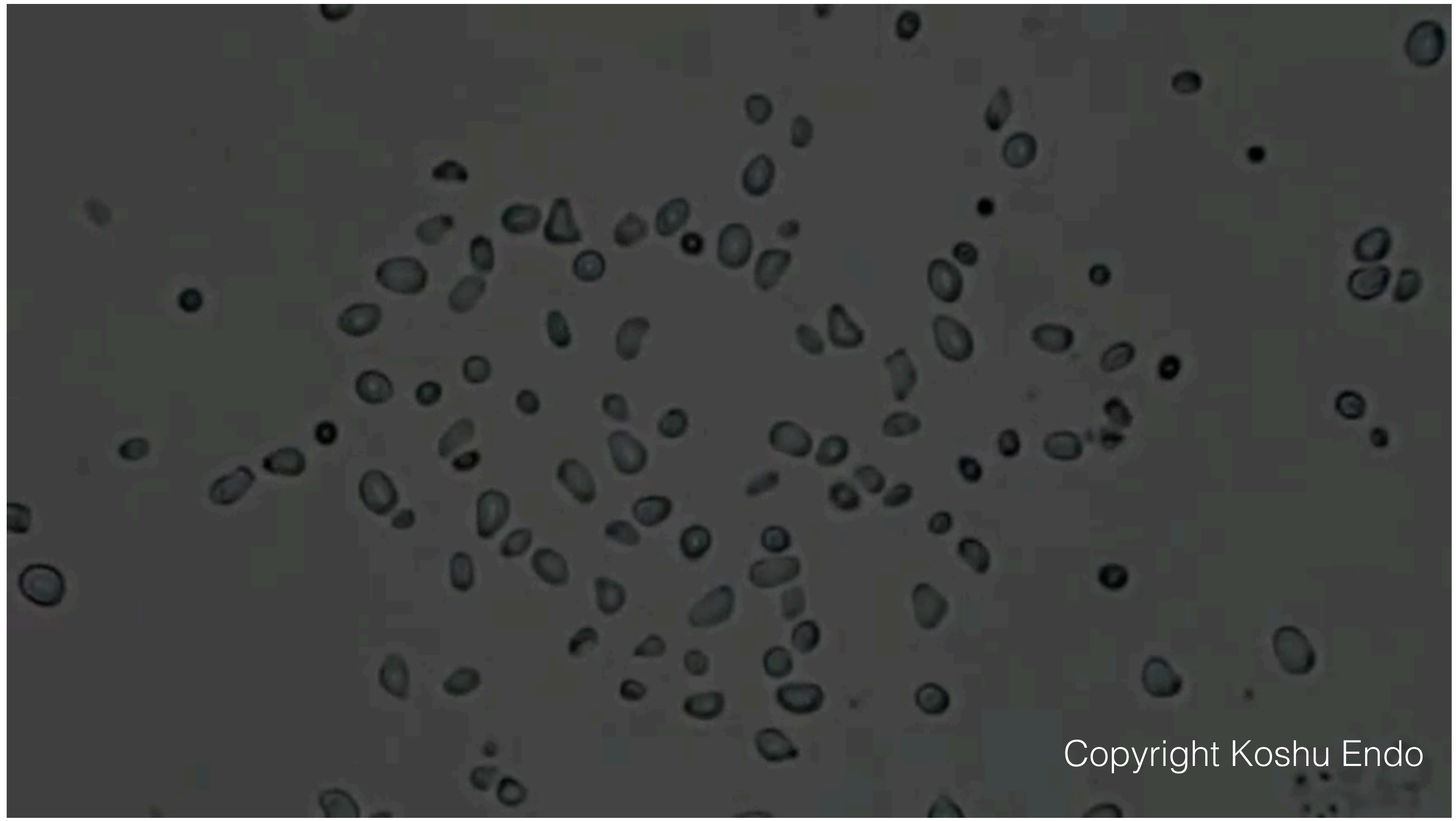


Brownian motion

1827

Robert Brown



Pollen grains (20 micrometers) under the microscope

Why do they move?

Brownian motion

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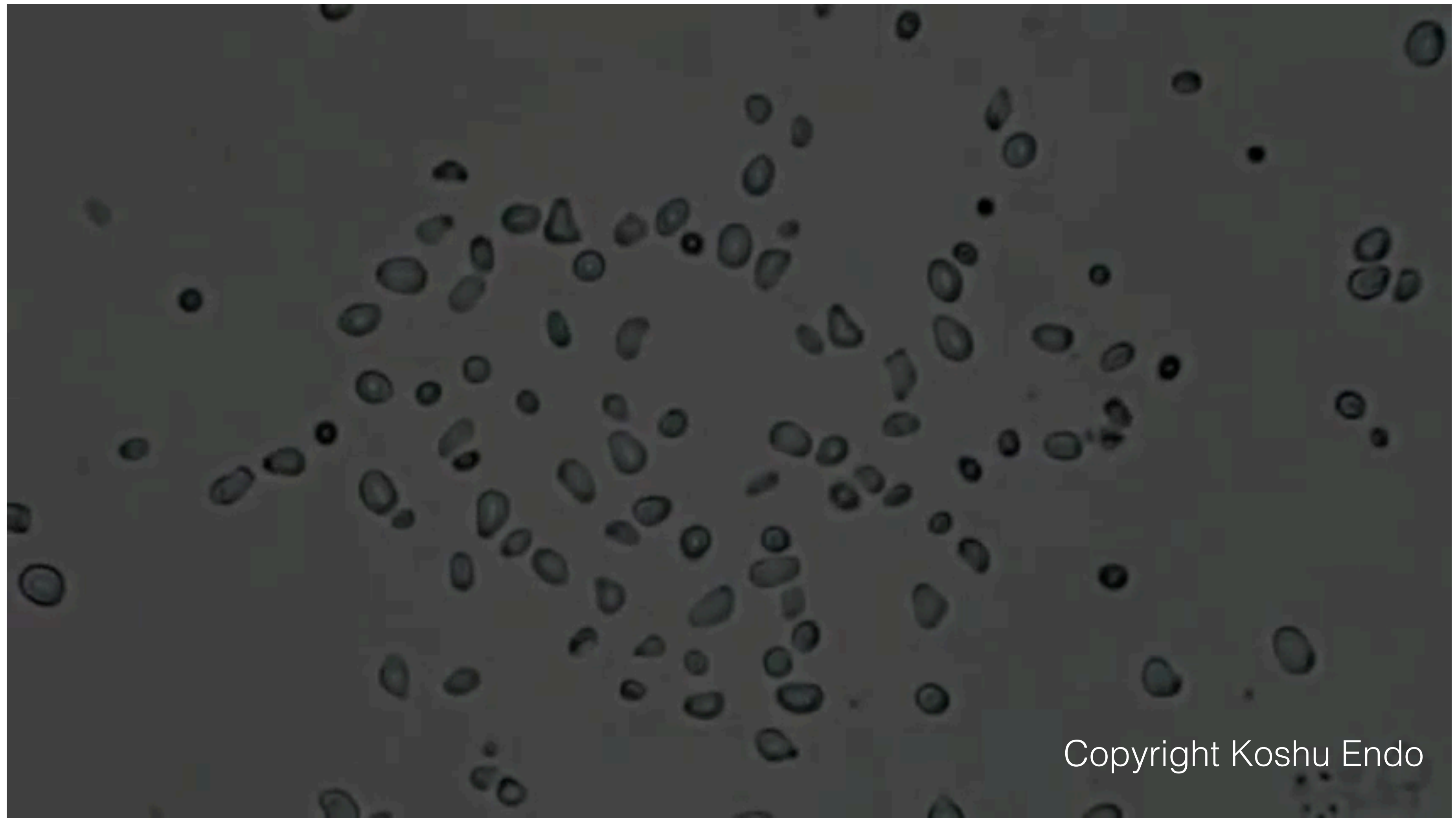

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Einstein's theory

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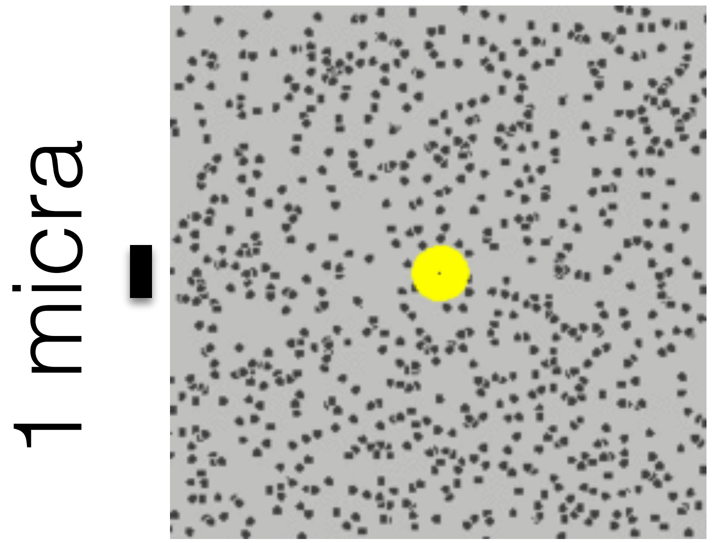
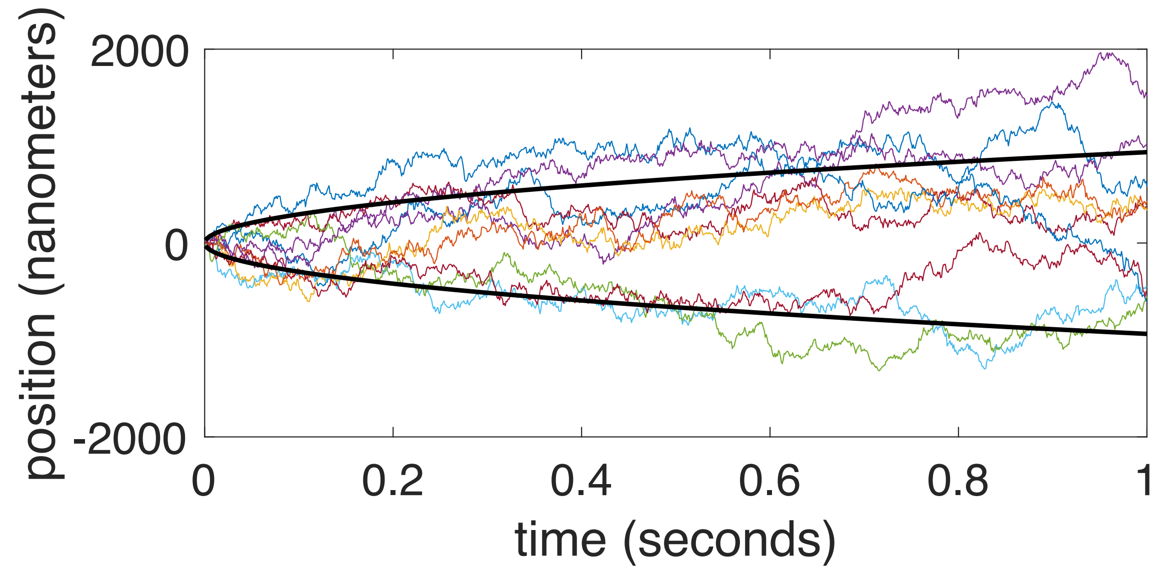




1905

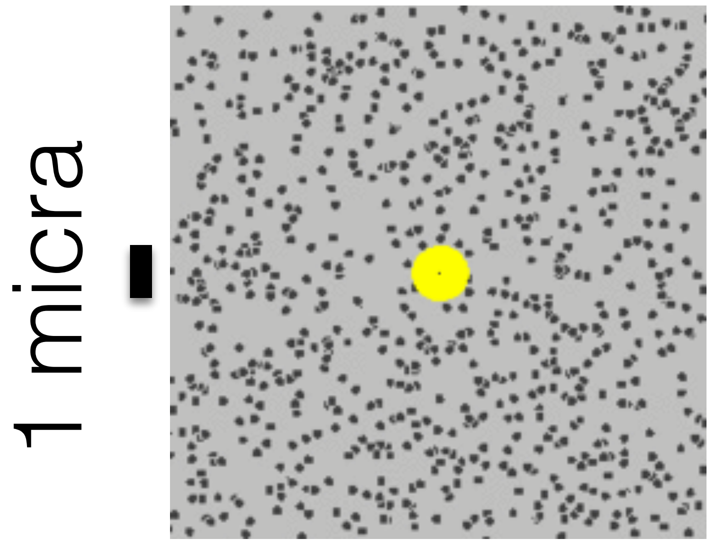
Brownian motion is a manifestation of the **thermal energy** of the molecules comprising the particle's environment

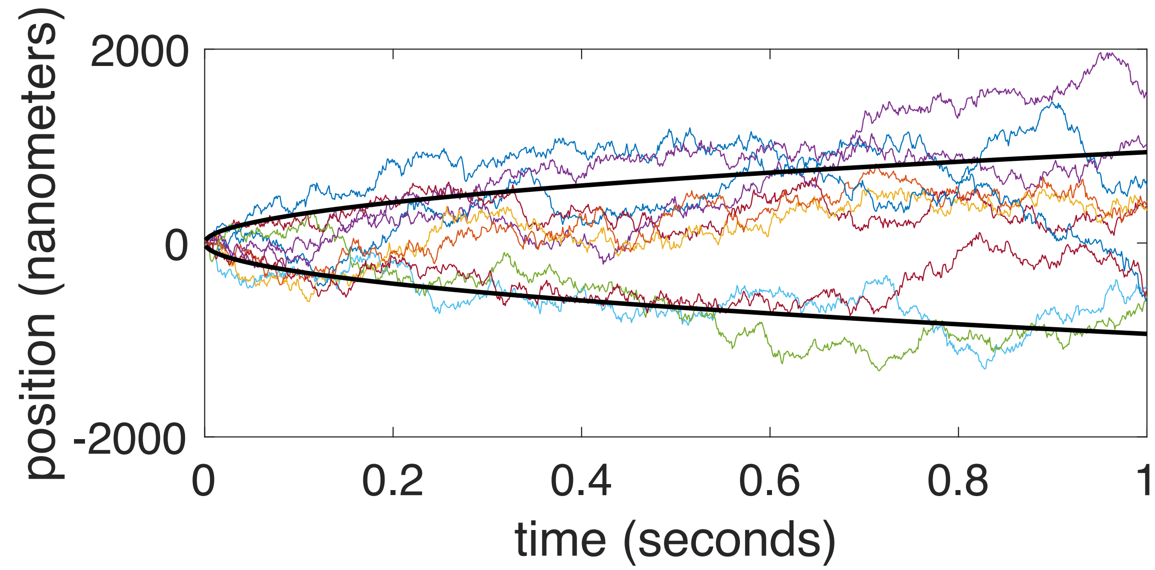
$$\langle x^2(t)\rangle = 2Dt = \frac{RT}{6\pi\eta R N_A}$$

Empirical evidence of molecular theory

Einstein's theory

1827





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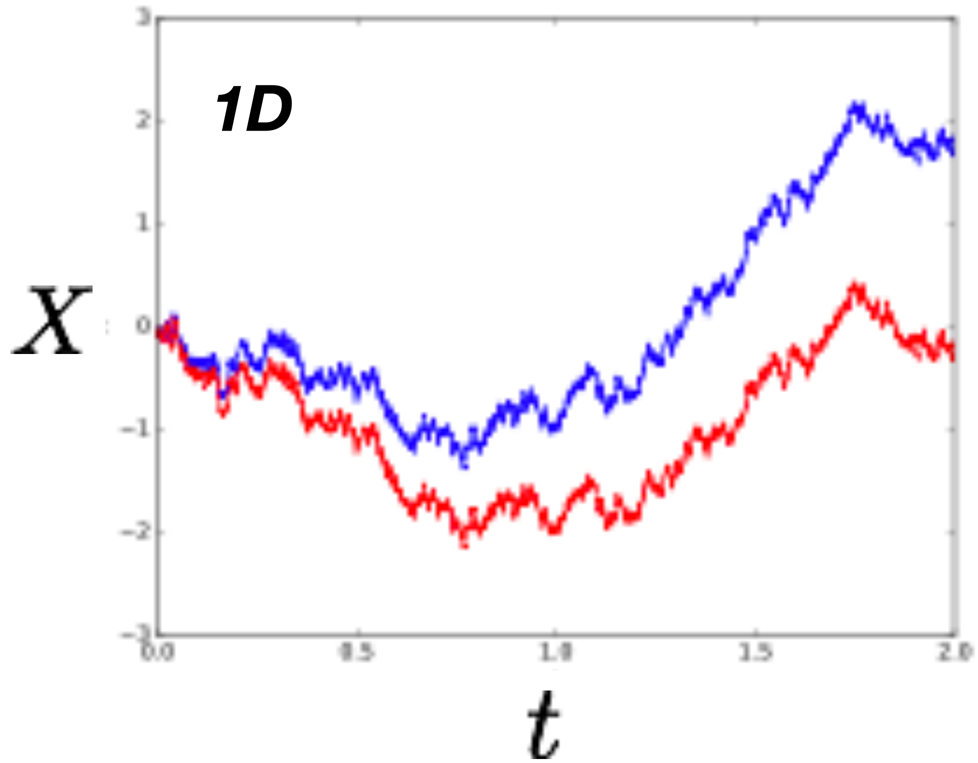
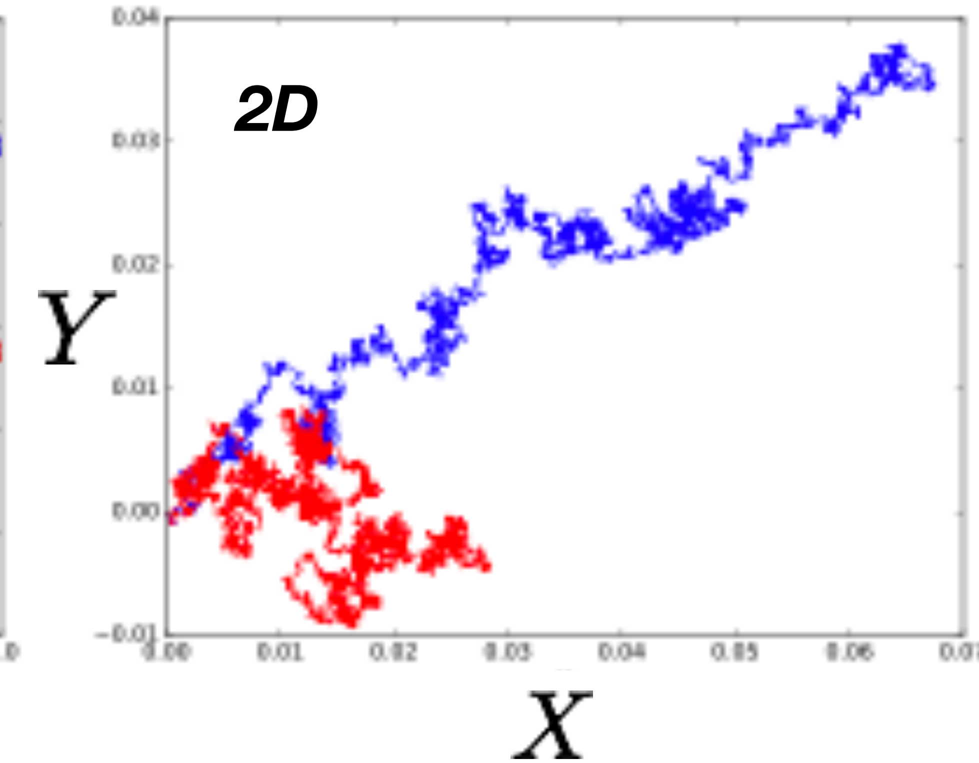
Empirical evidence of molecular theory

Statistical nature

1827





1905

Brownian motion is a **stochastic** process
Each realization of the *same* experiment produces a *different* output trajectory, even if the initial condition is the same

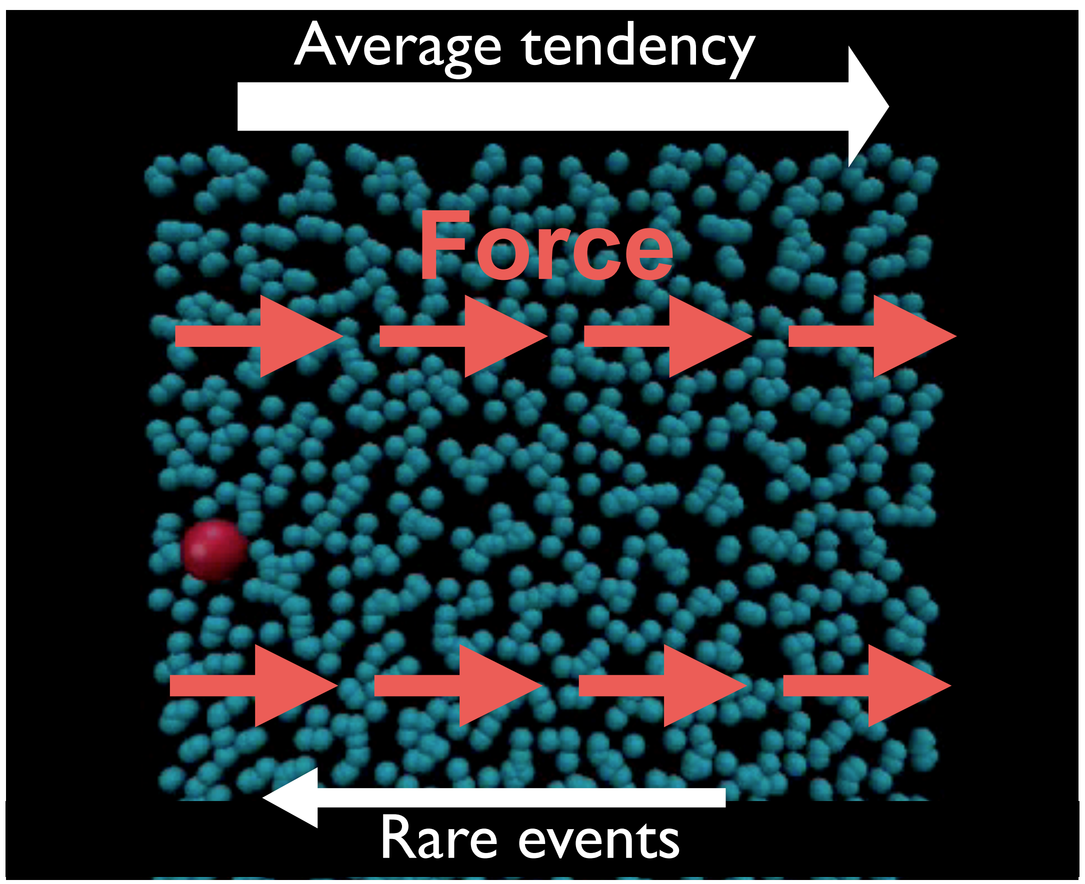
We study the particle position not as a "number" but as a probability density

$$x \to \rho(x)$$

Rare events at the microscale

Physics

Biased random walks



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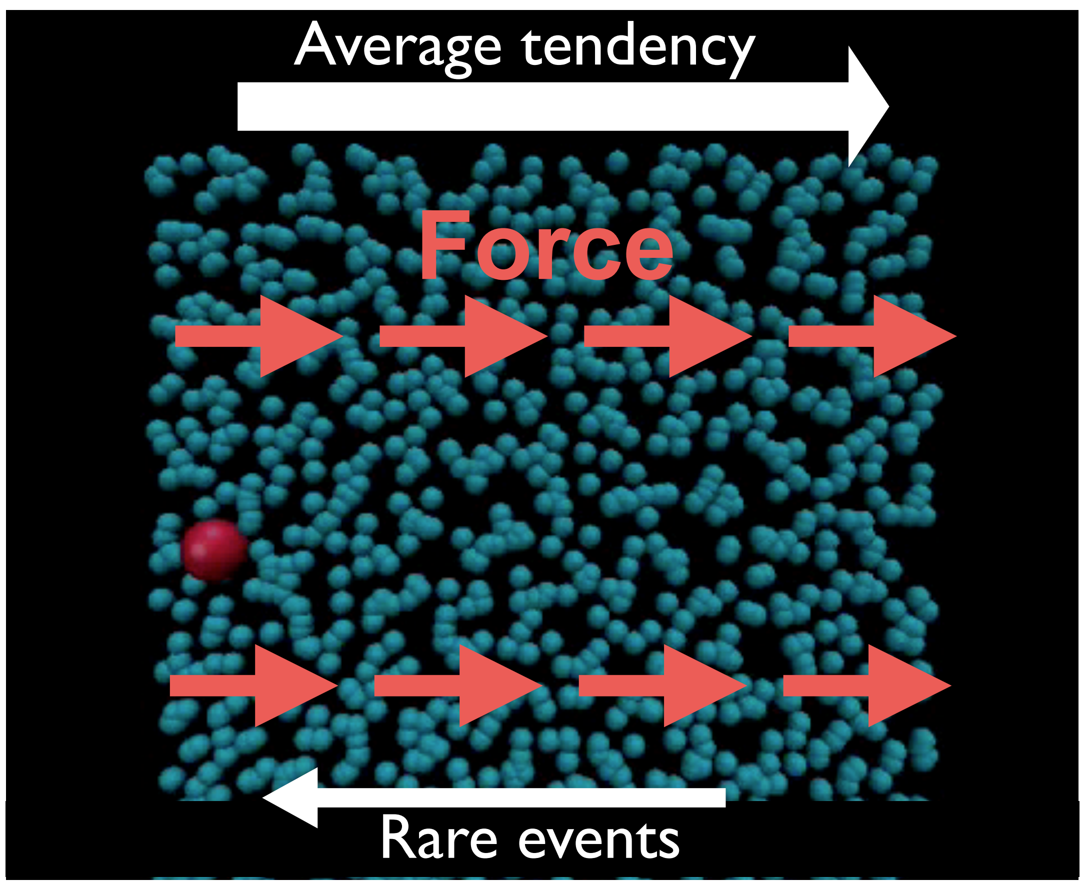

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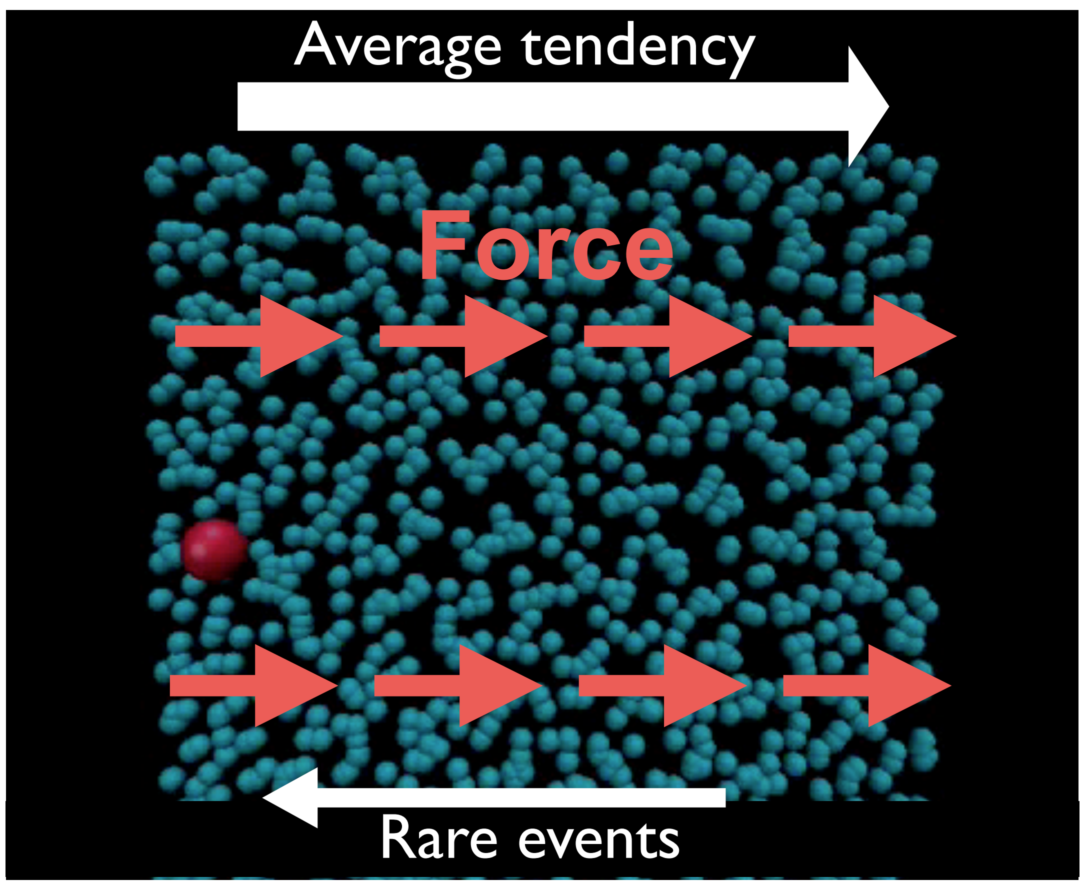
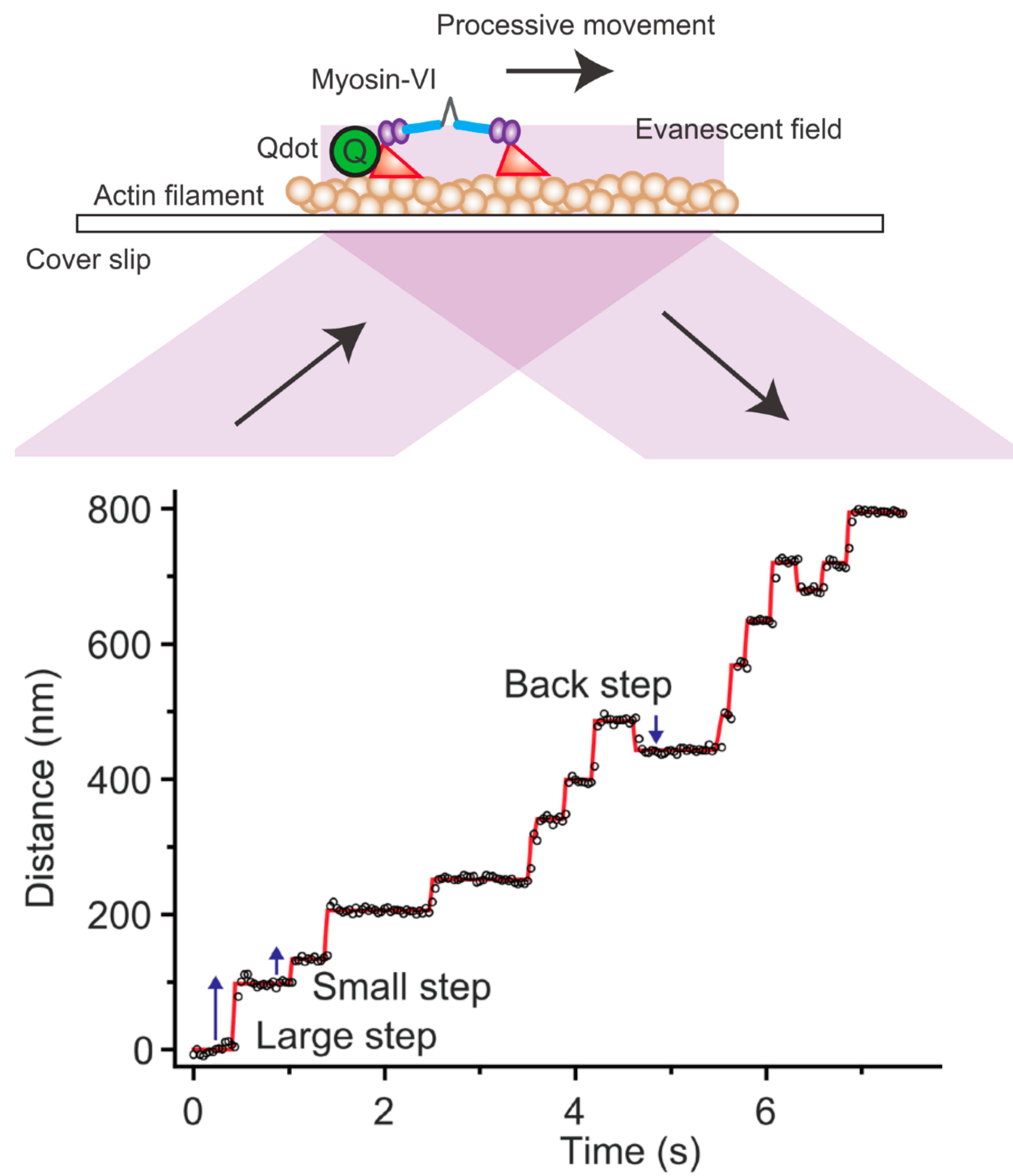


Biology

Molecular motor stepping

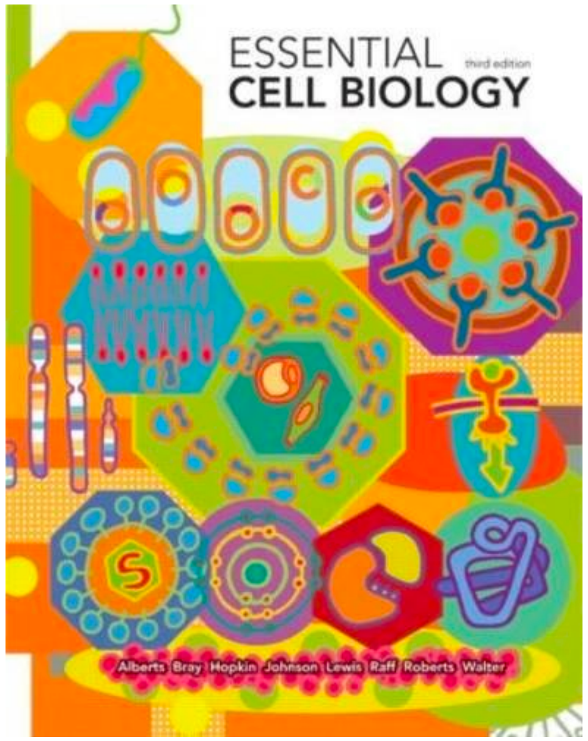


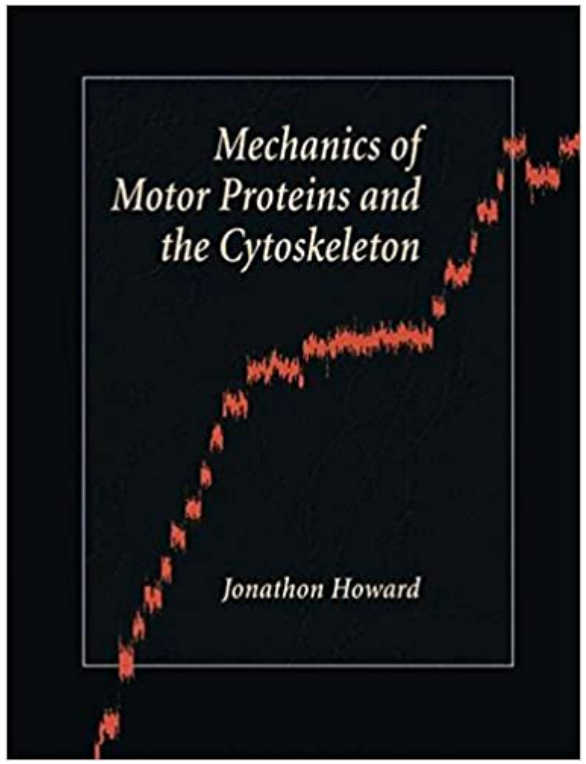
Minimal stochastic models in biophysics

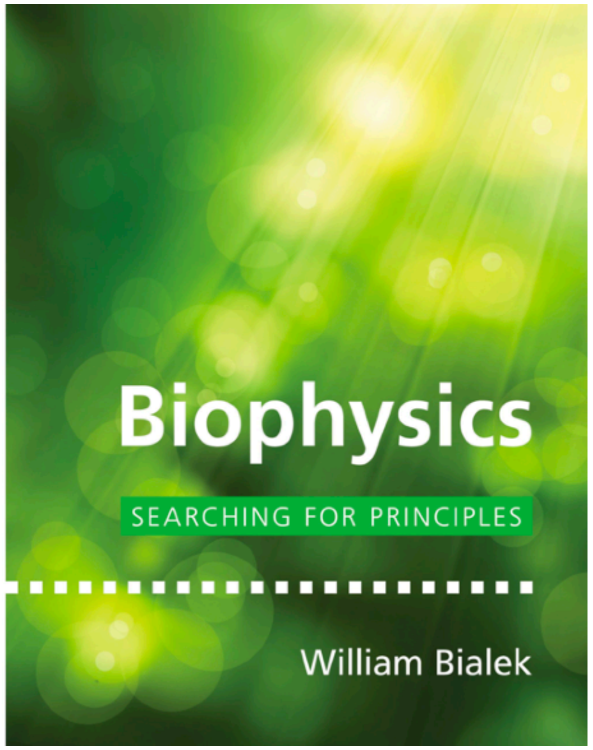
Molecular motors and beyond

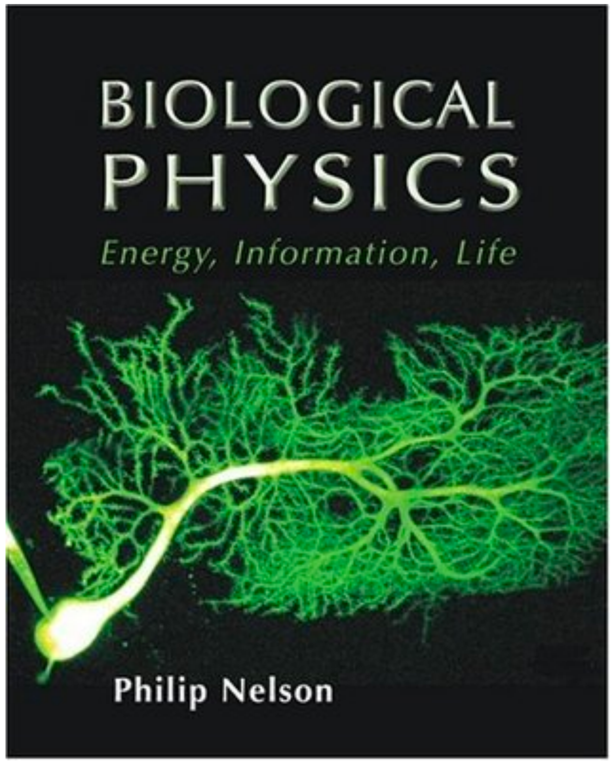
Biophysics YouTube lectures

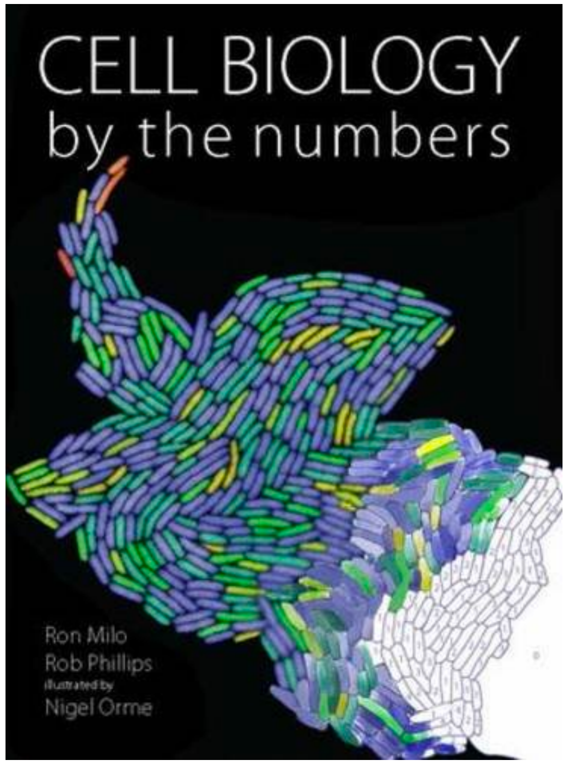
Reference textbooks

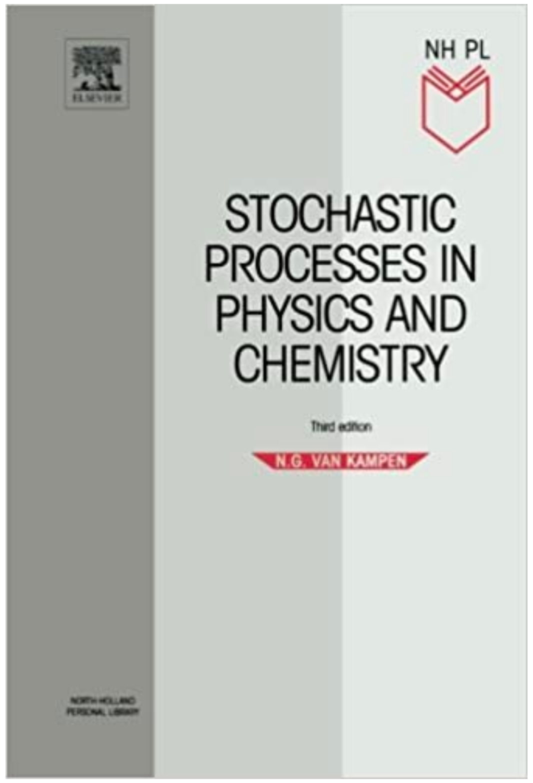


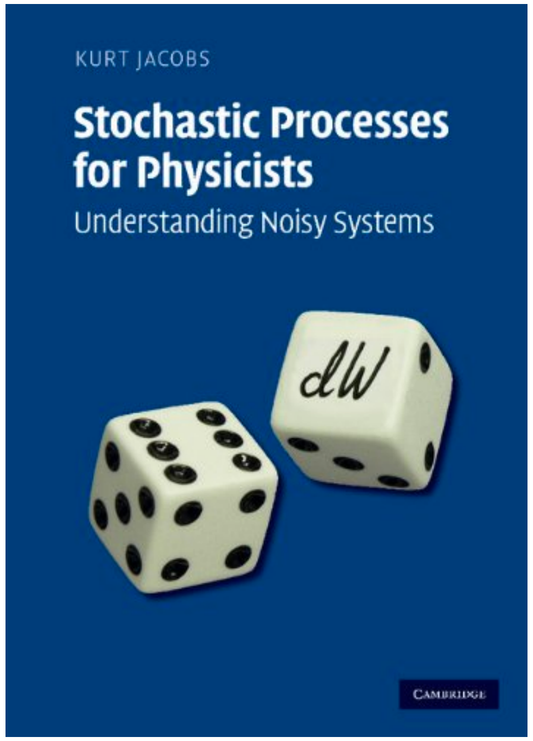


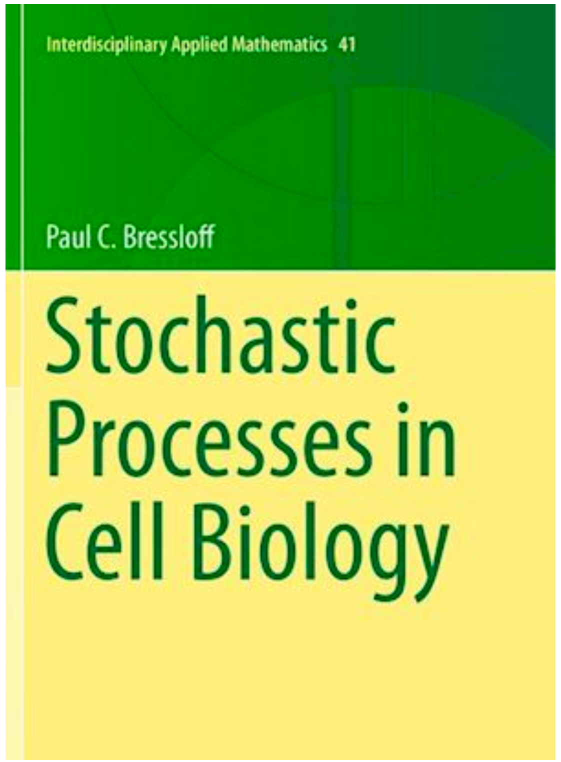




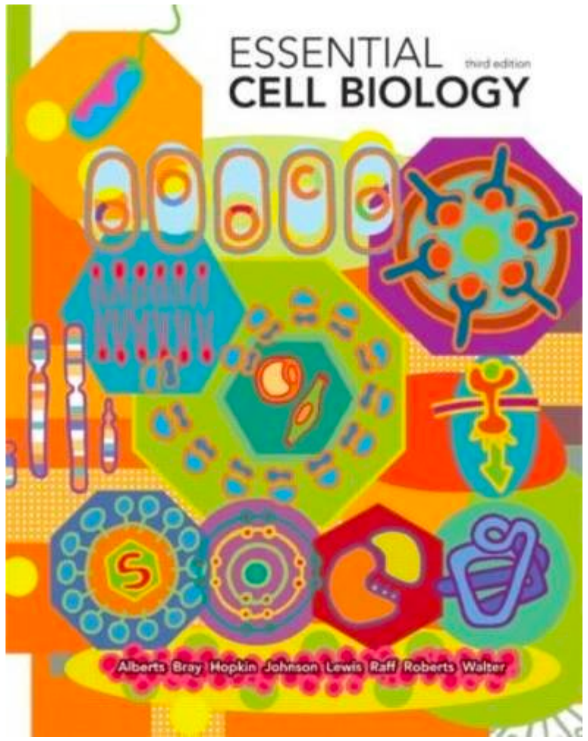


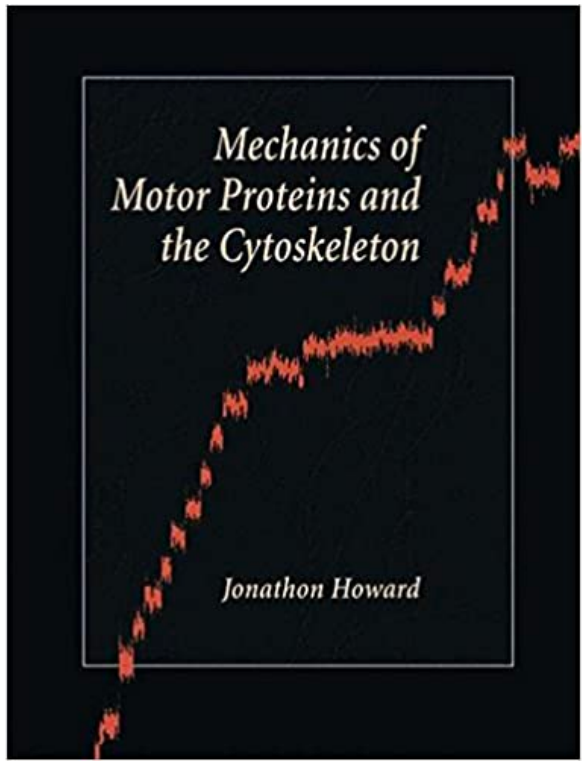


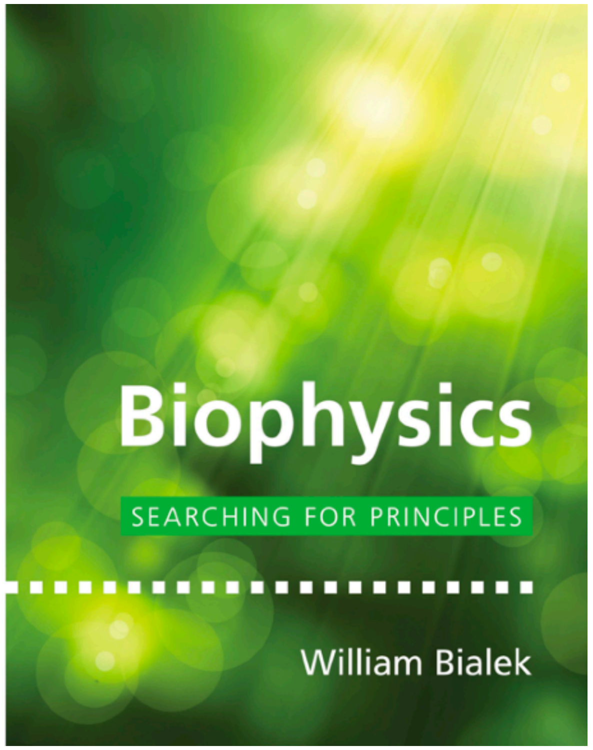


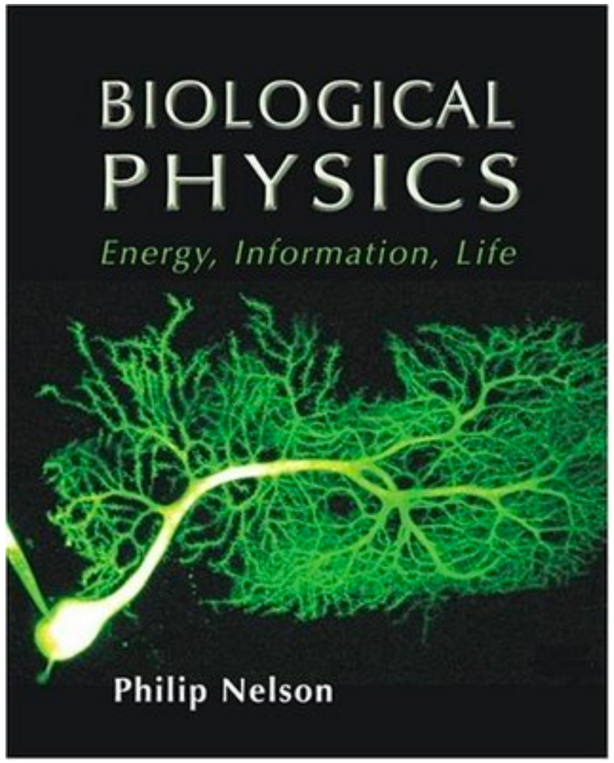


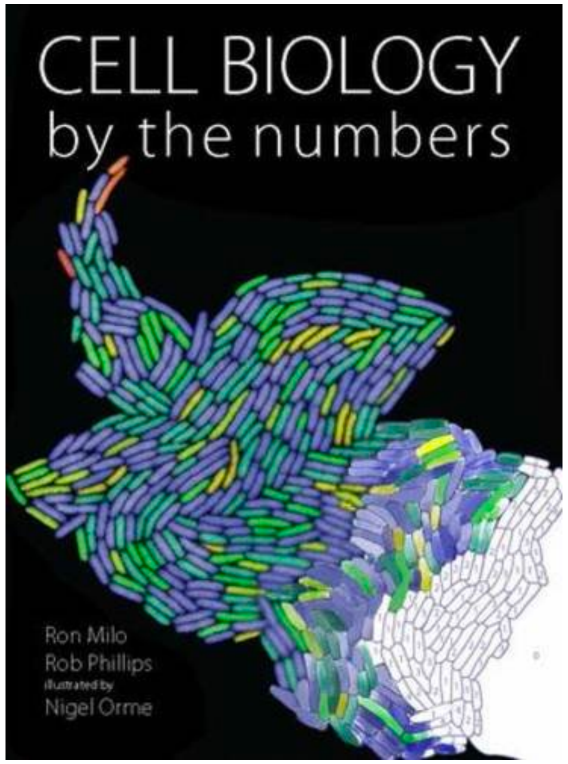
Reference textbooks

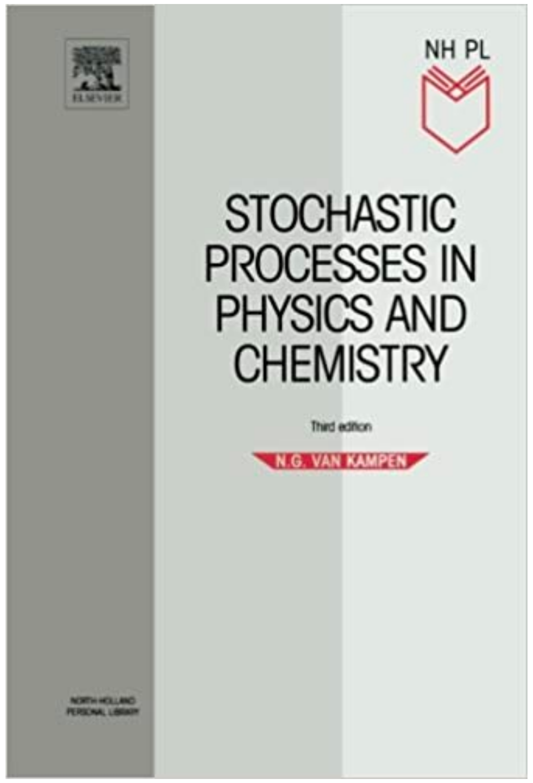


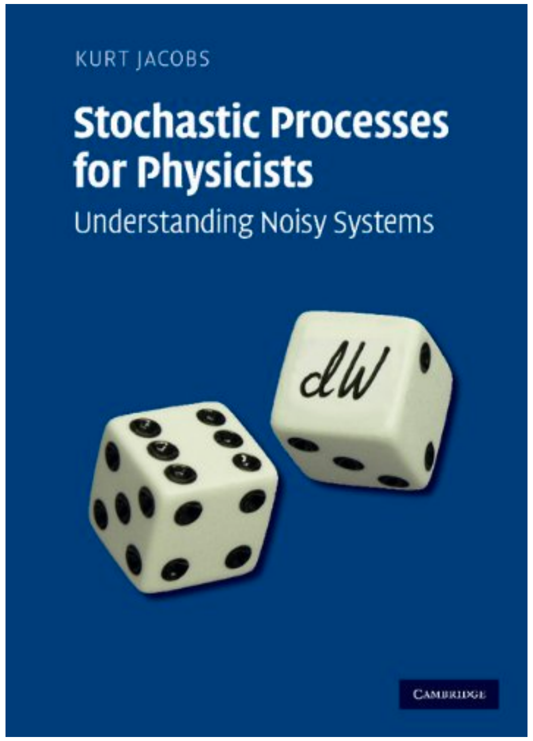


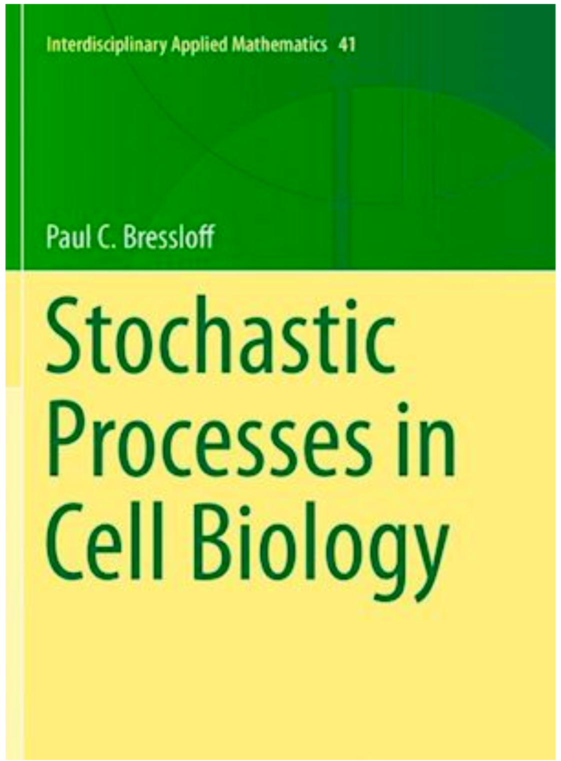




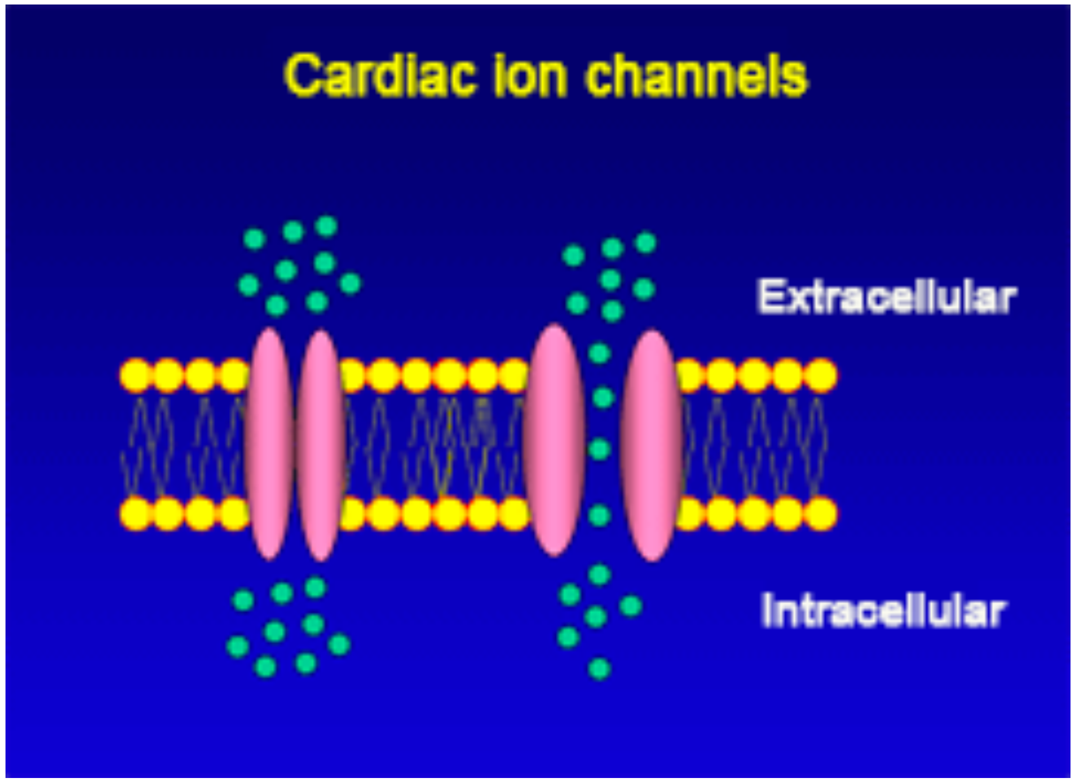


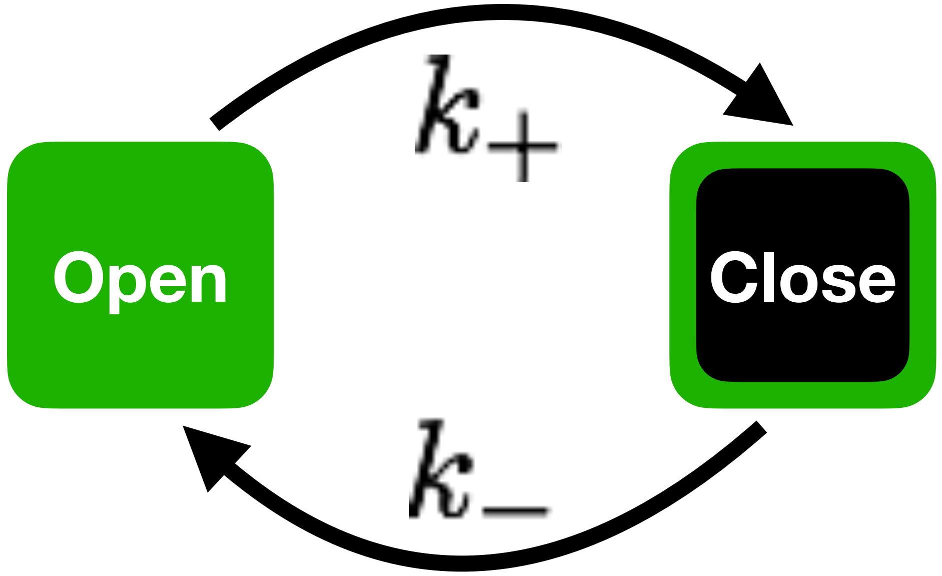


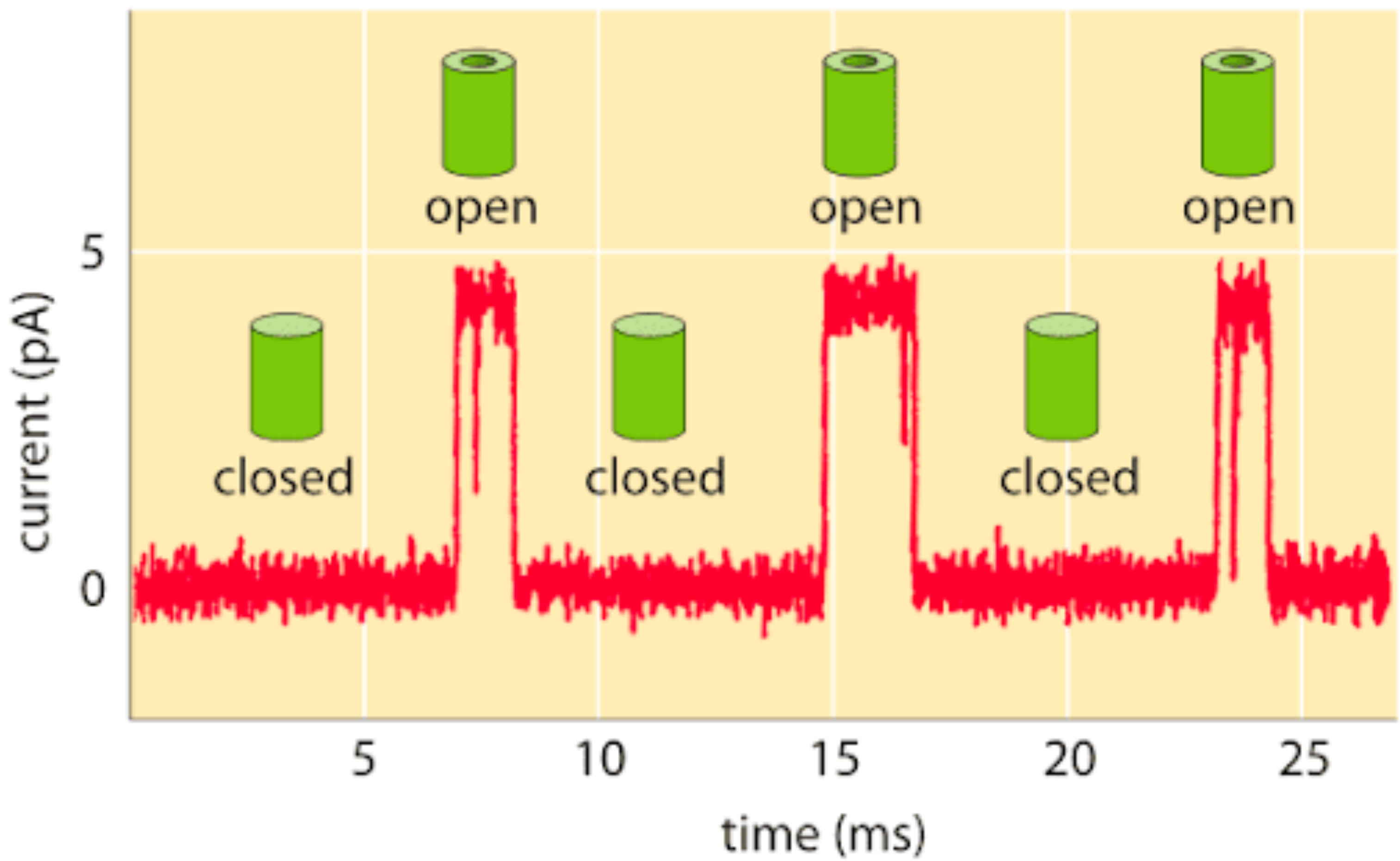




Ion channels

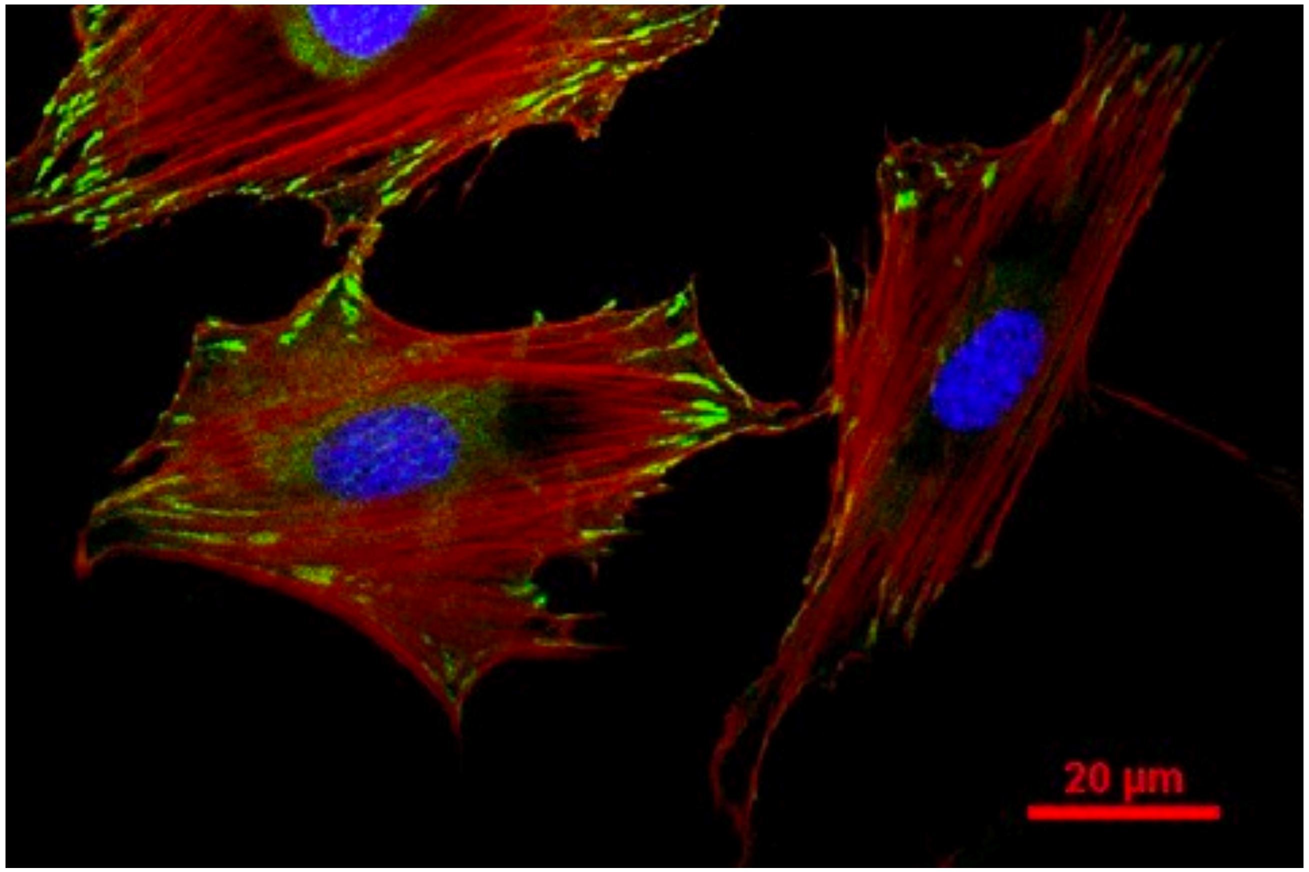


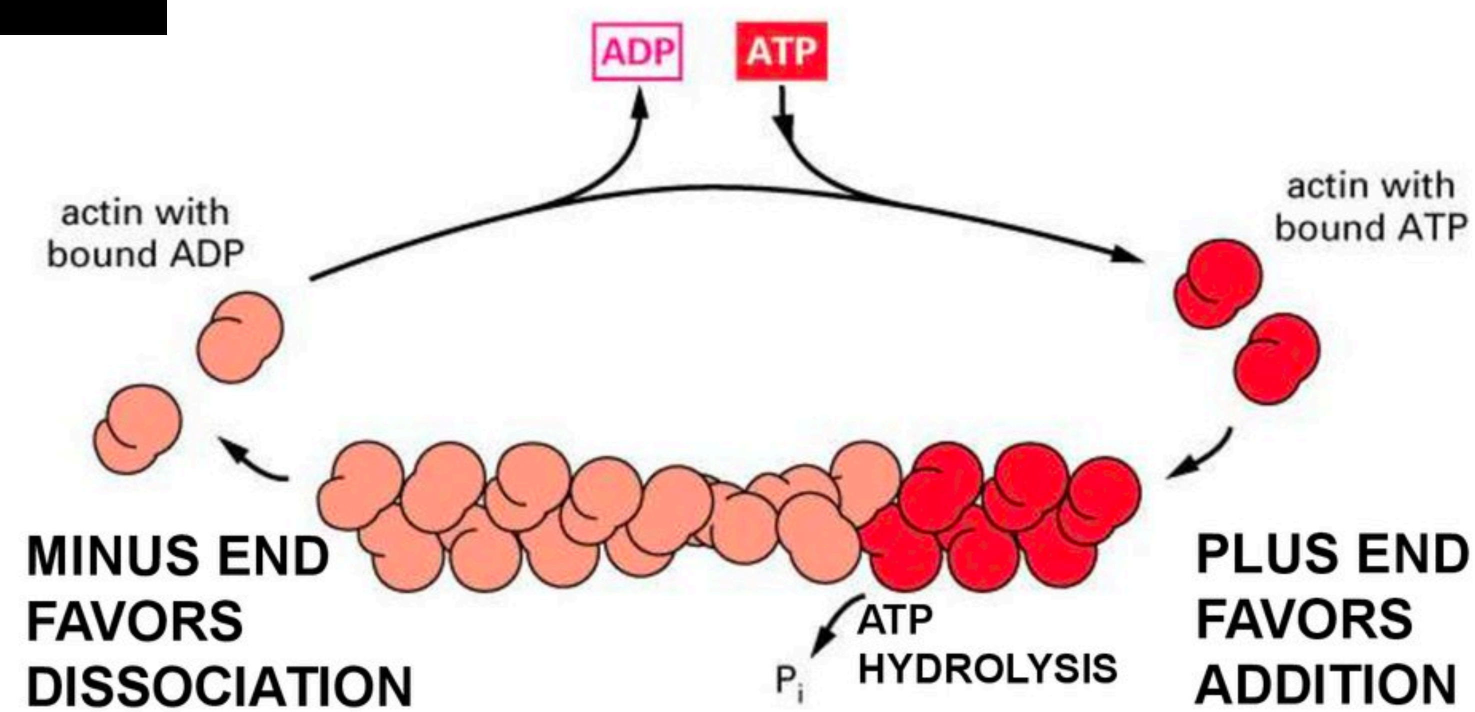




Biopolymer dynamics

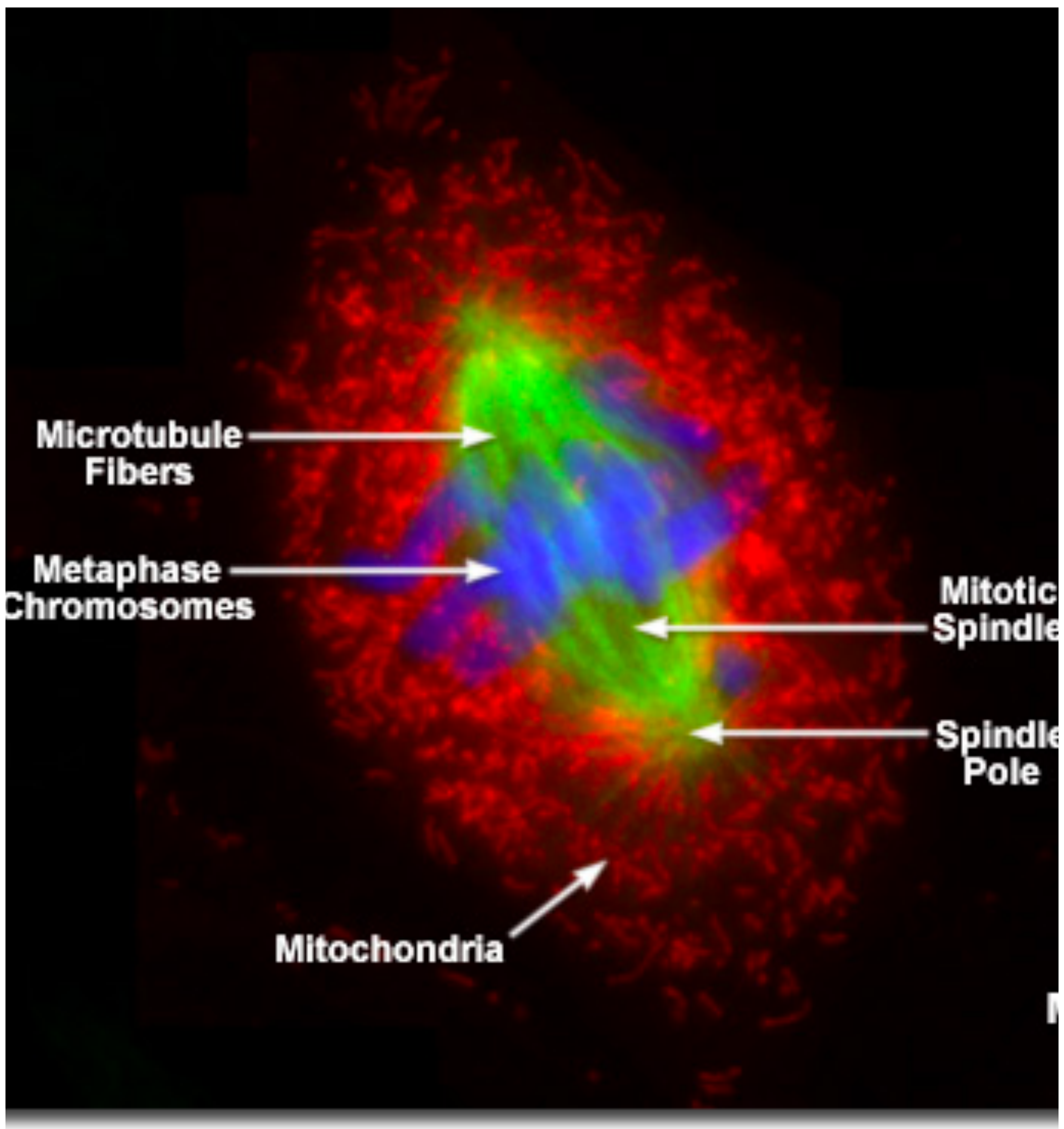
Actin polymerization and depolymerization

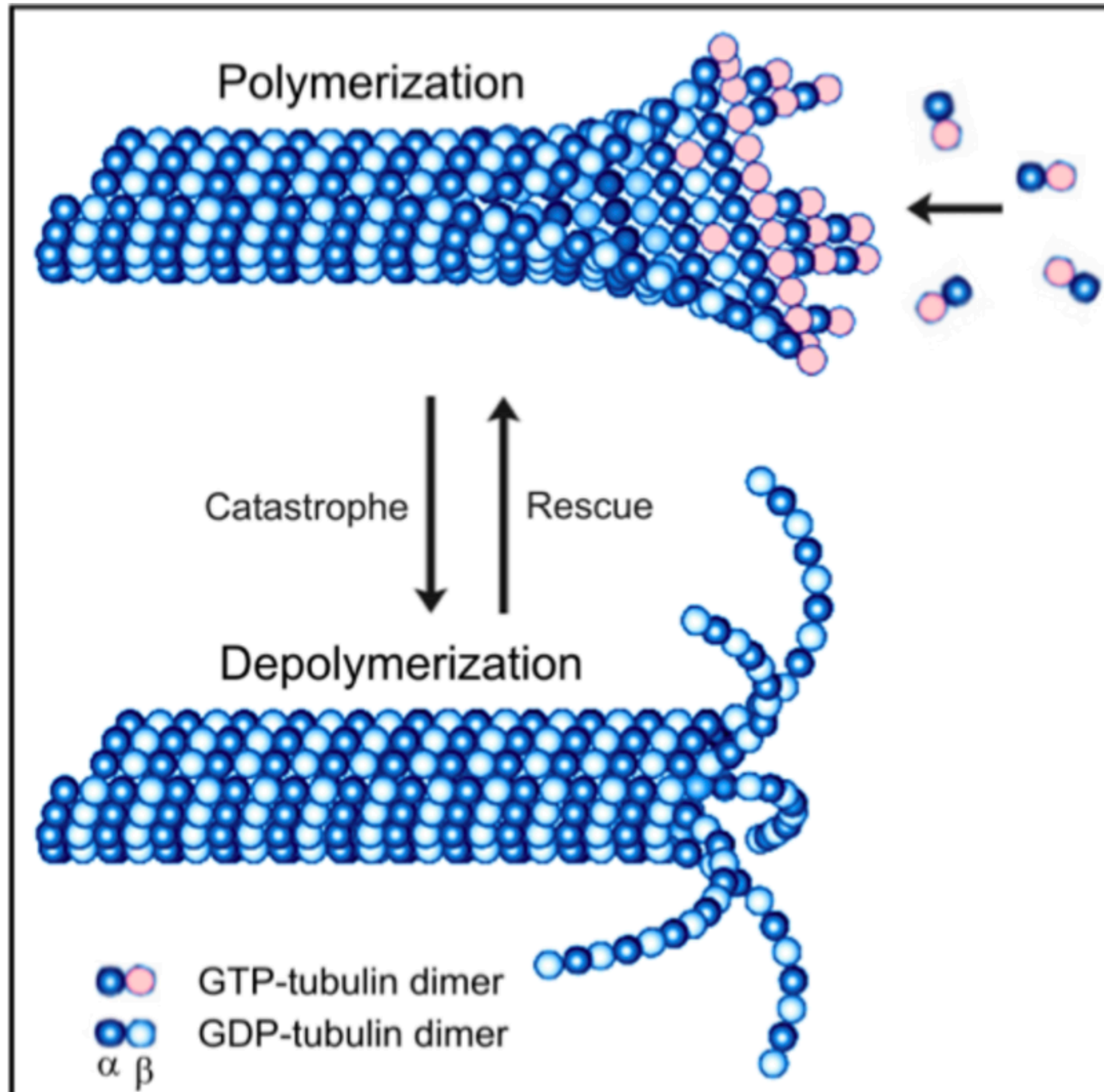




Biopolymer dynamics

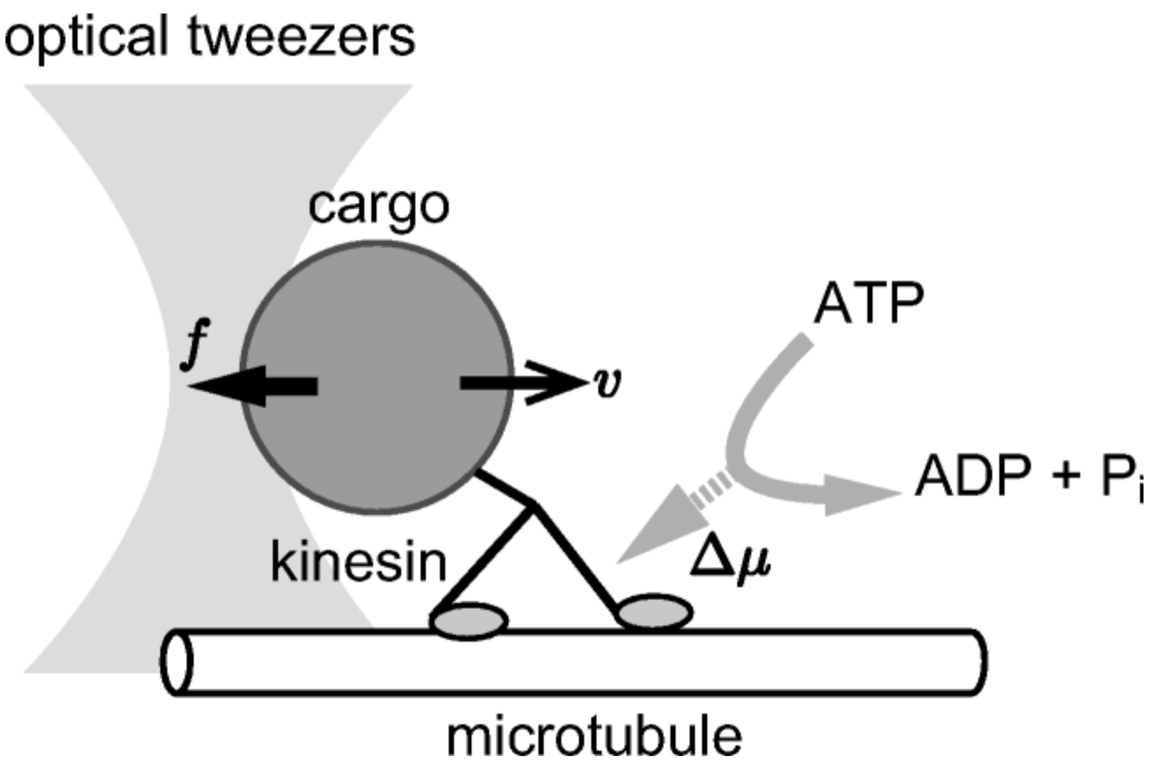
Microtubule growth and shrinkage





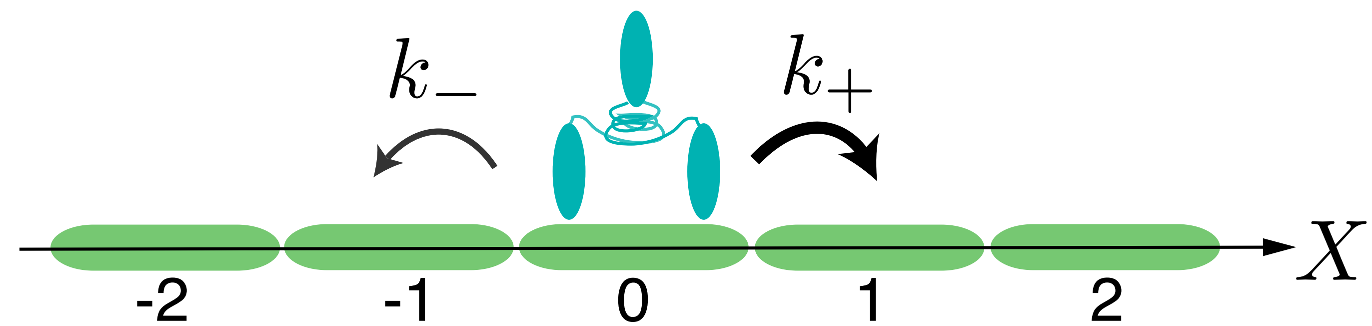
Molecular motors

Single-molecule experiments

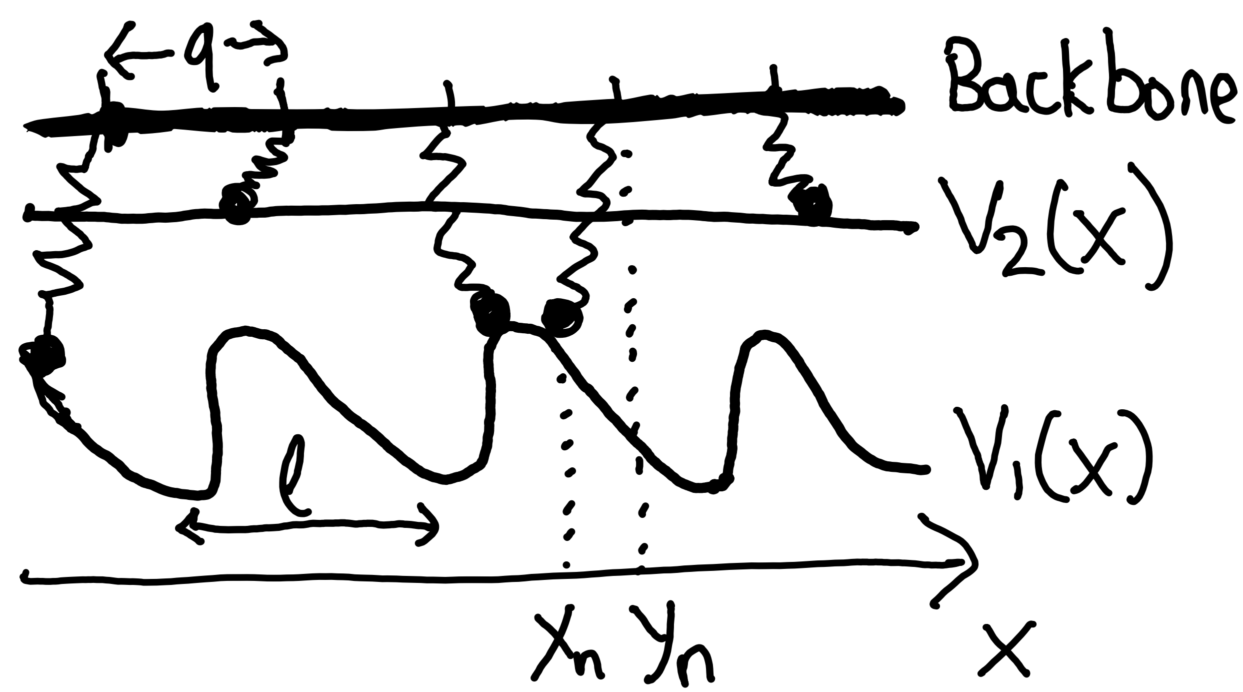


Biophysical reviews 12.2 (2020): 419-423

Biased random walks



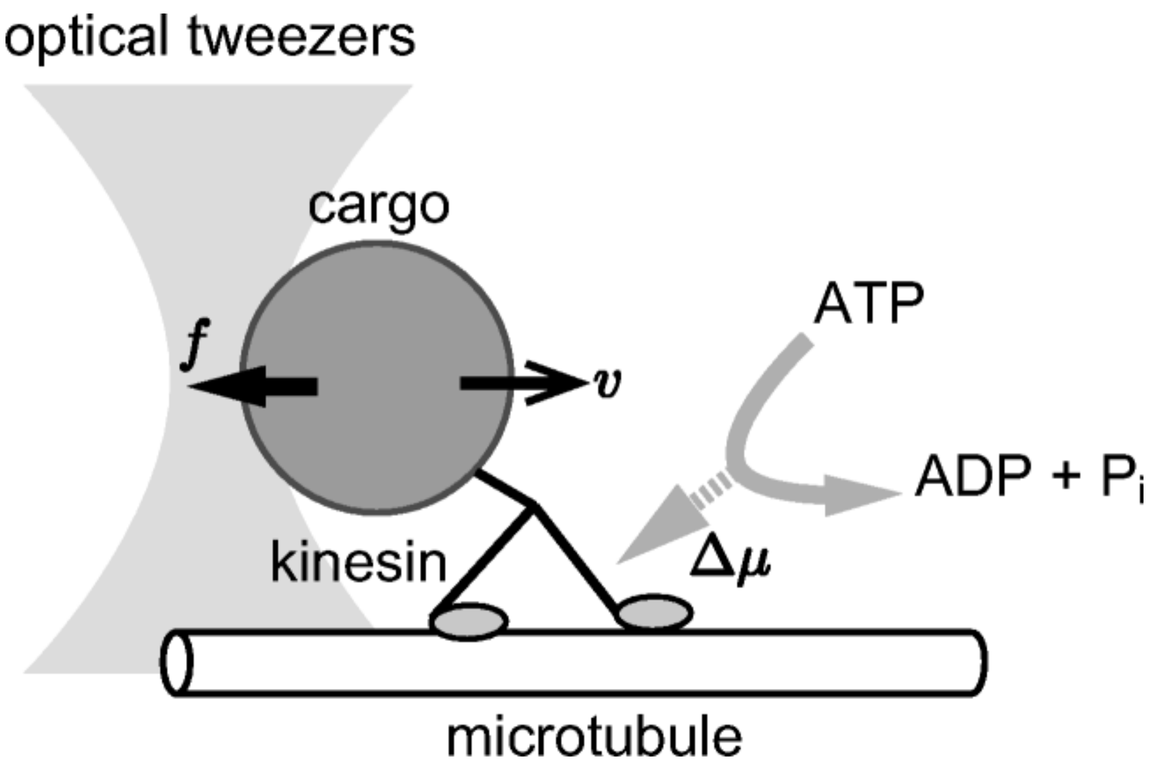
Flashing ratchets



Collective effects

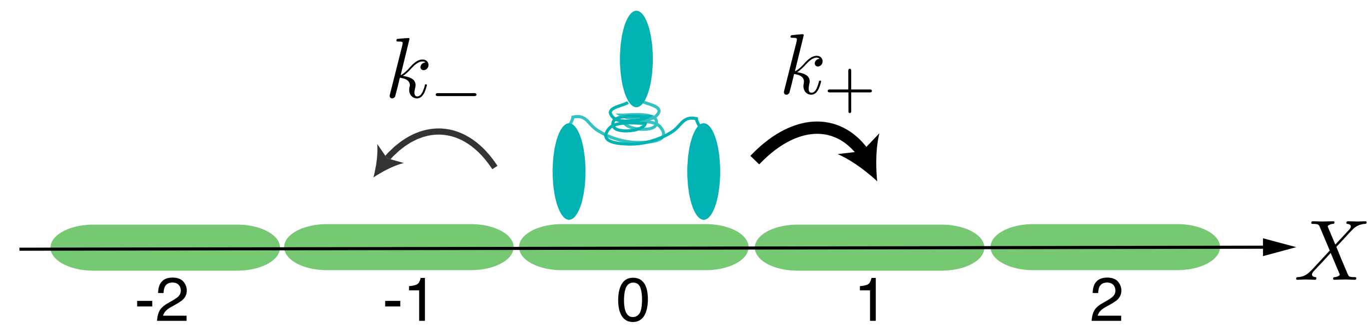
Molecular motors

Single-molecule experiments

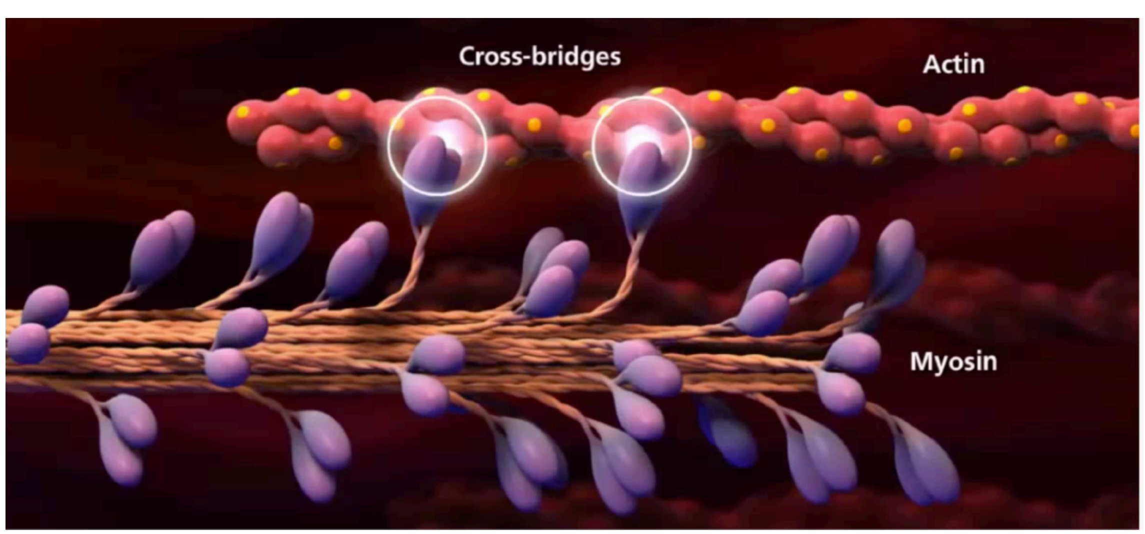


Biophysical reviews 12.2 (2020): 419-423

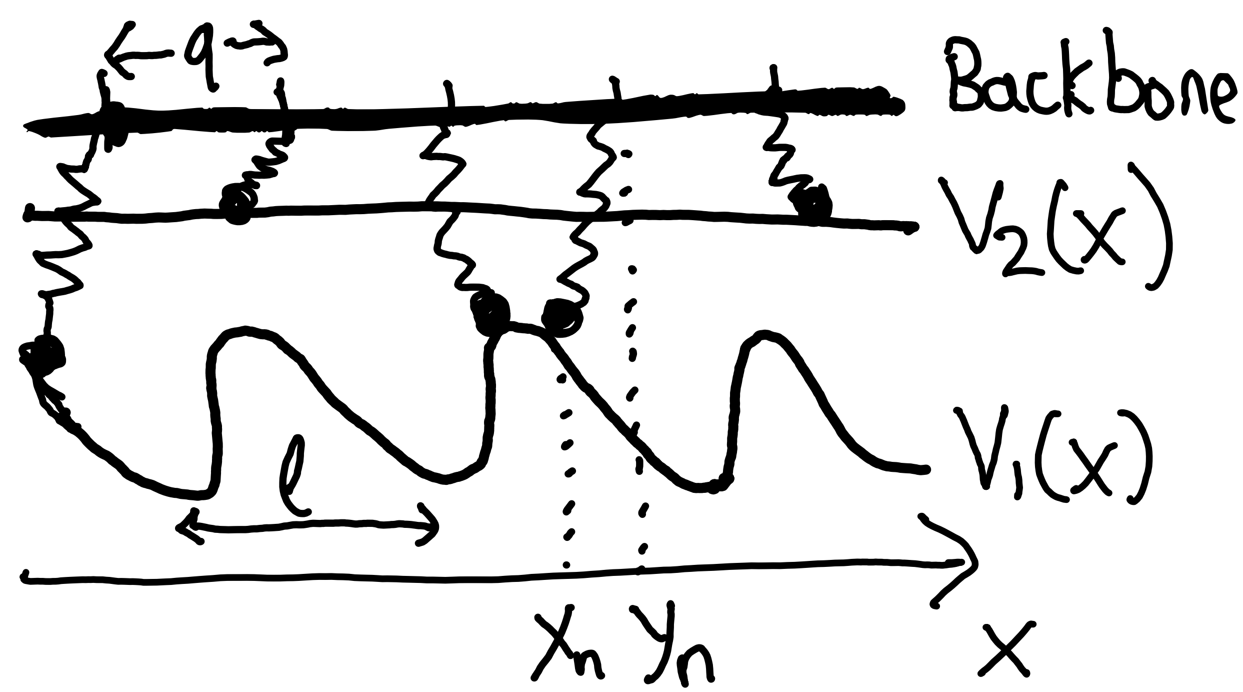
Biased random walks



Collective effects



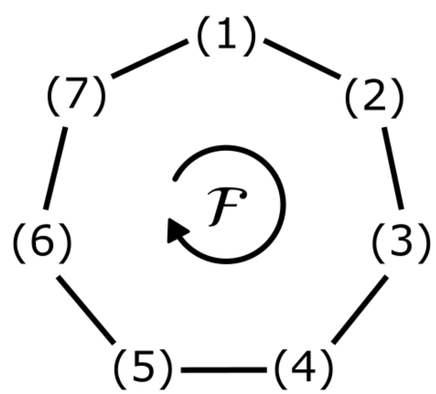
Flashing ratchets



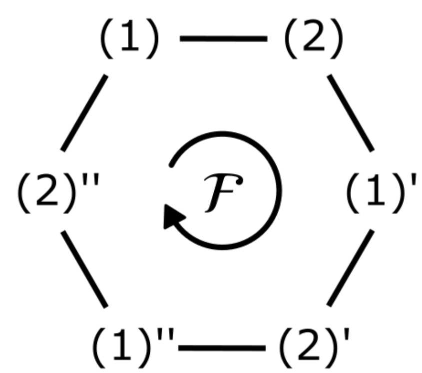
Enzymatic cycles

Dynein

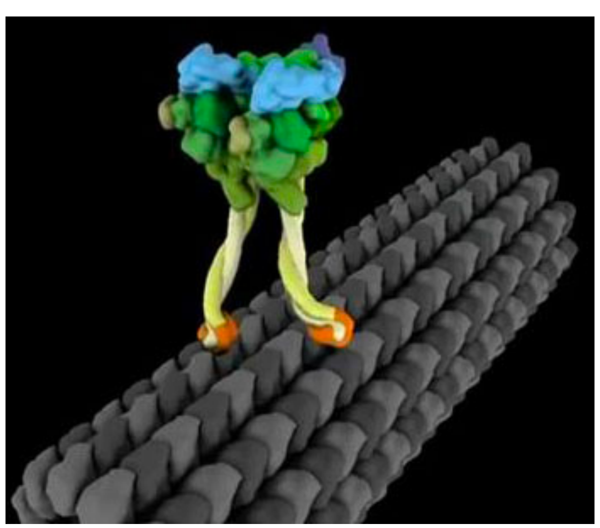
(N=7)-uni cyclic

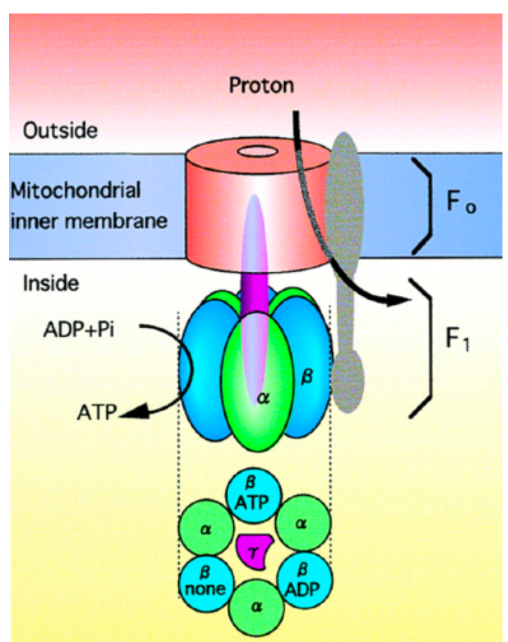


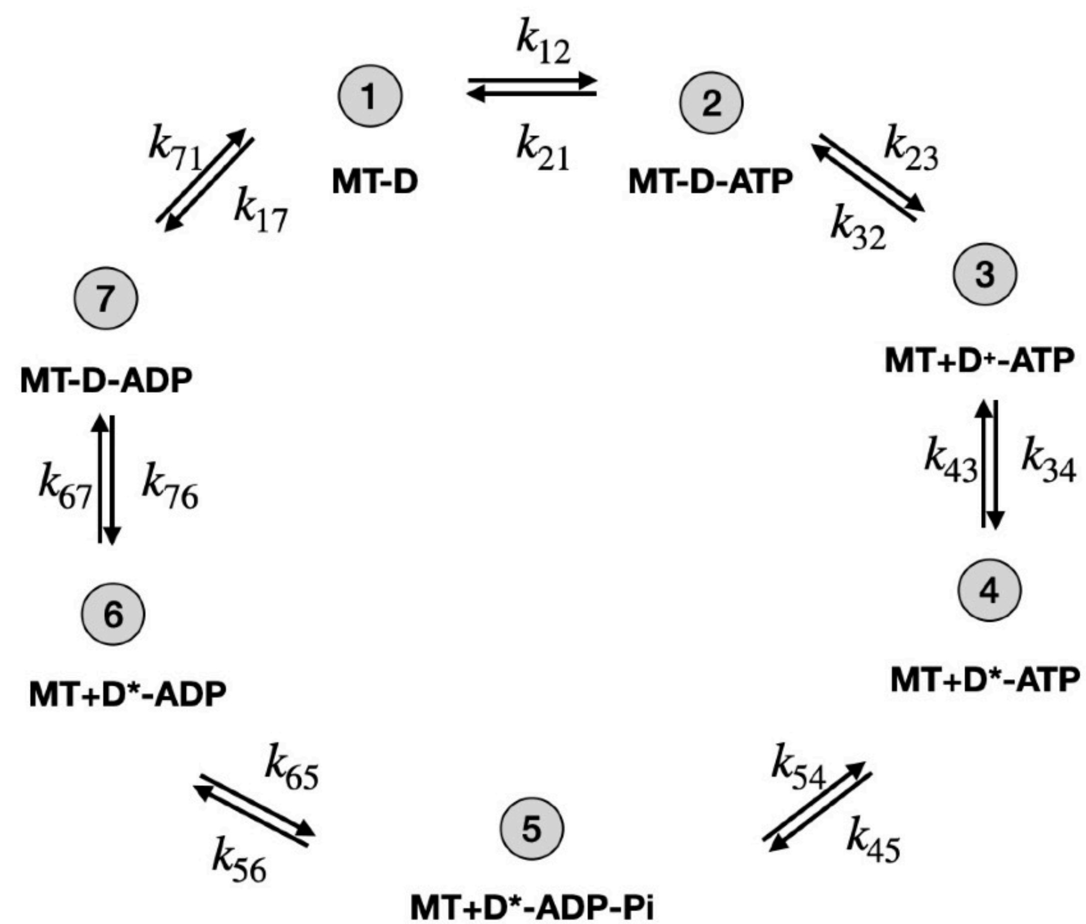
F_1-ATPase



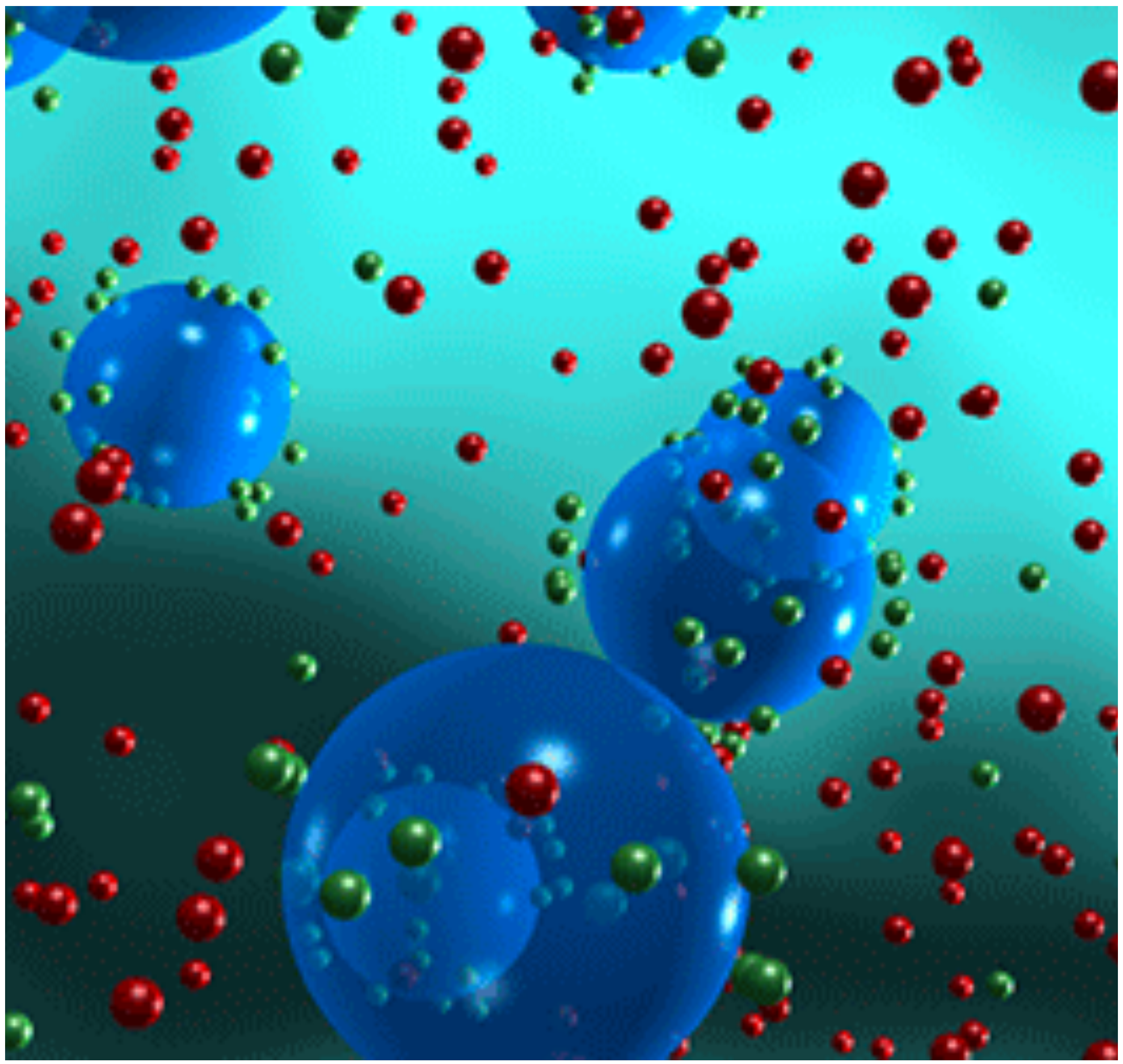
arXiv:1710.03499 (2017)

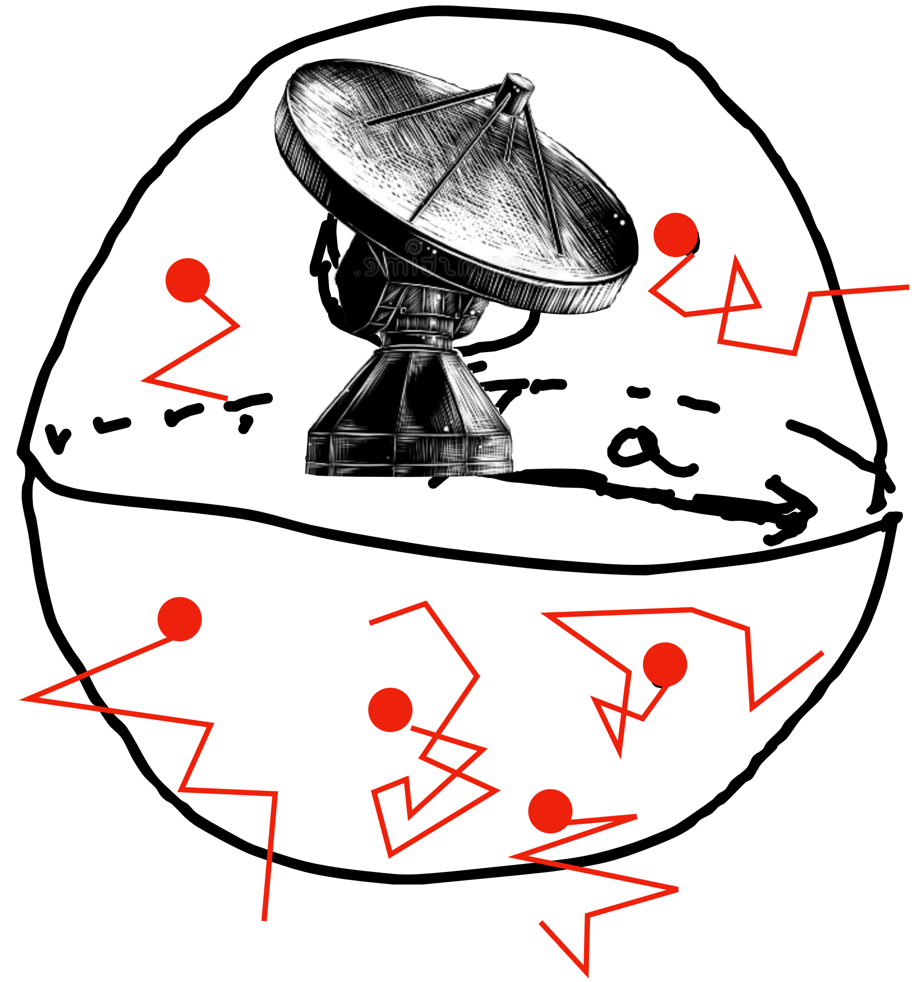


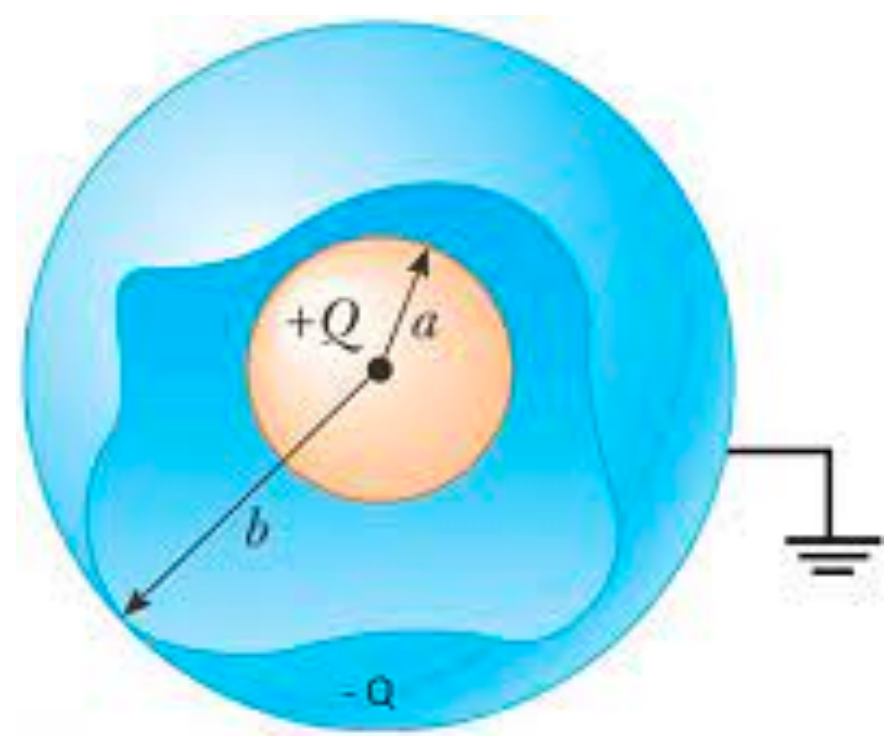




Cell sensing





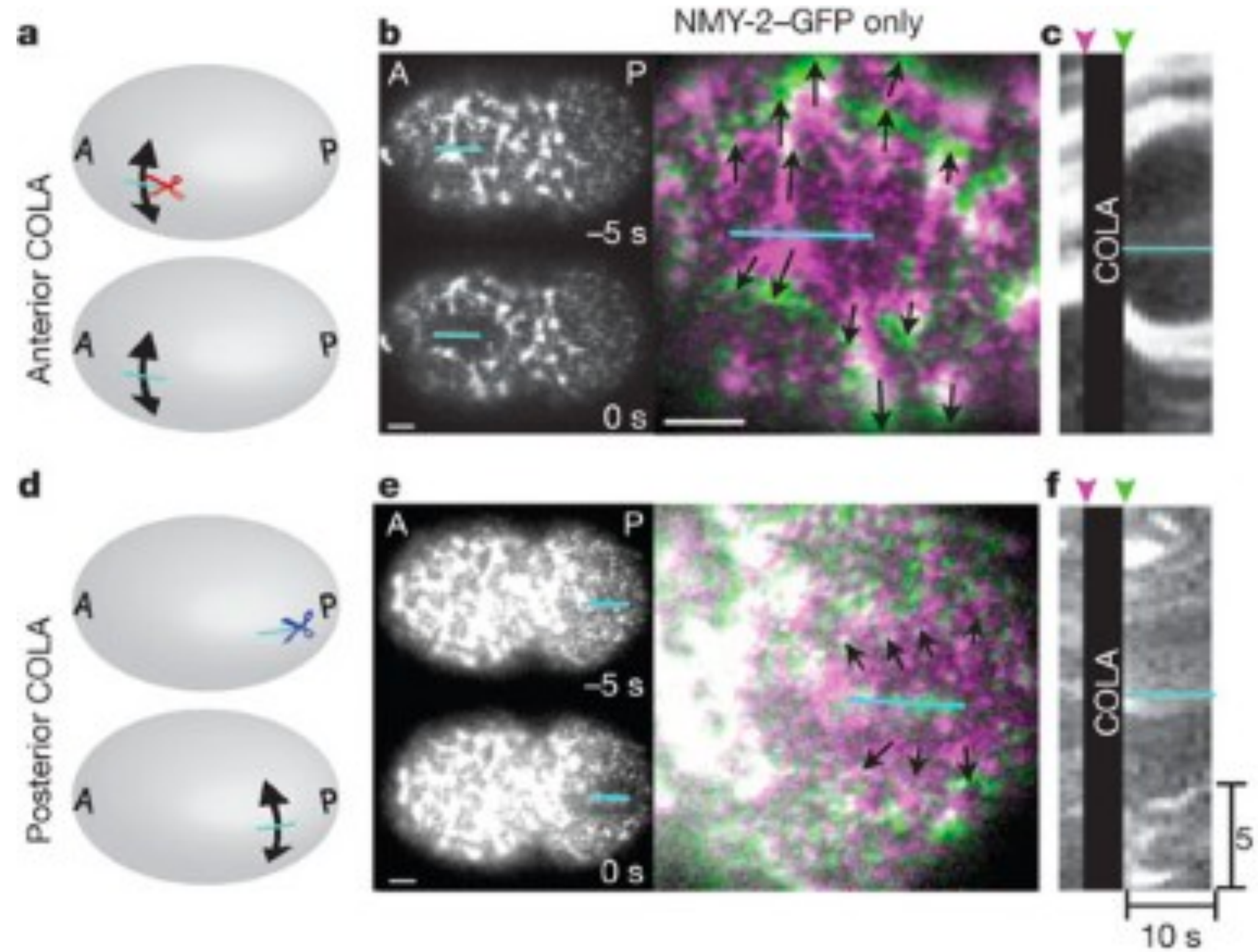


Further applications of biophysics

Beyond motors

Development of C. Elegans embryo

C. Elegans



[Nature](#) *467, 617–621 (2010)*

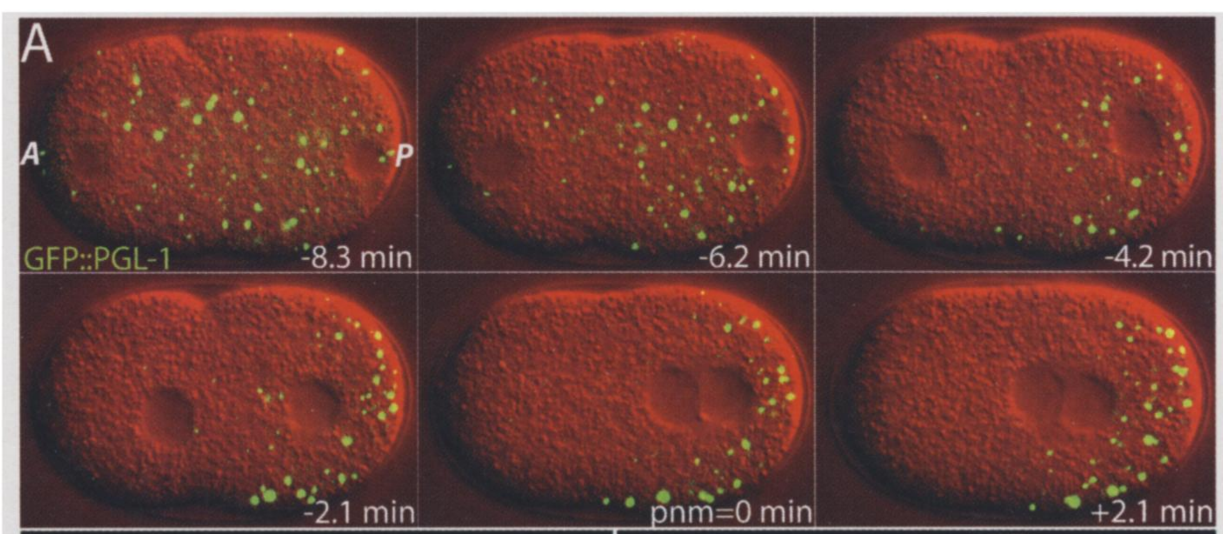
Physics tools: classical fluid dynamics, differential geometry

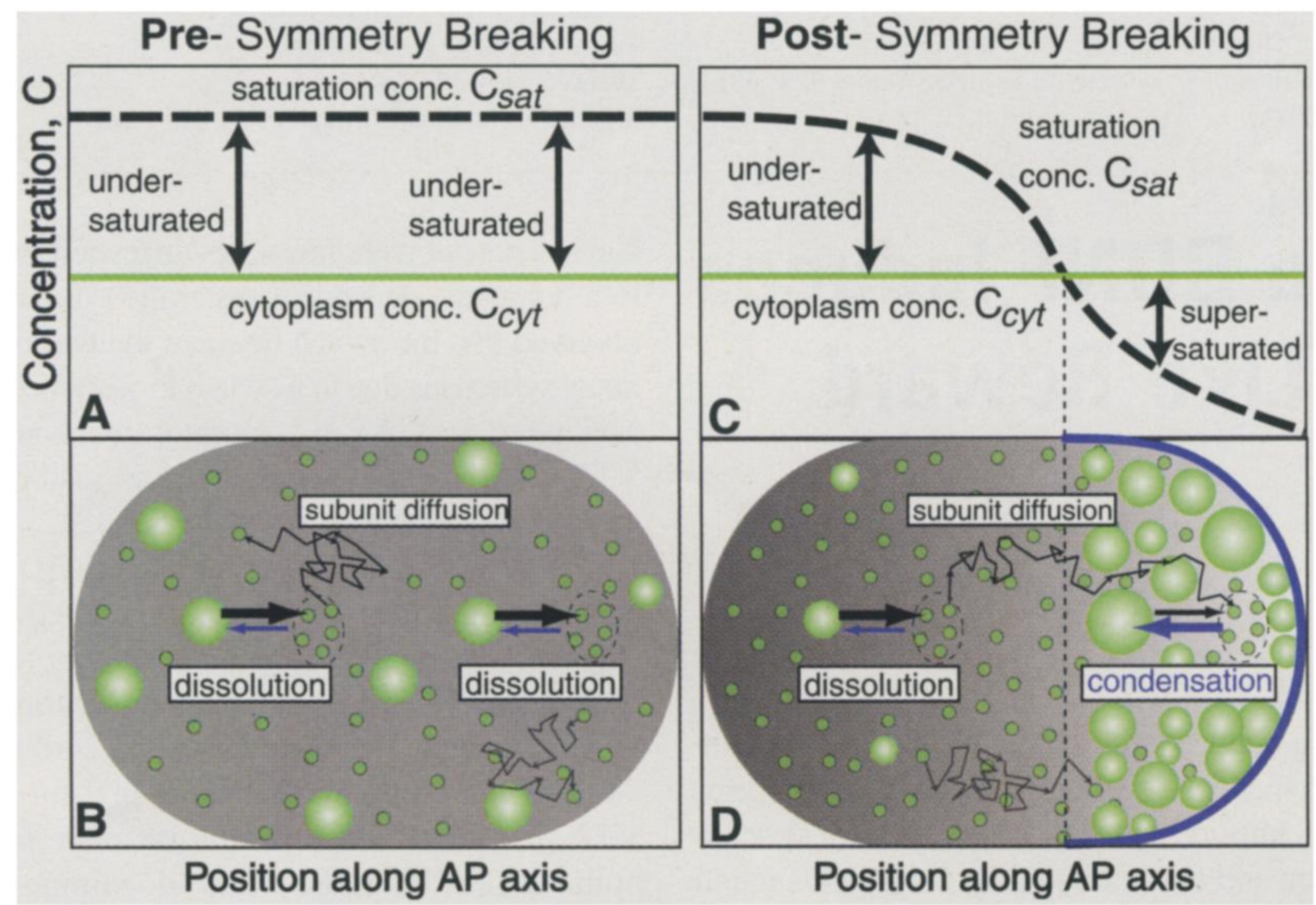
Membrane-free compartments

Science
AAAS

Germline P Granules Are Liquid Droplets That Localize by Controlled Dissolution/Condensation

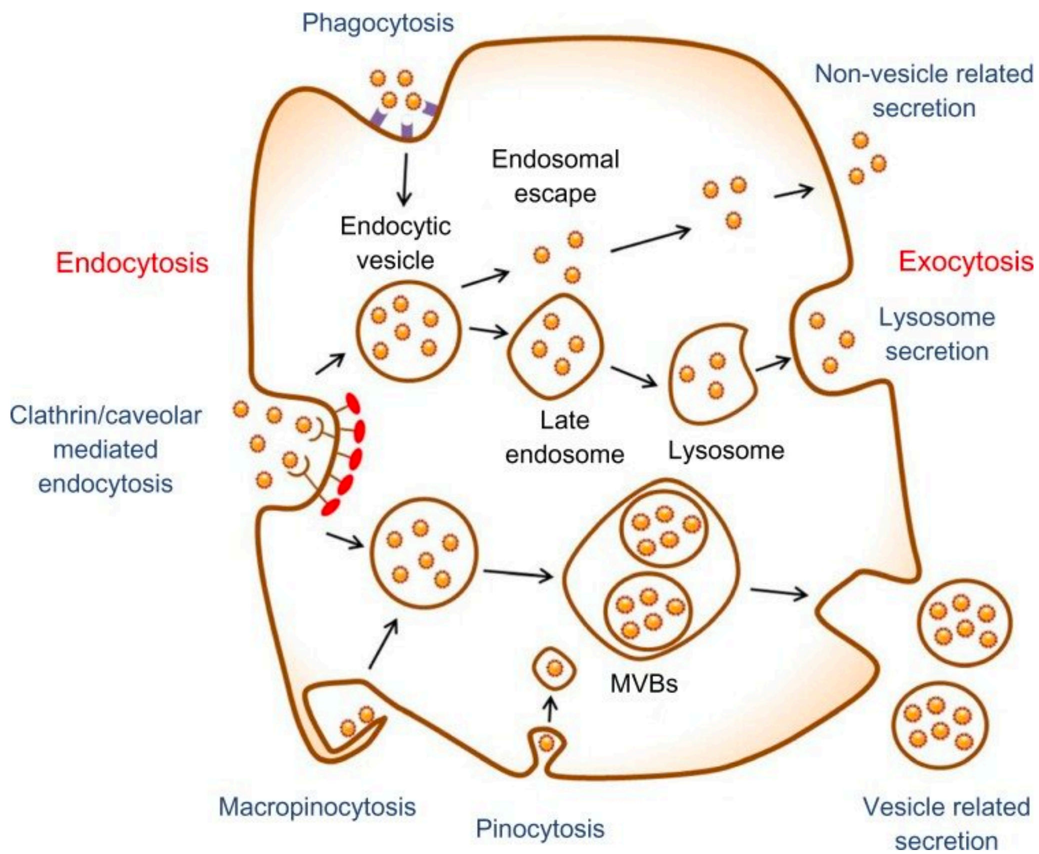
Clifford P. Brangwynne,[1,2,3] Christian R. Eckmann,[1] David S. Courson,[3] Agata Rybarska,[1] Carsten Hoege,[1] Jöbin Gharakhani,[2,3] Frank Jülicher,[2,3] Anthony A. Hyman[1,3]*

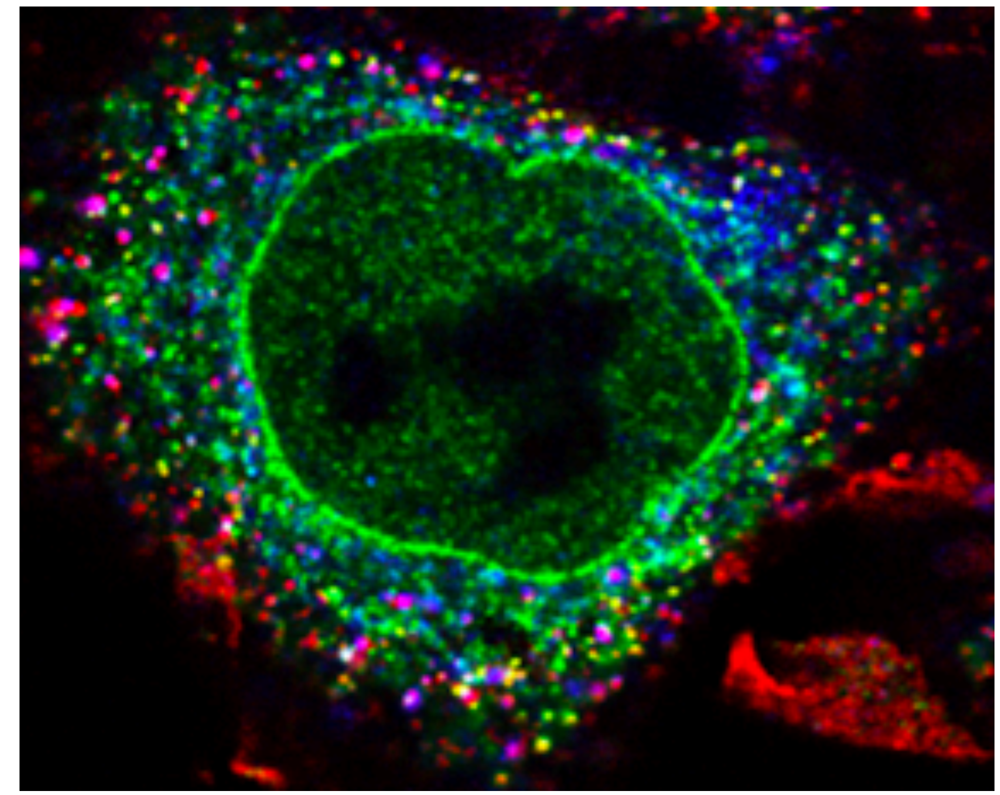




Physics tools: equilibrium thermodynamics, phase transitions

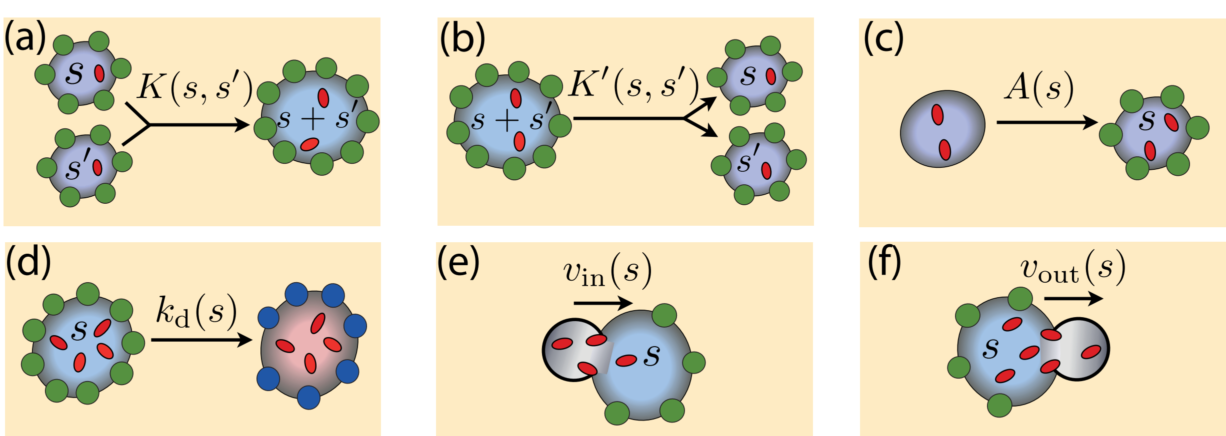
Endocytosis in human cells





Imaging of endocytic vesicles (Zerial Lab)

B



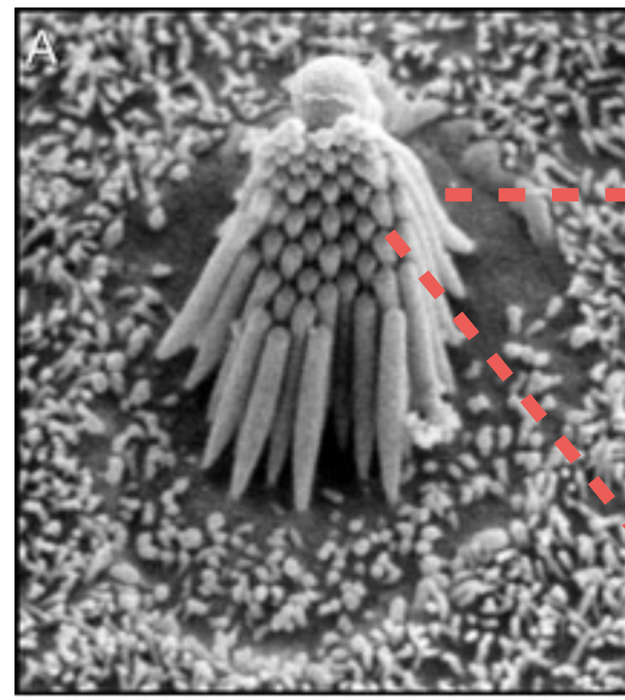
$$\frac{\partial n(s,t)}{\partial t} = \frac{1}{2}\int_0^s K(s', s-s')n(s')n(s-s')ds' - \int_0^\infty K(s,s')n(s)n(s')ds' \quad \text{(a)}$$

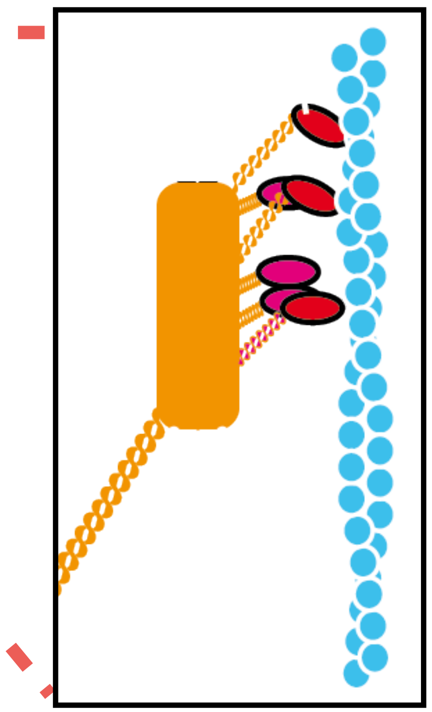
$$+\int_0^\infty K'(s,s')n(s+s')ds' - \frac{1}{2}\int_0^s K'(s', s-s')n(s)ds' \quad \text{(b)}$$

$$+\underbrace{A(s)}_{\text{(c)}} - \underbrace{k_{\rm d}(s)n(s)}_{\text{(d)}} - \underbrace{\frac{\partial}{\partial s}(v_{\rm in}(s)n(s))}_{\text{(e)}} + \underbrace{\frac{\partial}{\partial s}(v_{\rm out}(s)n(s))}_{\text{(f)}}$$

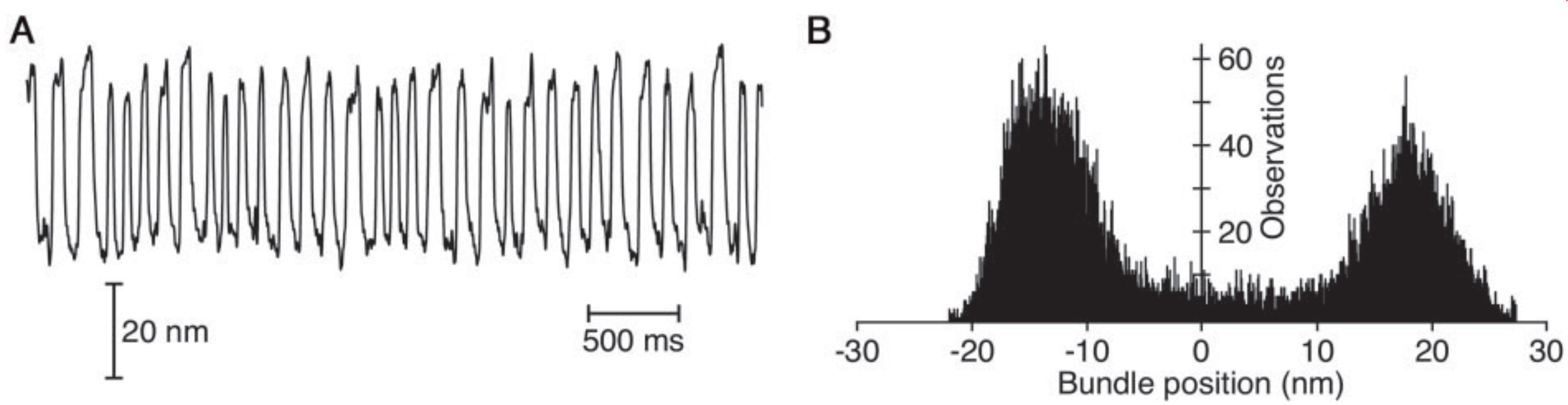
Physics tools:
statistical physics, population dynamics

Hearing in bullfrogs





P. Martin et. al, PNAS (2011)



Physics tools: dynamical systems, stochastic thermodynamics

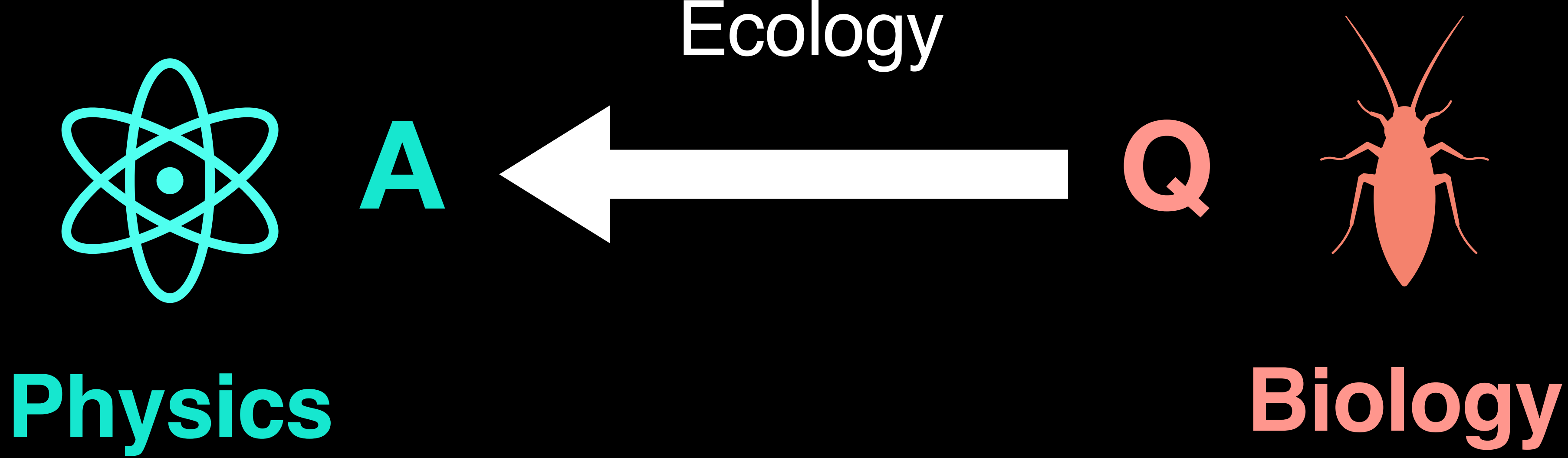
A two-way journey

Biophysics

Bioinformatics

Mathematical biology

Ecology



A two-way journey

Biophysics

Bioinformatics

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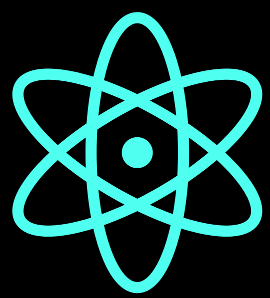
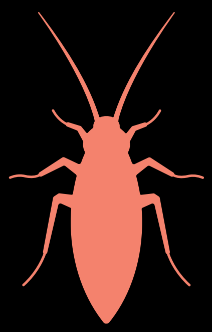
Ecology



A ⟵ **Q**



Physics **Biology**

Q

How can molecular motors move such big loads ?

How do birds fly in flocks?

A

Conversion of chemical energy into mechanical work

Collective phenomena of complex systems

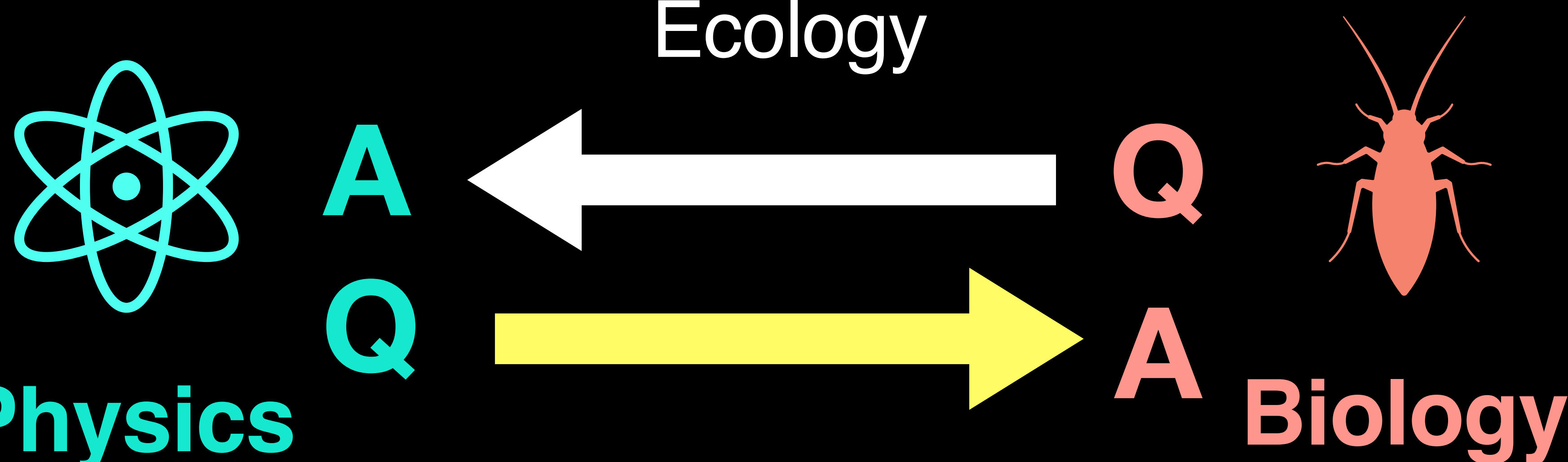
A two-way journey

Biophysics

Bioinformatics

Mathematical biology

Ecology



Active Matter

Stochastic thermodynamics

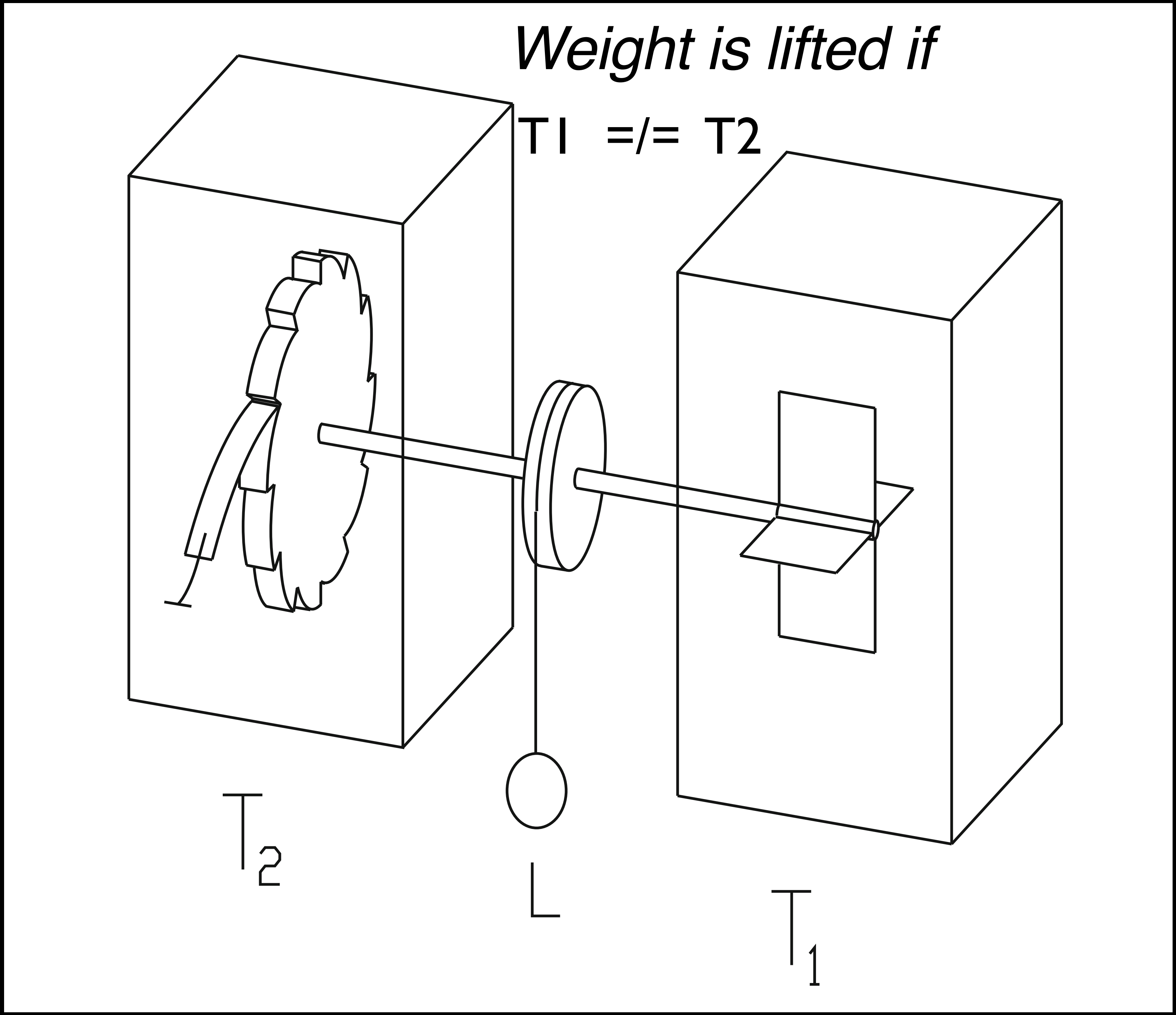
Tribiology

Q *What is the heat capacity of a bacteria?*

Active matter

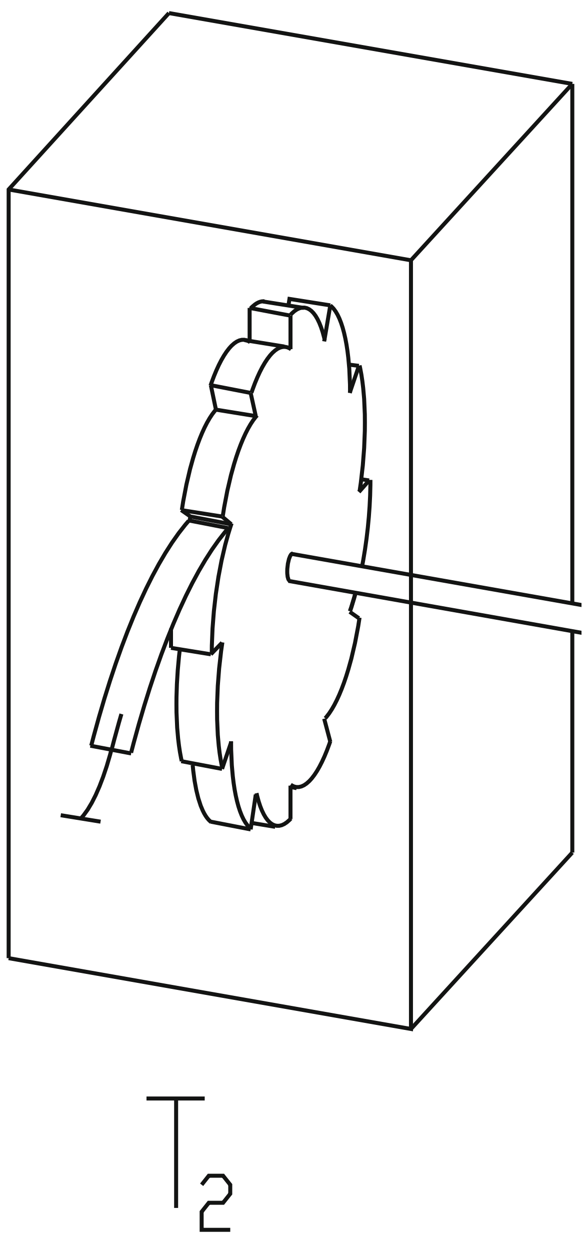
Recent experimental insights

Feynman's Ratchet



1. Feynman, Leighton, Sands, Hafner, Am.J.Phys. **33**,750 (1965)

Feynman's Ratchet



Without an external torque the wheel DOES NOT rotate

1. Feynman, Leighton, Sands, Hafner, Am.J.Phys.**33**,750 (1965)

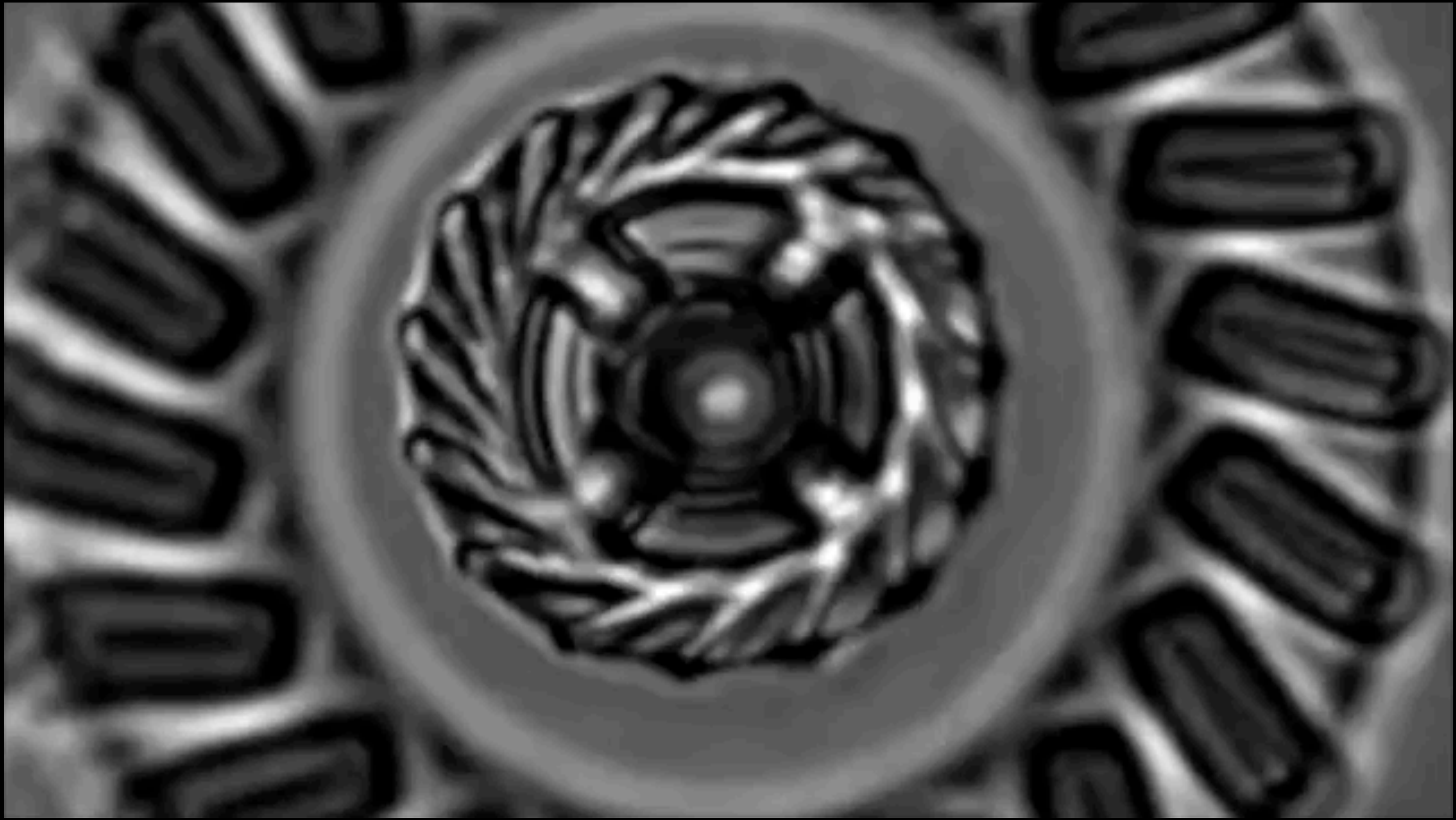
Bacterial ratchets

R. Di Leonardo et. al, PNAS **107** 9541 (2010)

Bacterial ratchets

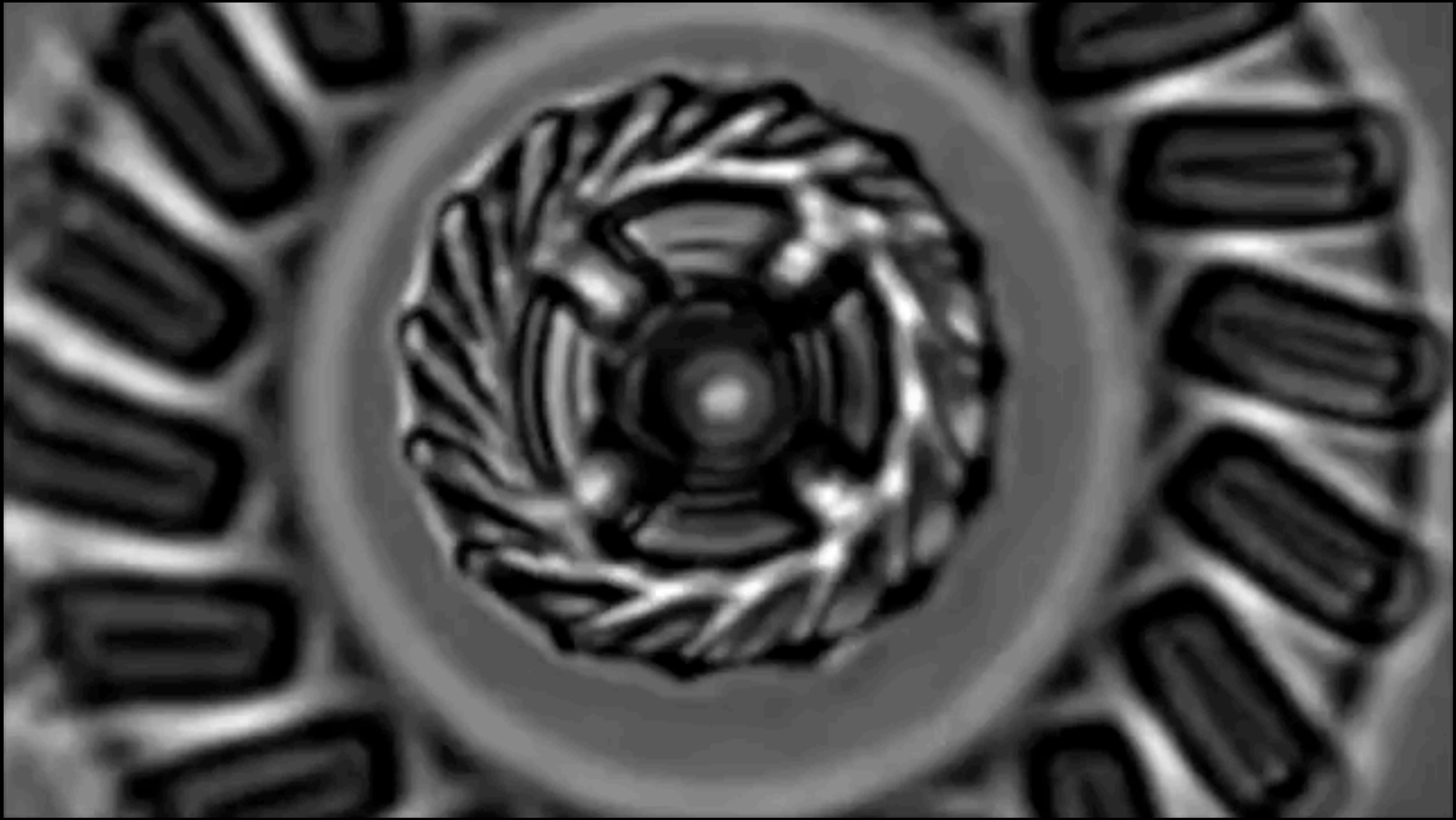
R. Di Leonardo et. al, PNAS **107** 9541 (2010)

Bacterial ratchets



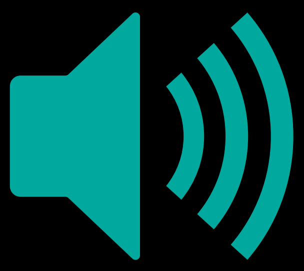
G Vizsnyiczai et. al, Nature Comms. 8 (1), 1-7(2017)

Bacterial ratchets



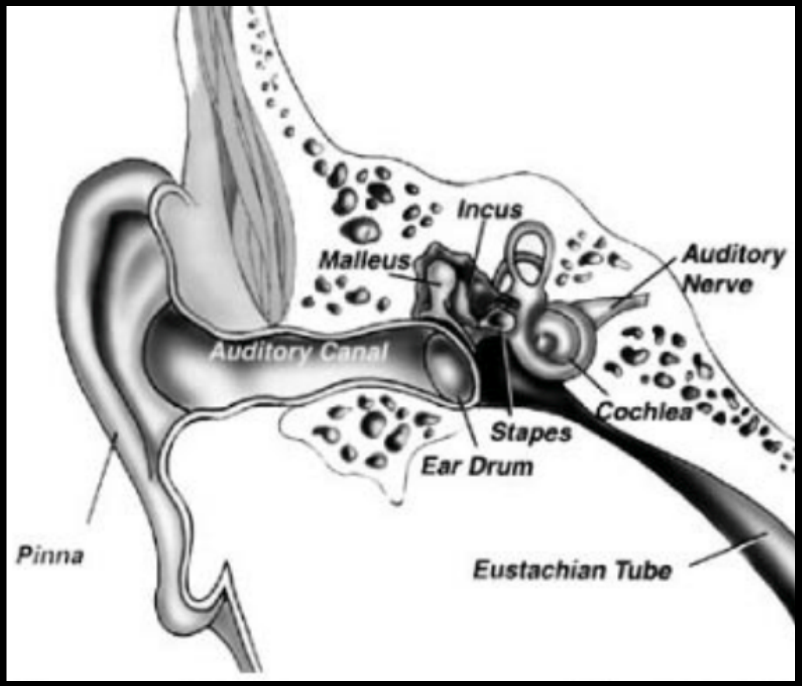
G Vizsnyiczai et. al, Nature Comms. 8 (1), 1-7(2017)

“Photoelectric effect” in active matter



Sound

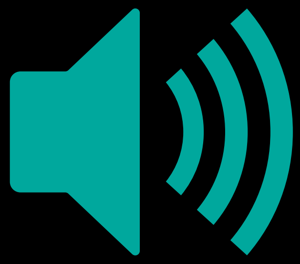
Mechanical stimuli



Electric current

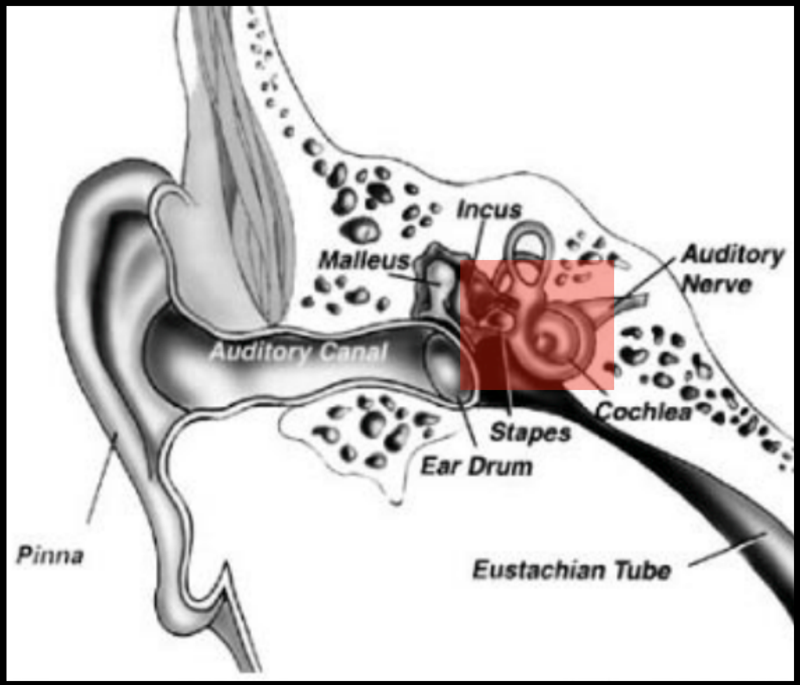
To the auditory nerve

“Photoelectric effect” in active matter



Sound

Mechanical stimuli



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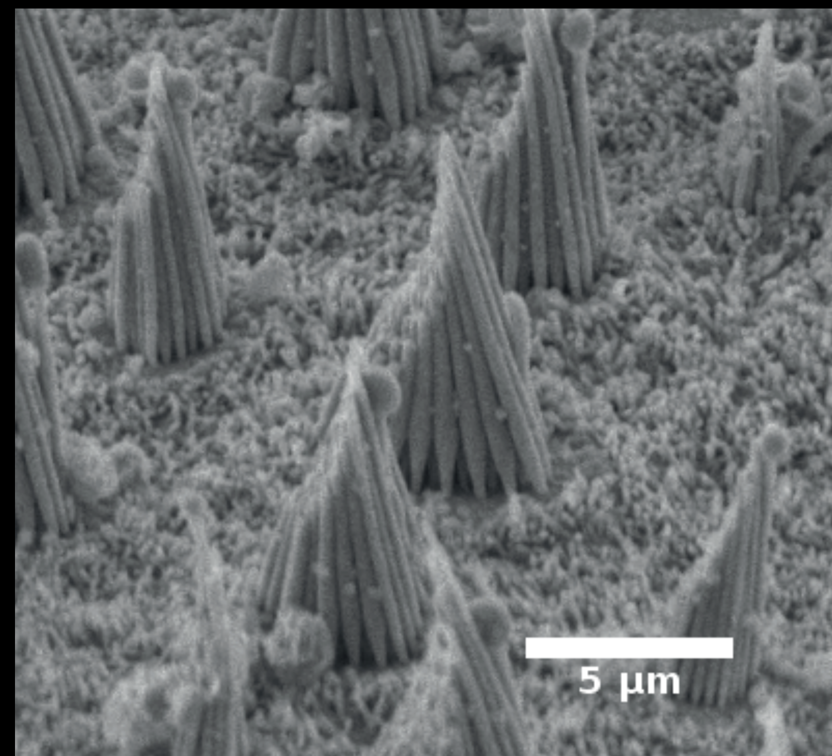
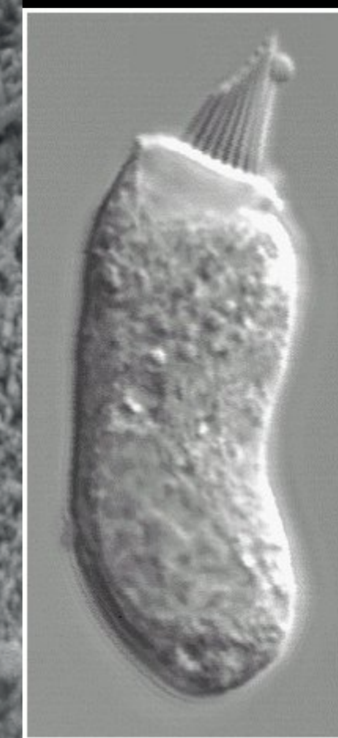


Epithelium bullfrog’s sacculus
(P. Martin Lab)



Ear hair cell
(A. J. Hudspeth)

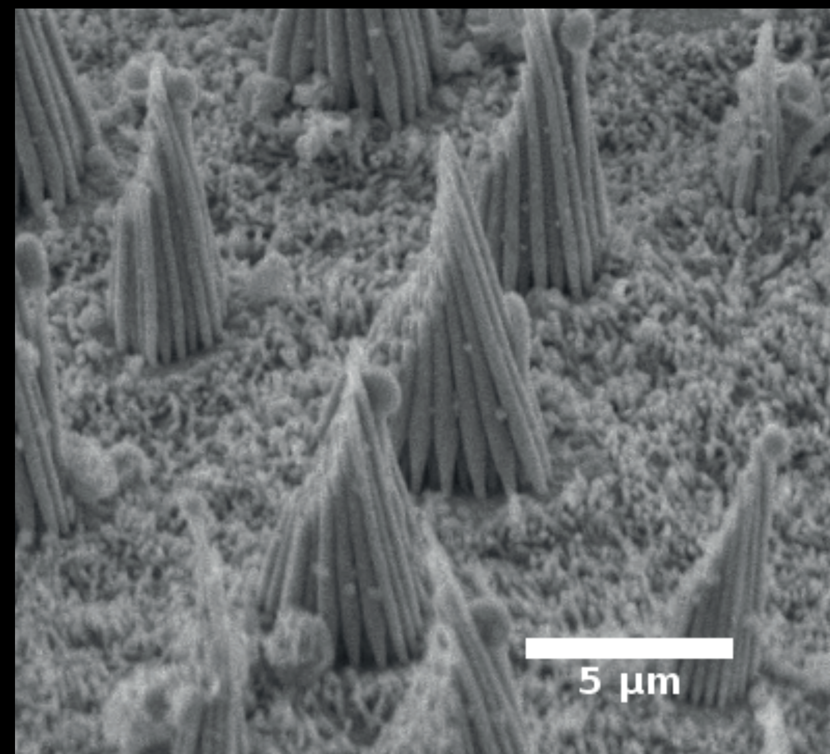
Electric current

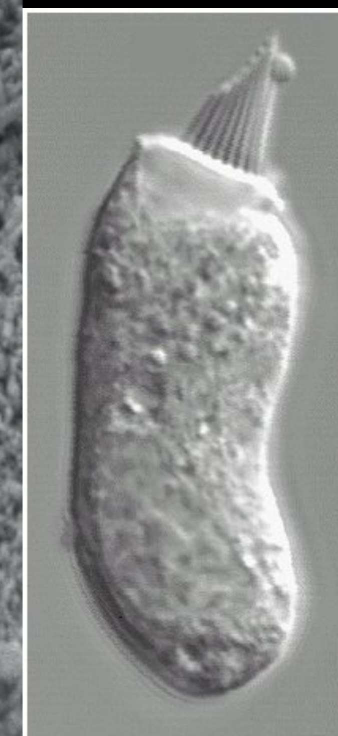
To the auditory nerve

"Photoelectric effect" in active matter

Sound

Mechanical stimuli





Electric current

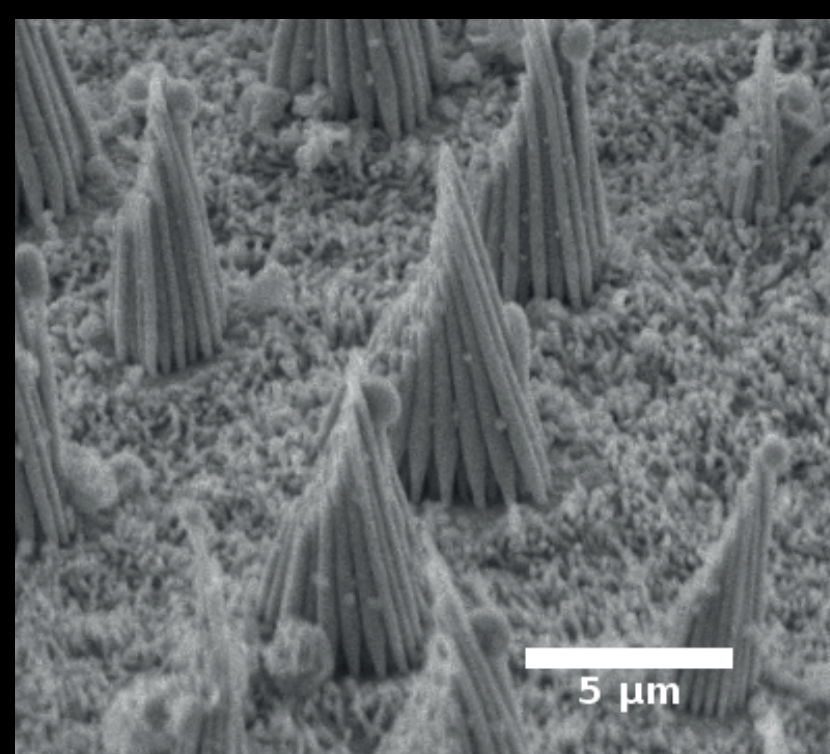
To the auditory nerve

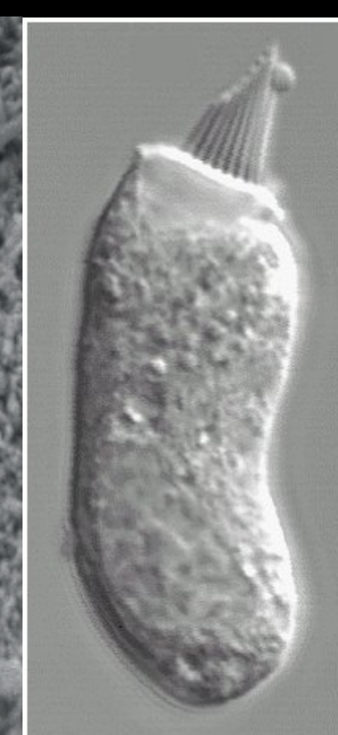
Epithelium bullfrog's sacculus
(P. Martin Lab)

Ear hair cell
(A. J. Hudspeth)

Light

UV light

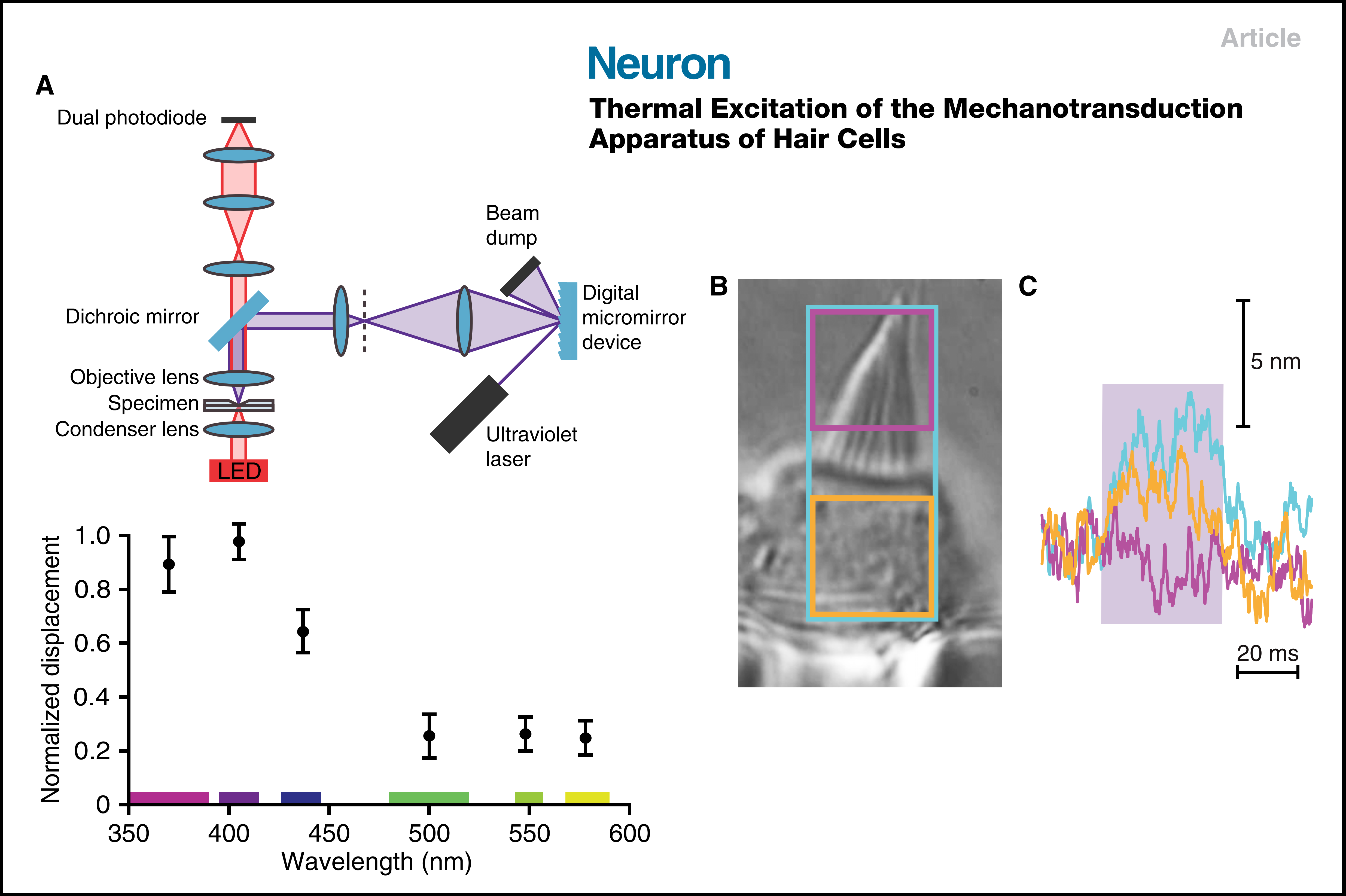




Electric current

To the auditory nerve

“Photoelectric effect” in active matter

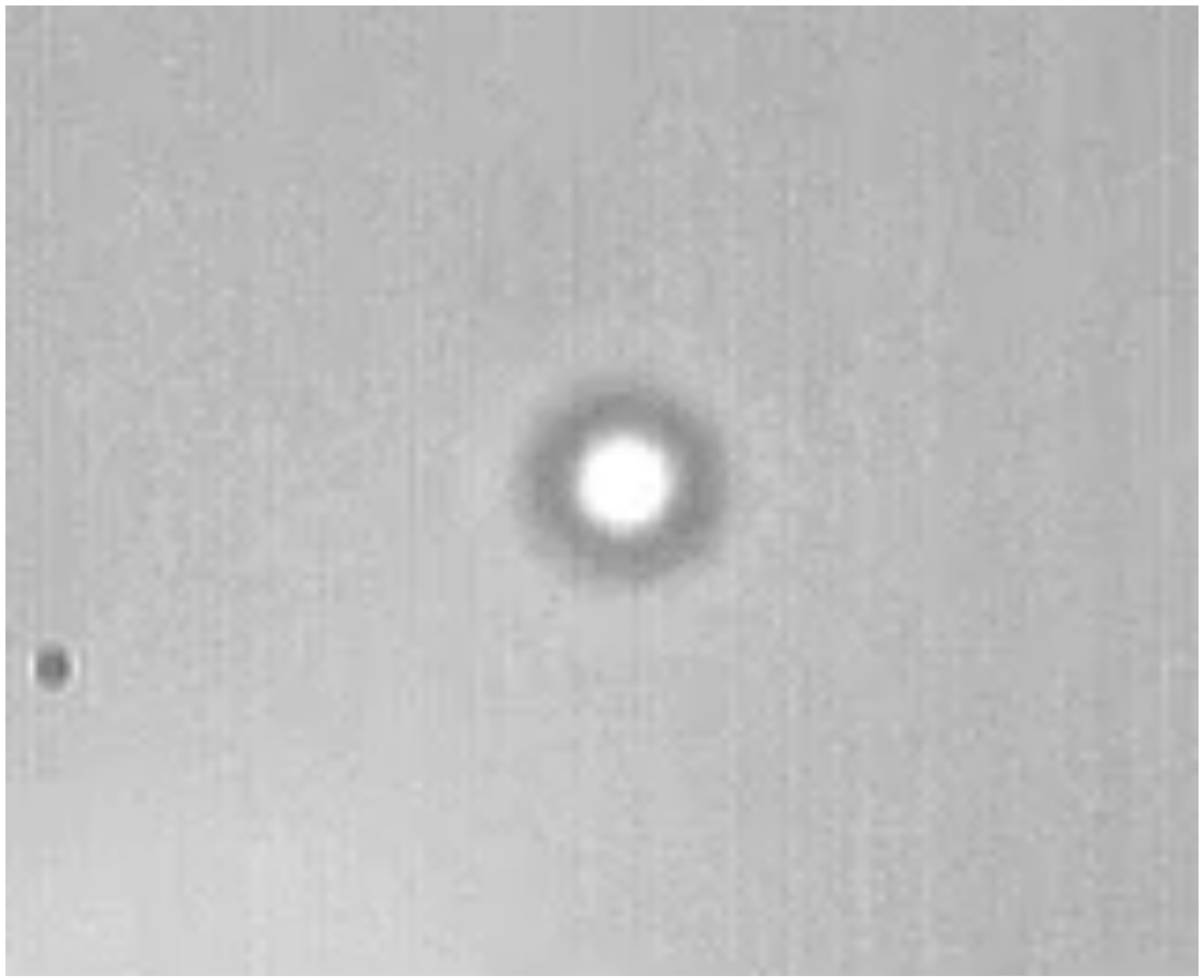


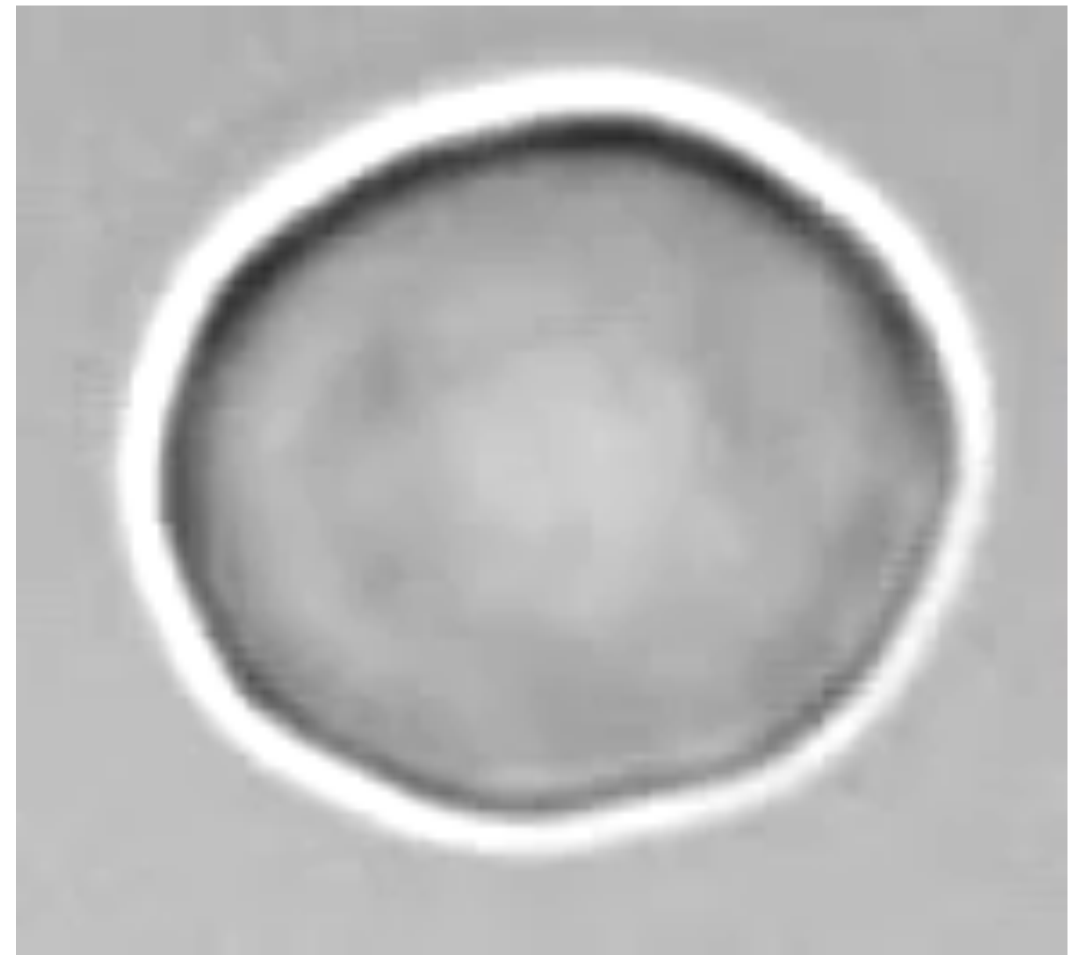
Azimzadeh, Fabella, Kasteh, Hudspeth, Neuron (2018)

Stochastic thermodynamics

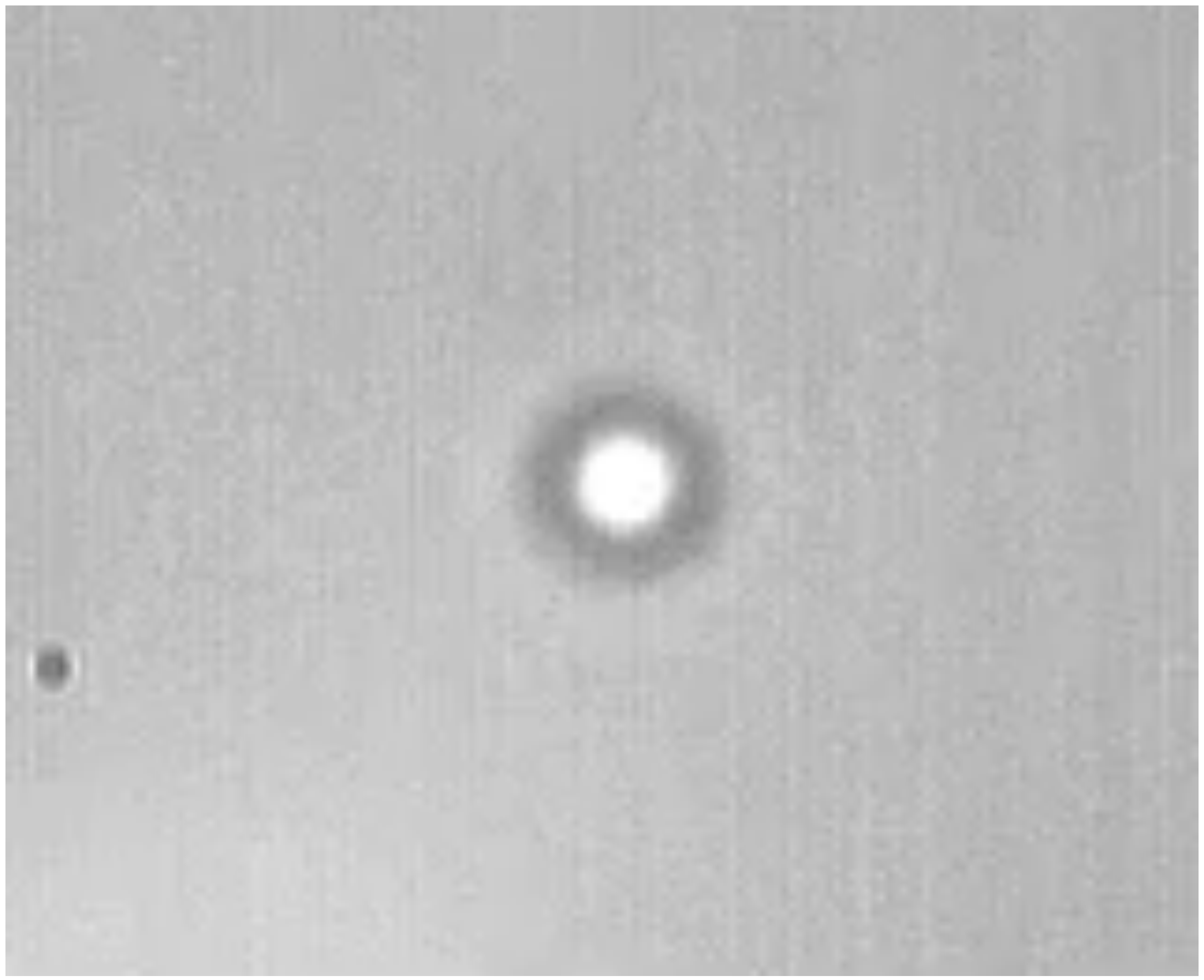
Searching for universal laws governing biological phenomena

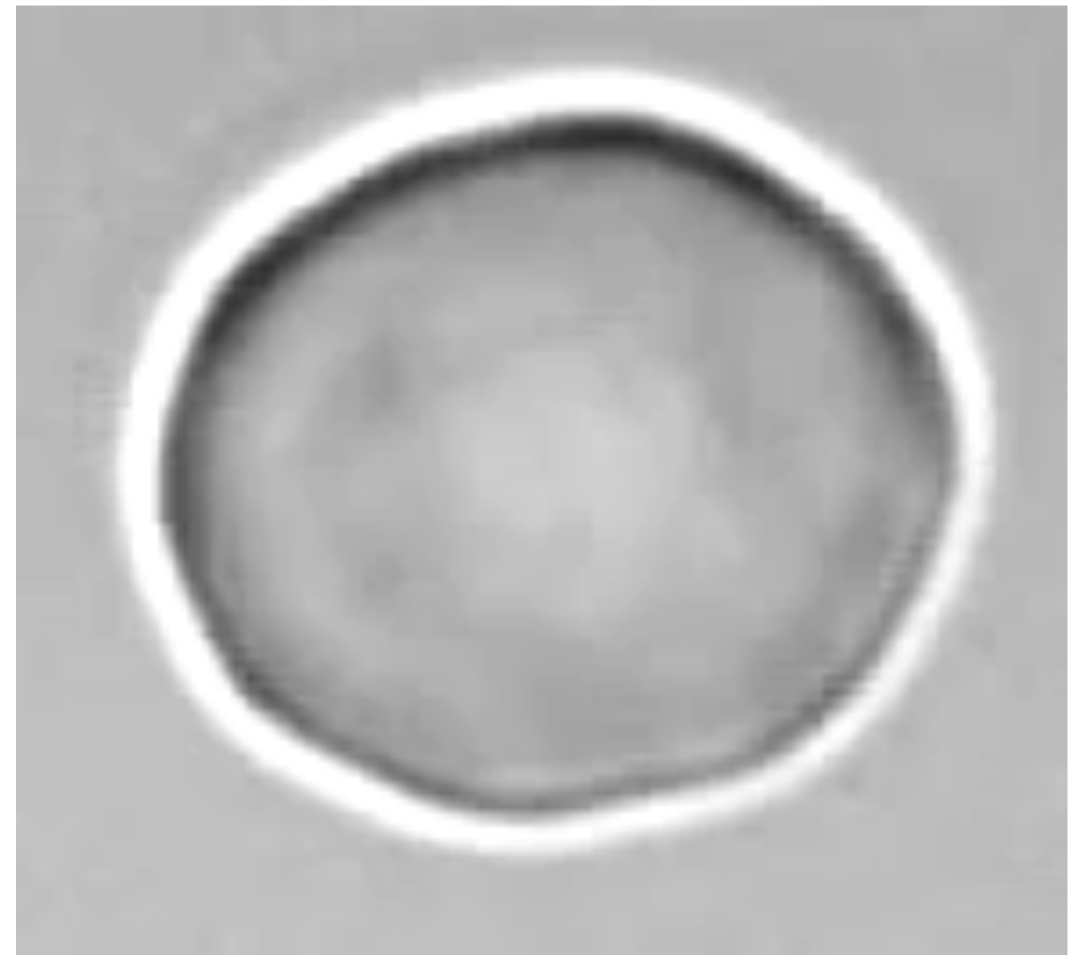
Nonequilibrium signatures of life?





Nonequilibrium signatures of life?





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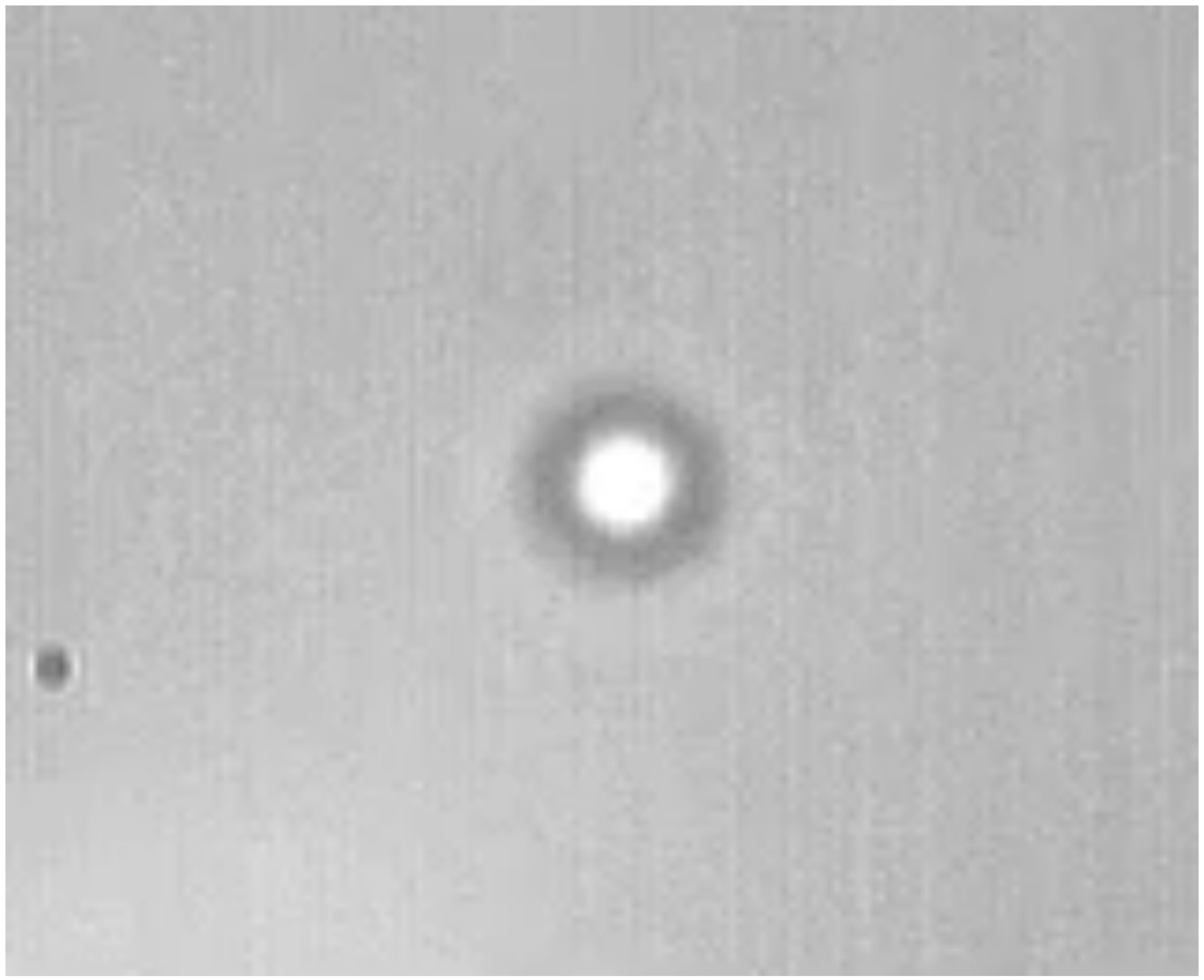
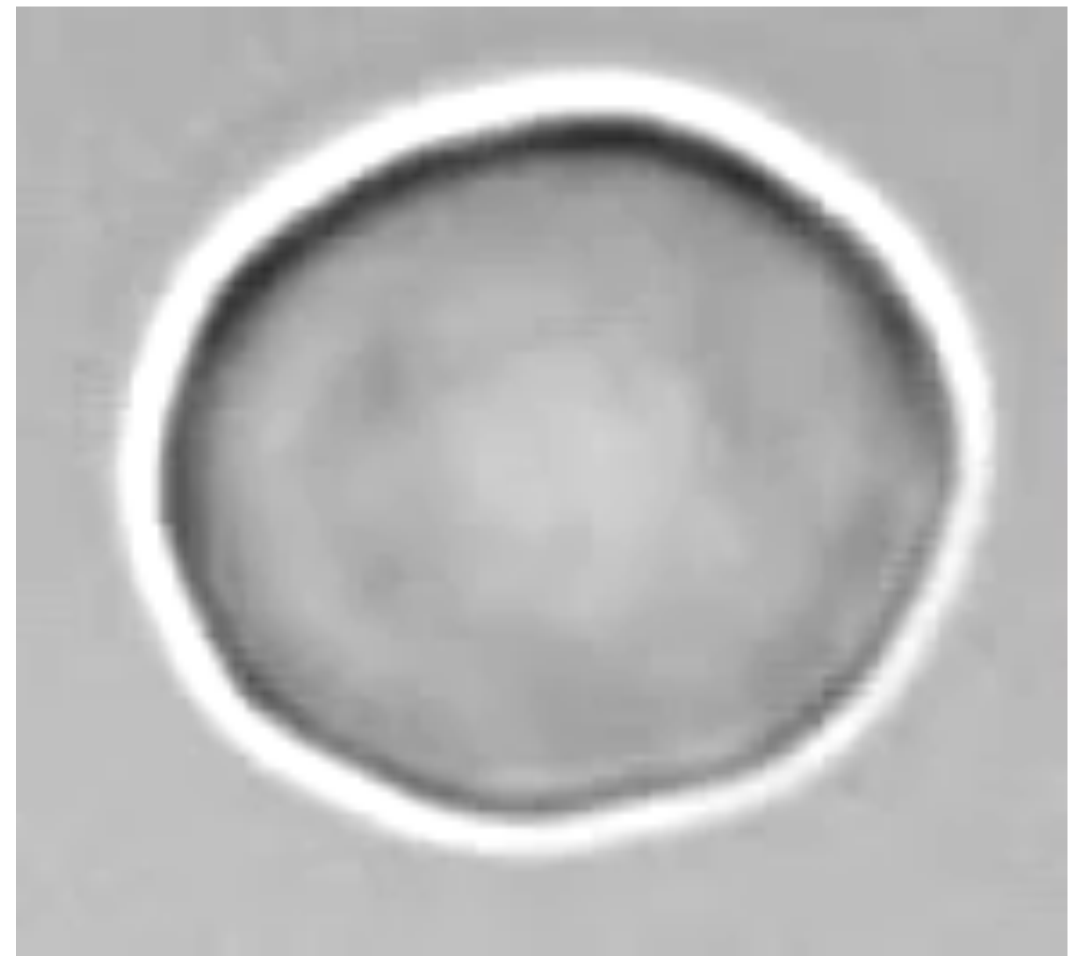


Colloidal particle

“Passive” equilibrium dynamics

Reversibility

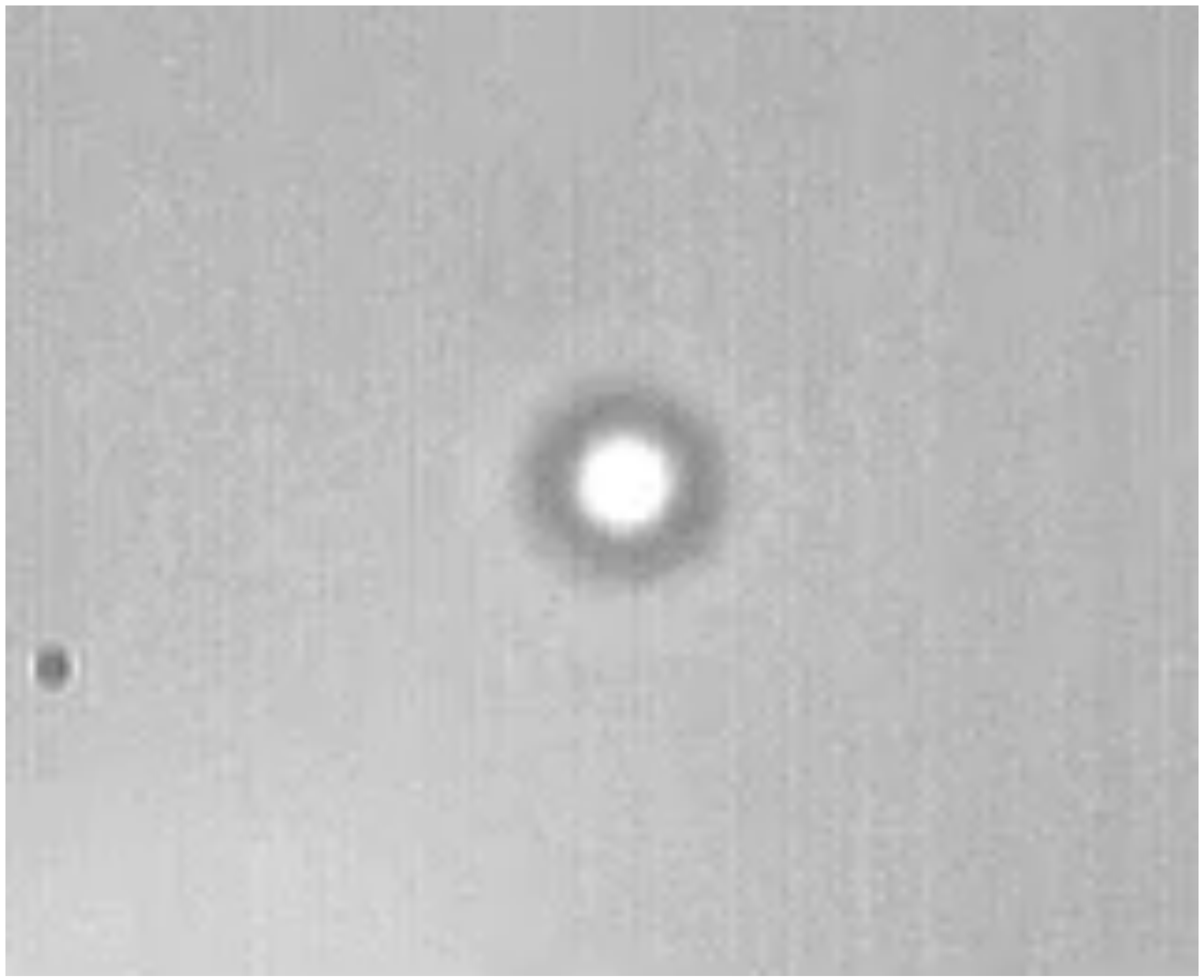


Red-blood cell

“Active” nonequilibrium dynamics

Irreversibility, heat dissipation

Nonequilibrium signatures of life?



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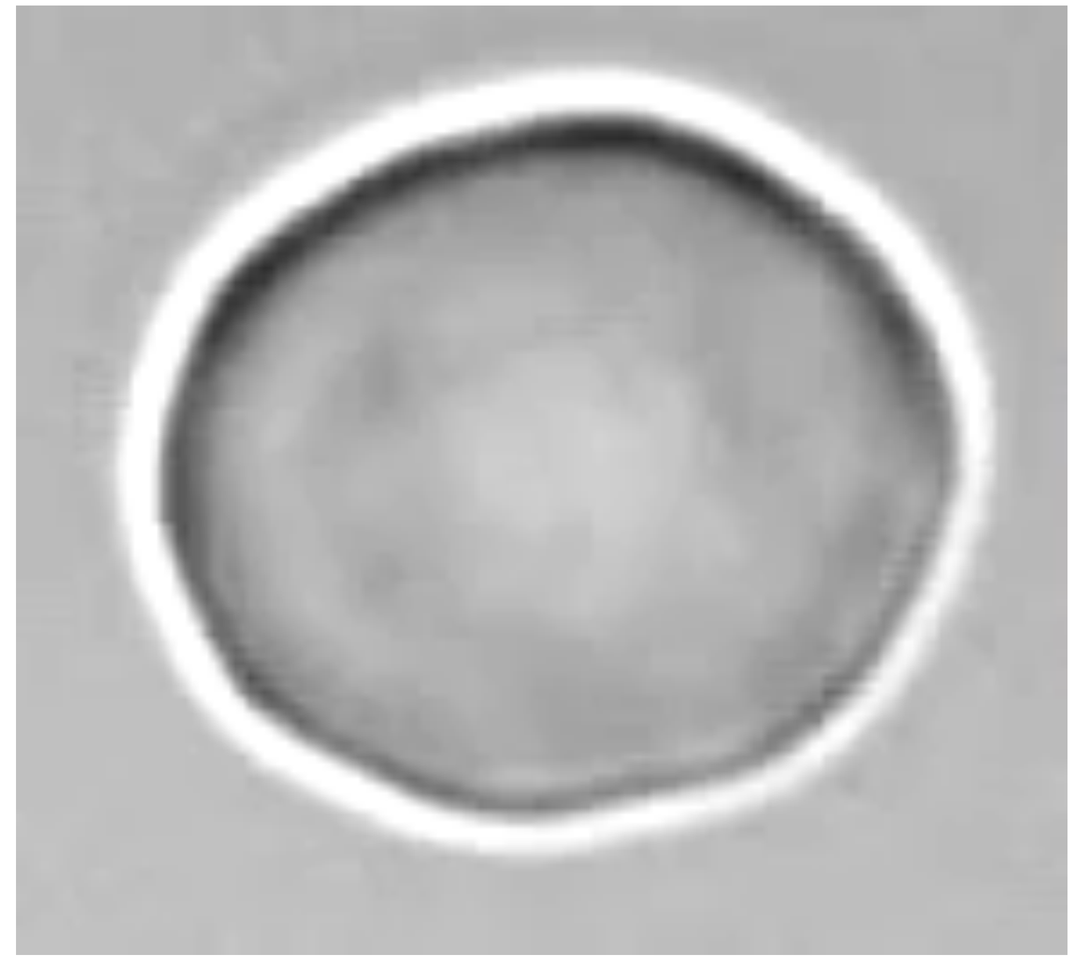

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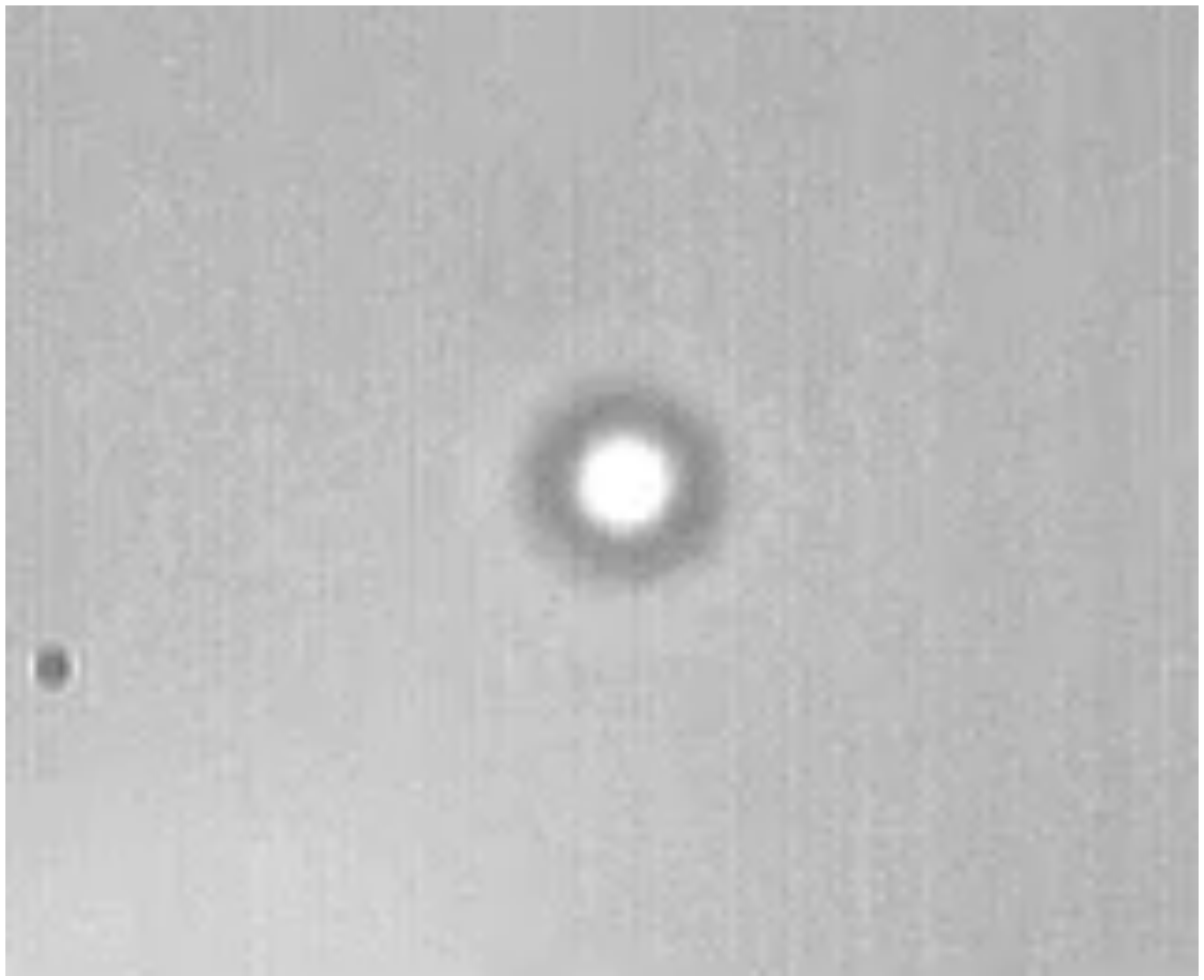

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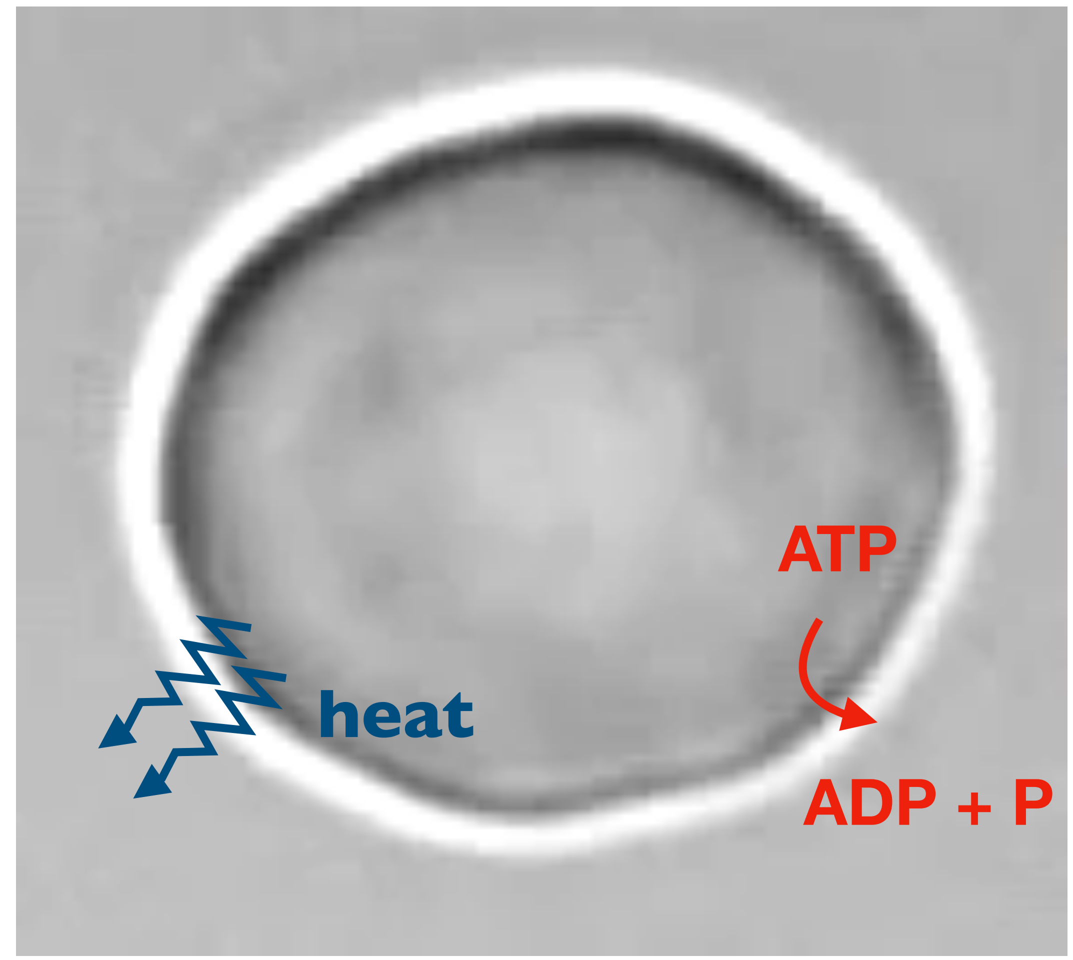

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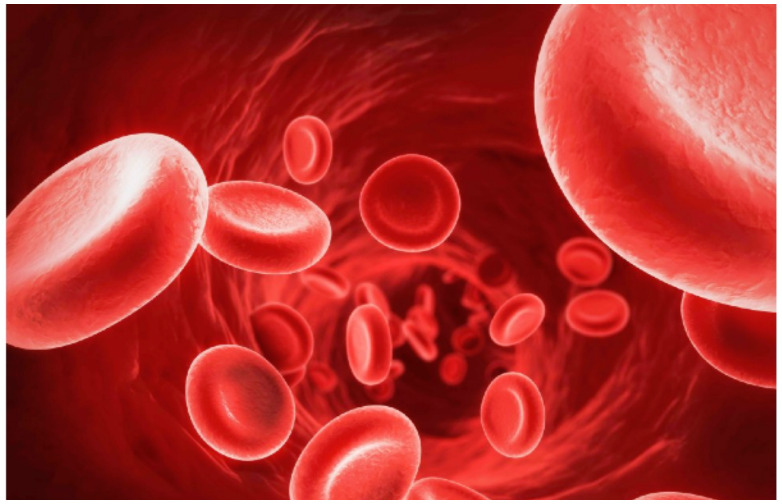
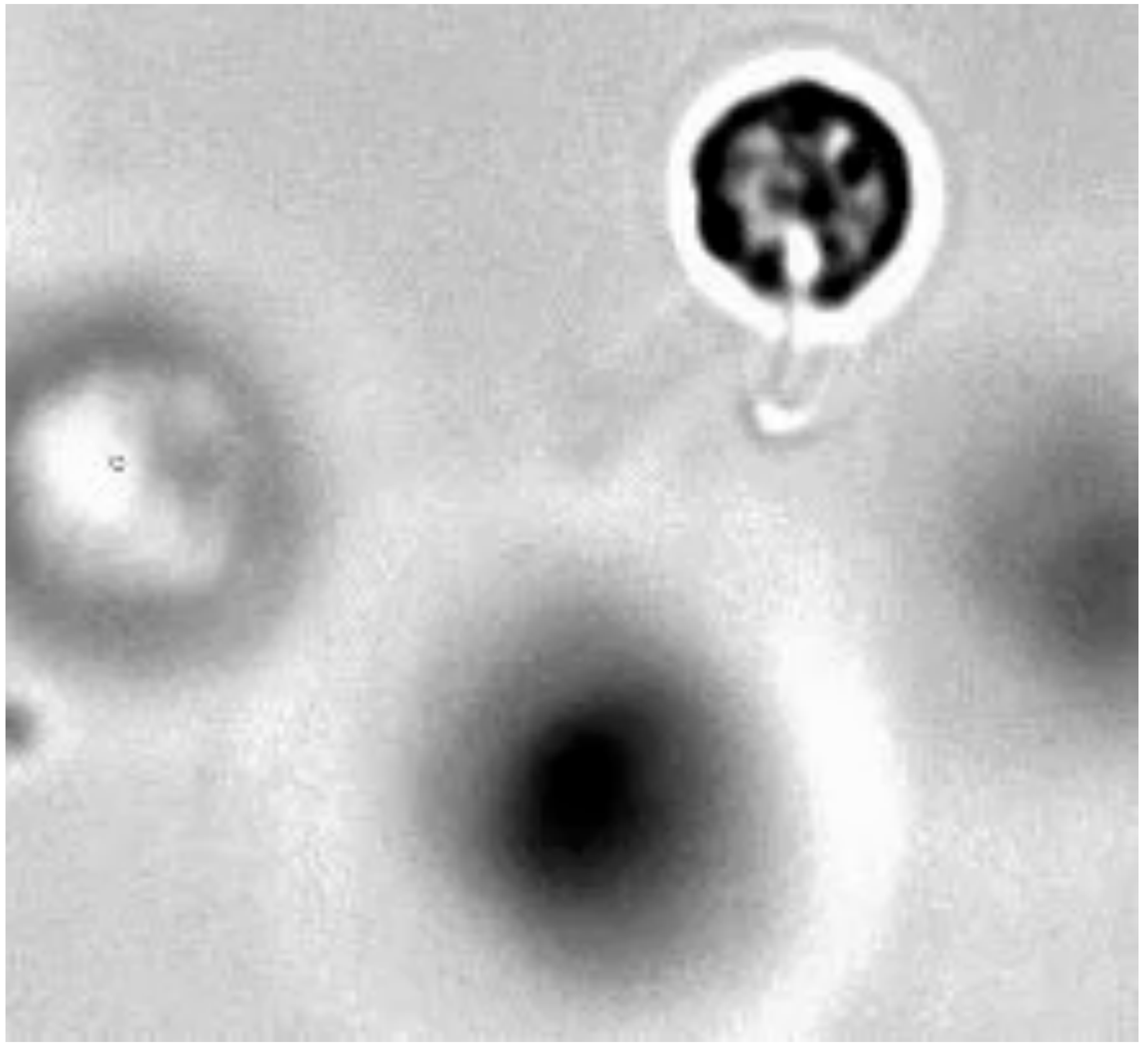


Red Blood Cell:
weak irreversibility

Swimming Clamydomonas:
strong irreversibility



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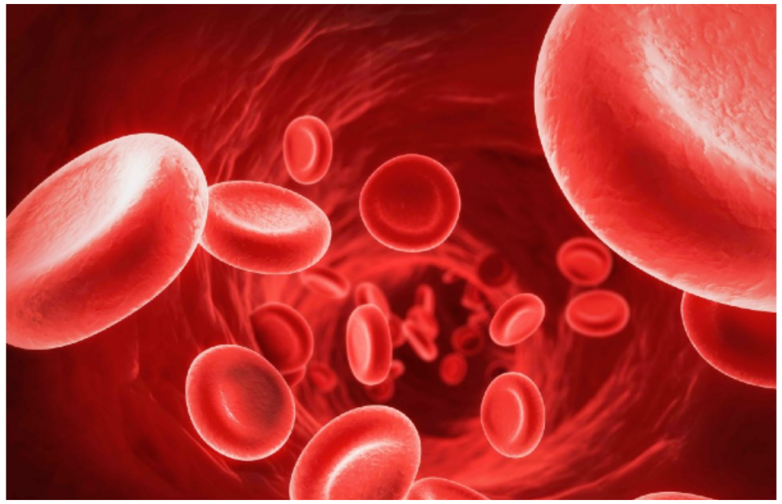

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Swimming Clamydomonas:
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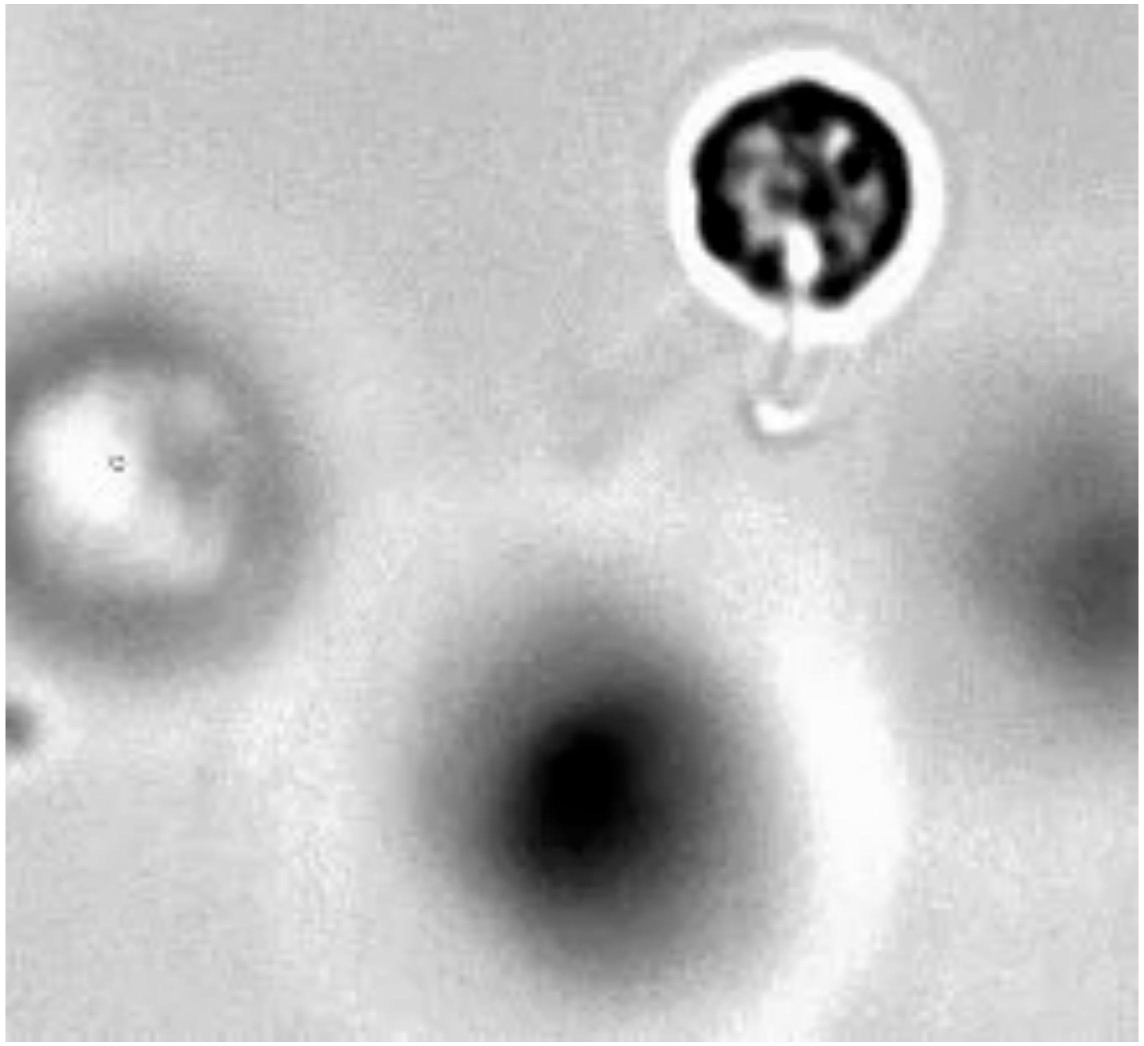
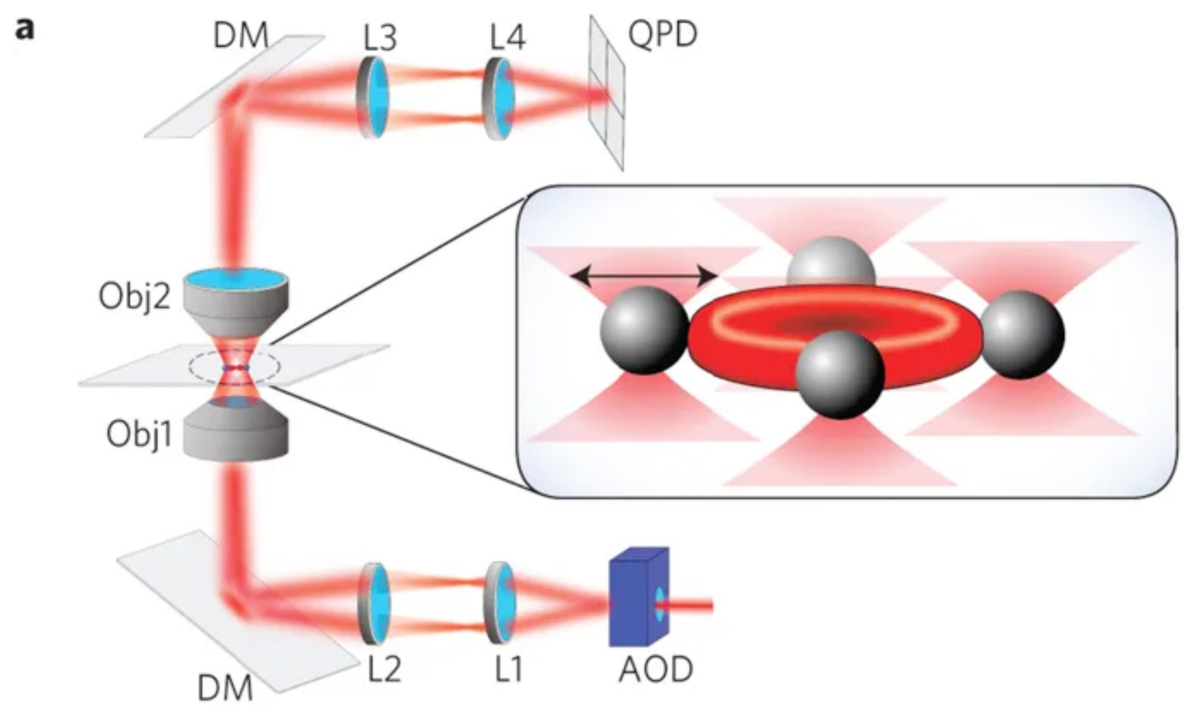
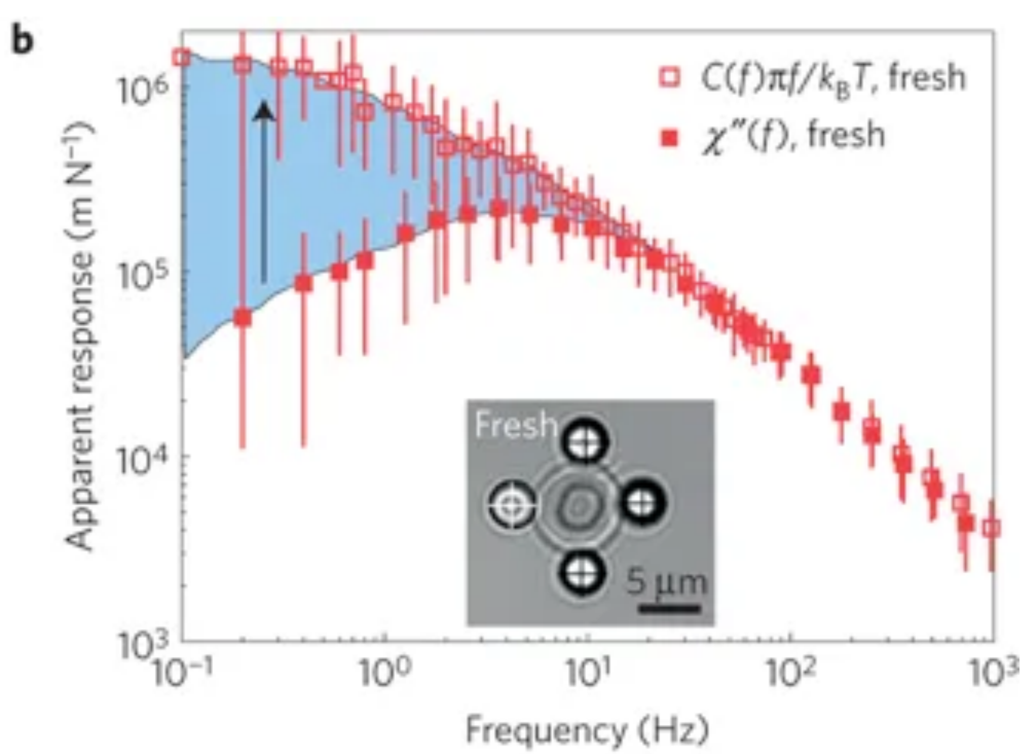
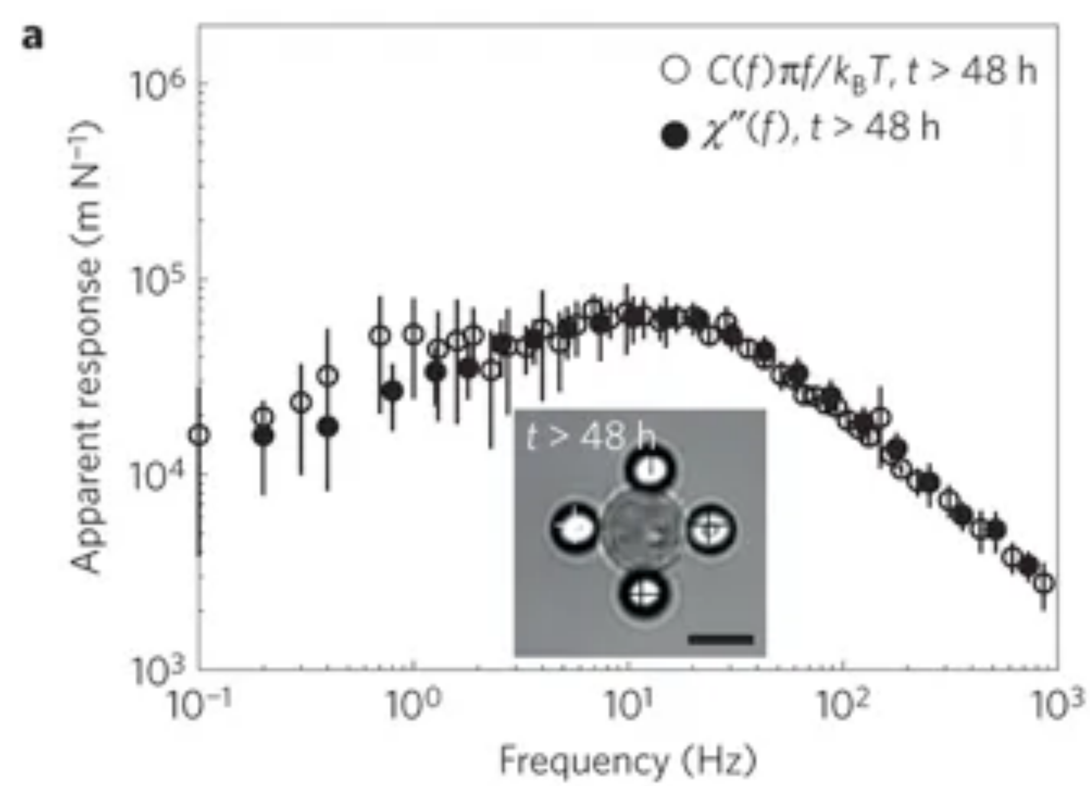


Fluctuation-response of red blood cells





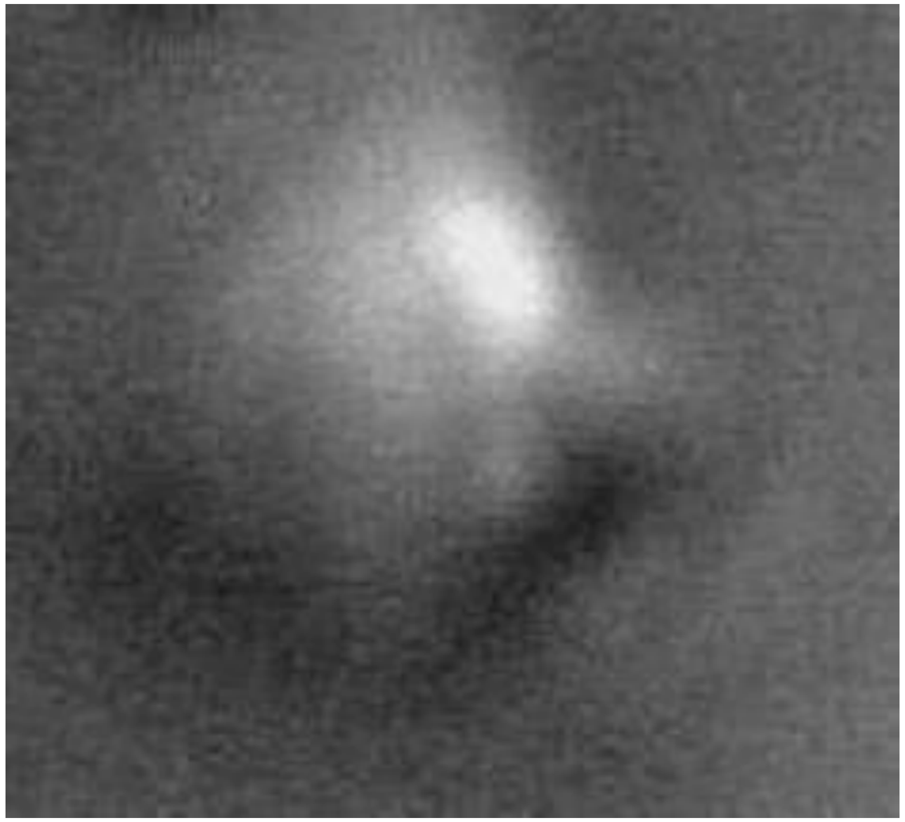


H. Turlier et. al, Nature Phys. **12**, 513 (2016)

Arrow of time in hair-cell bundles

J. Barral, PhD Thesis (2014)

LOTHAR



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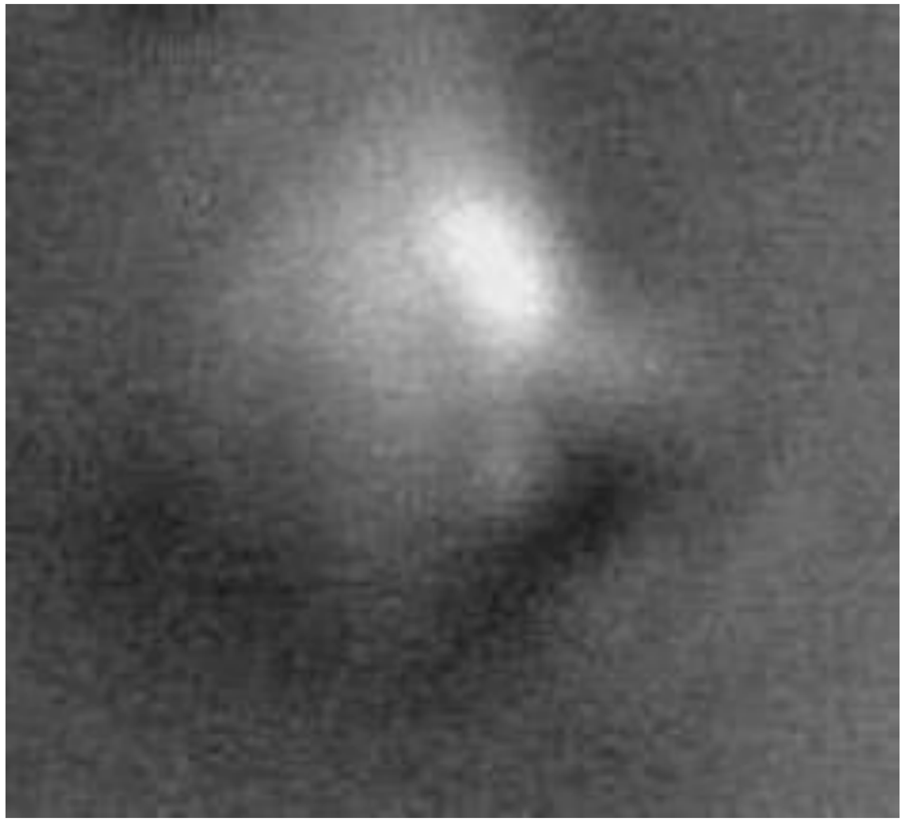

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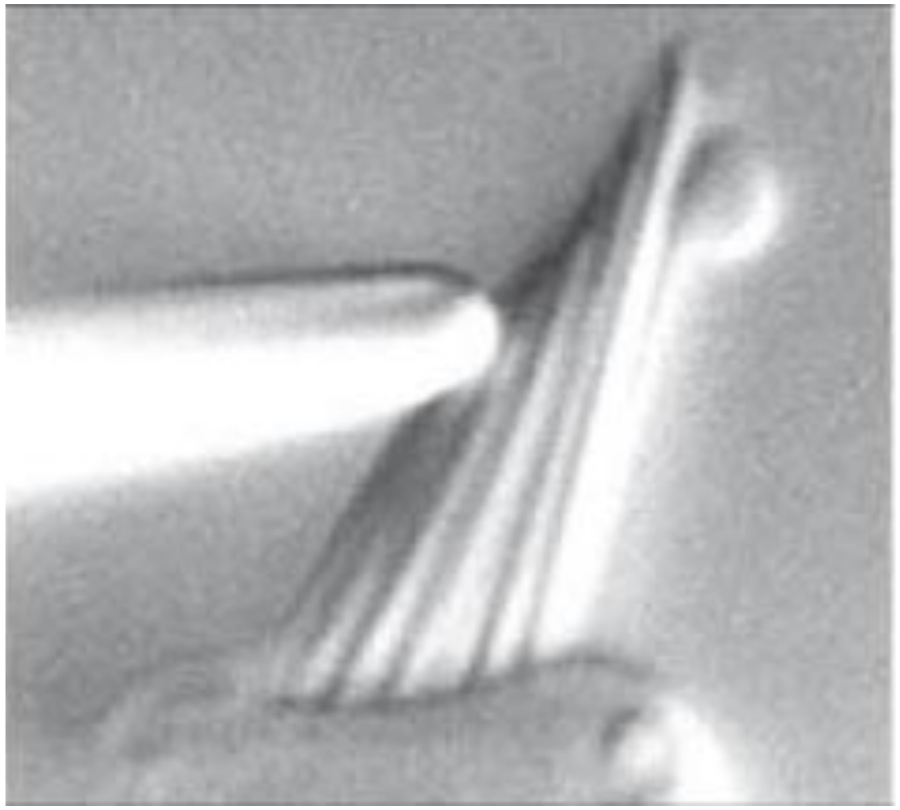

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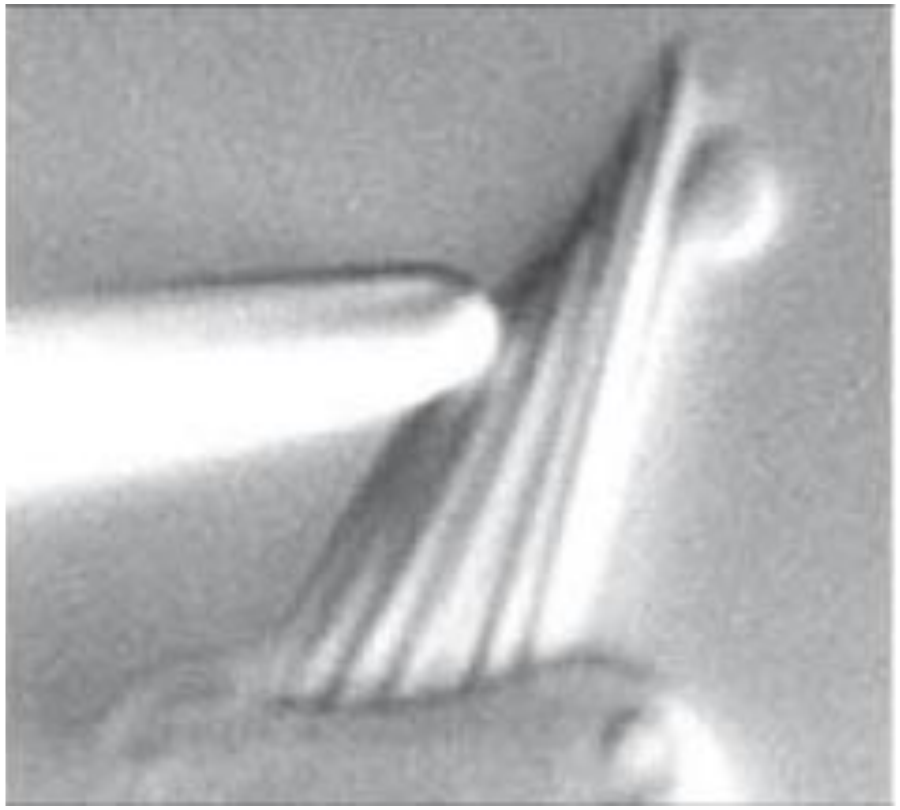
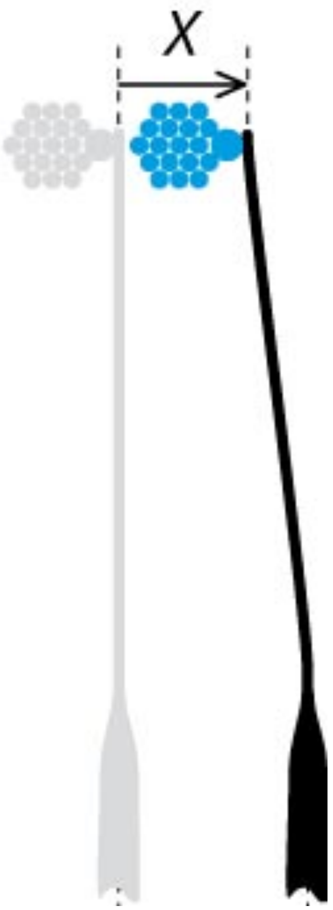
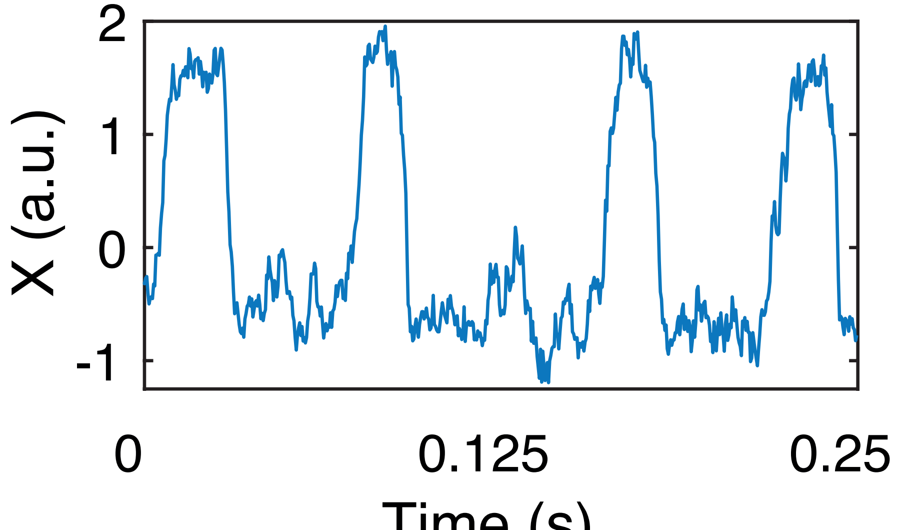
LOTHAR





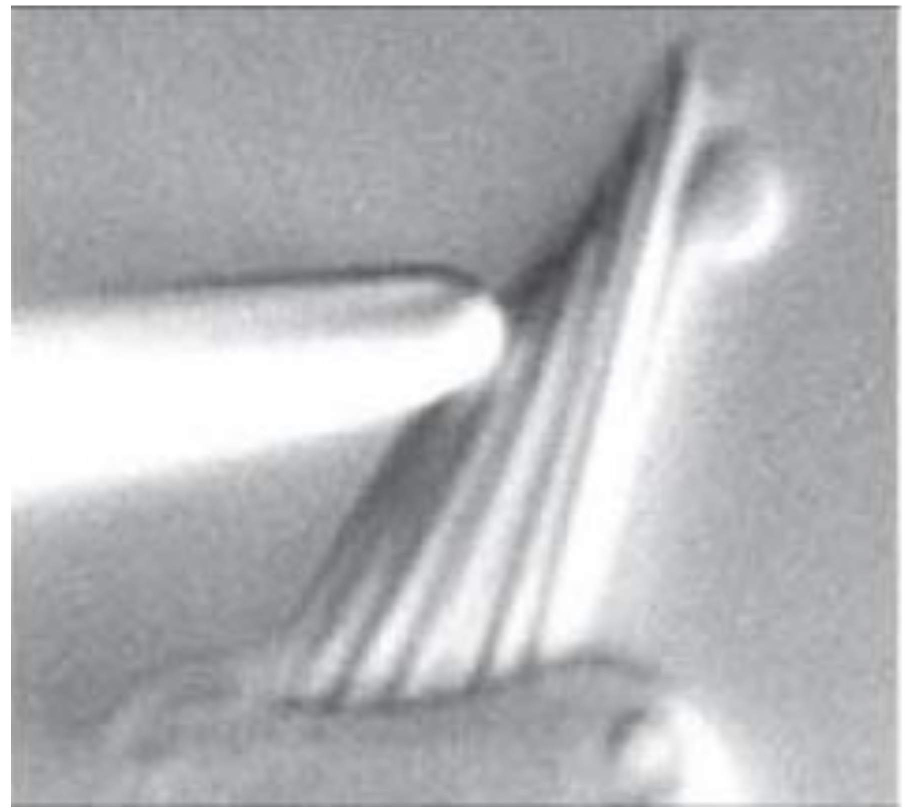
Experimental time series



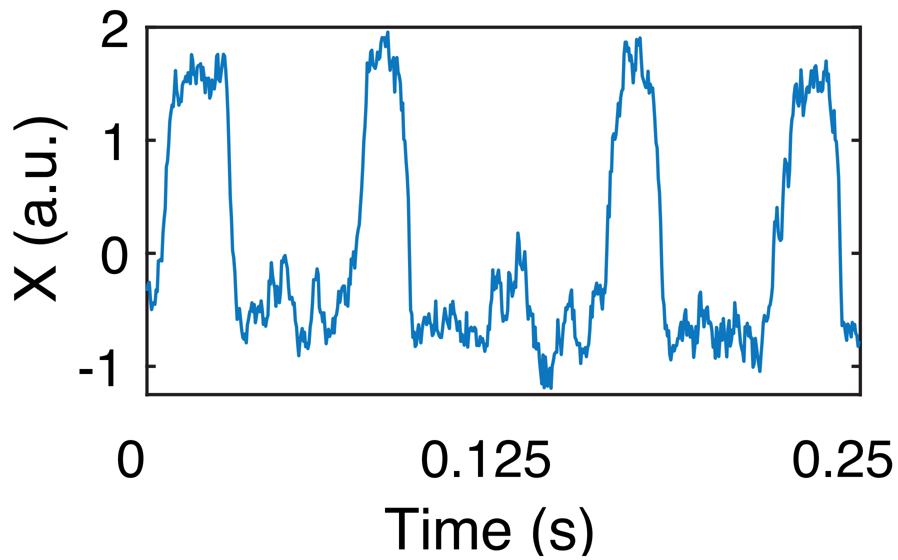
Arrow of time in hair-cell bundles

J. Barral, PhD Thesis (2014)

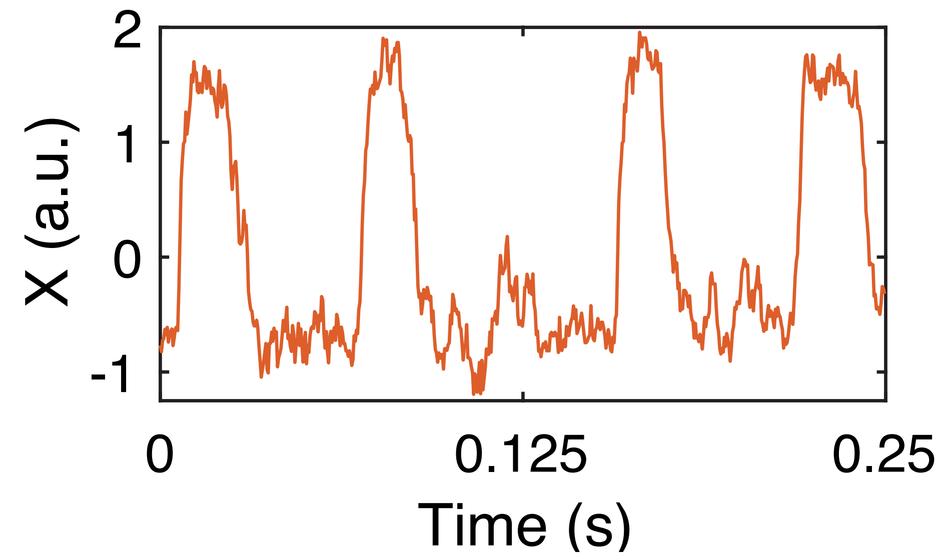
LOTHAR



Experimental time series



Time-reversed signal

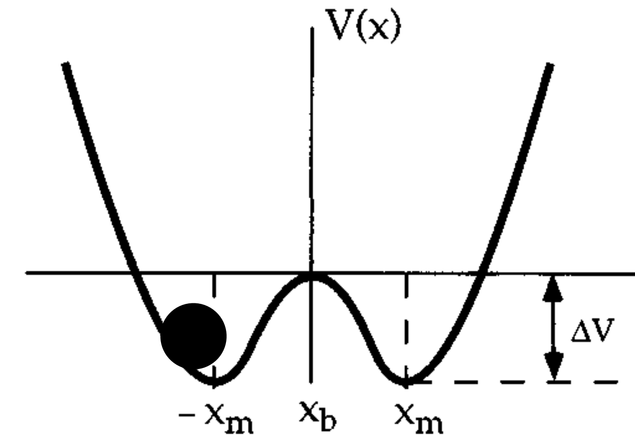


Arrow of time in hair-cell bundles

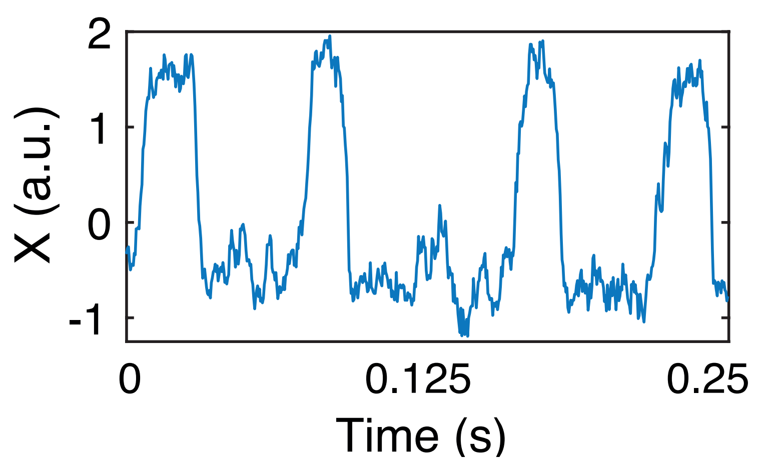
LOTHAR

MANFRED

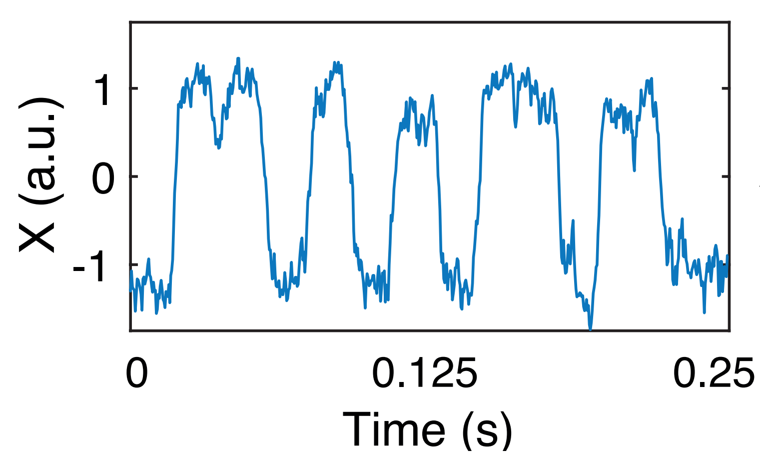
Gammaitoni et al, RMP 98



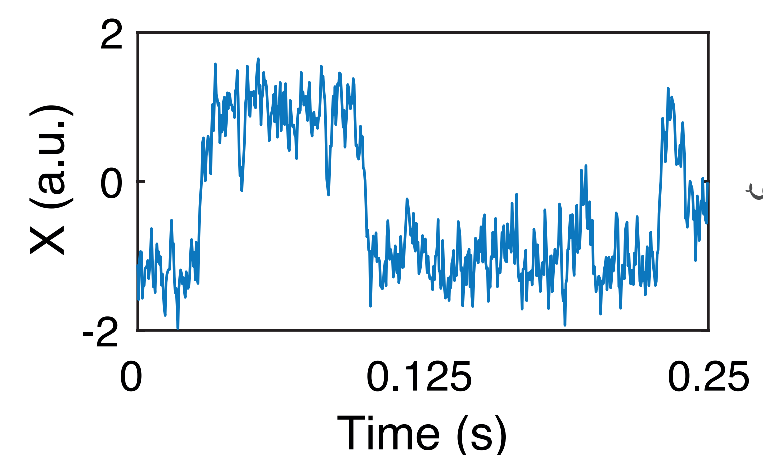
Experimental time series "Lothar"



Experimental time series "Manfred"



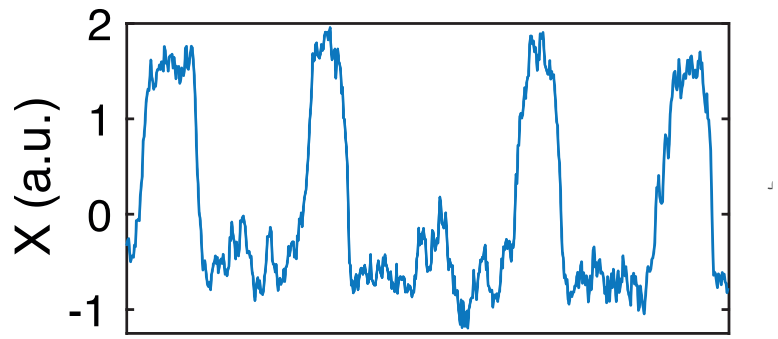
Simulation: equilibrium fluctuations



ER, et al., New J. Phys. **23**, 083013 (2021)

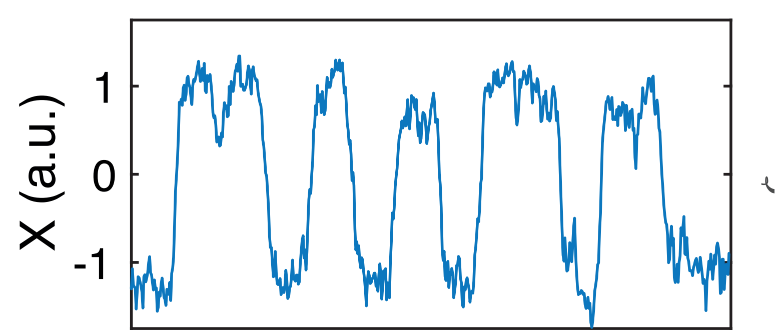
Arrow of time in hair-cell bundles

B) Strongly irreversible



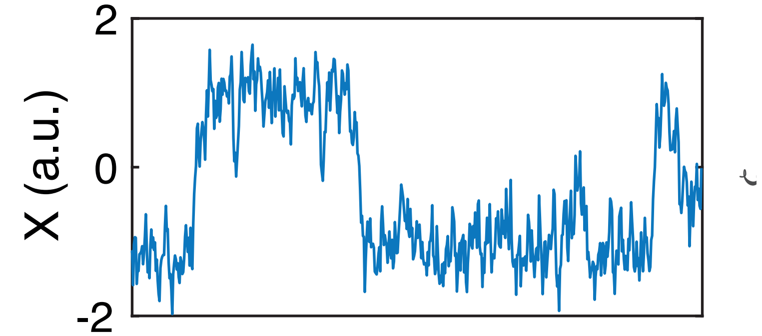
Experimental

C) Weakly irreversible

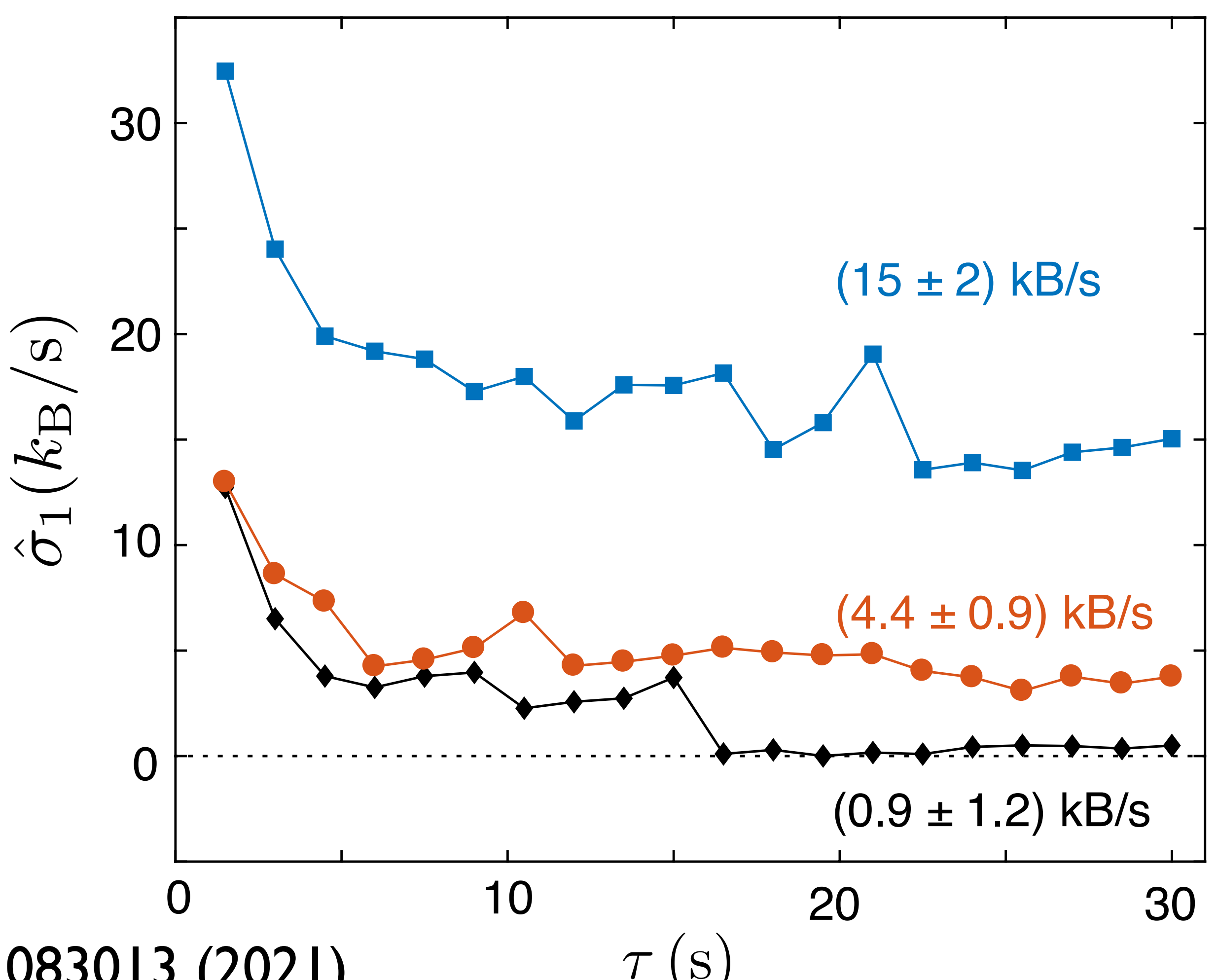


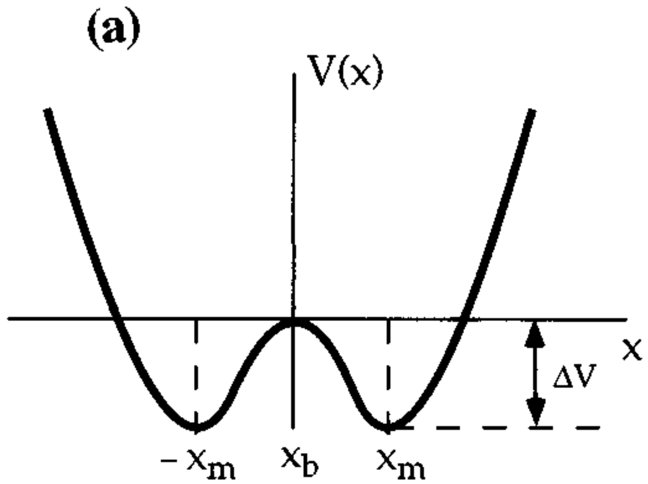
Experimental

D) Reversible



Simulation



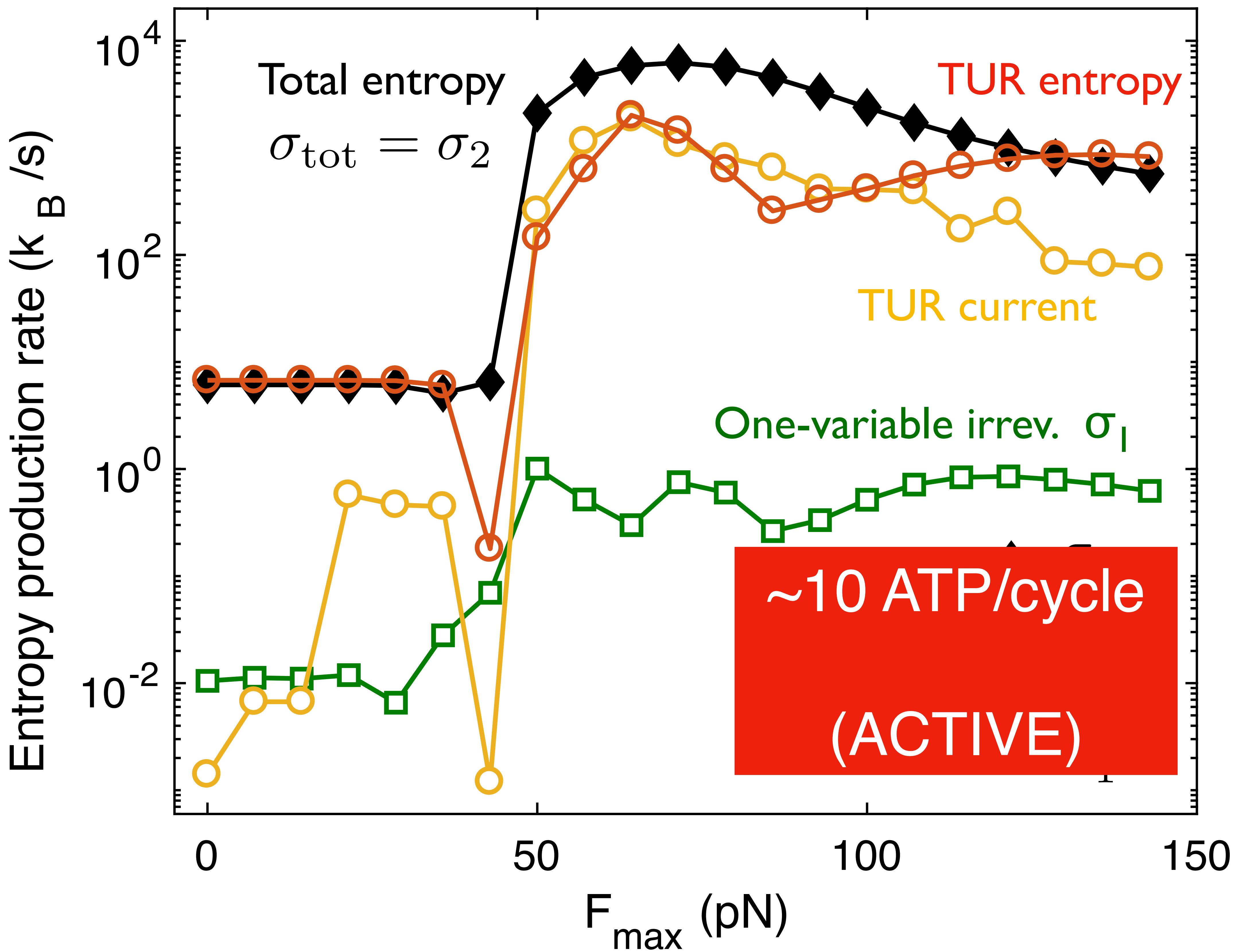


Gammaitoni et al, RMP 98

ER, et al., New J. Phys. **23**, 083013 (2021)

Energy dissipation

ER, et al., New J. Phys. **23**, 083013 (2021)



Thanks for your attention!

Хвала на пажњи!