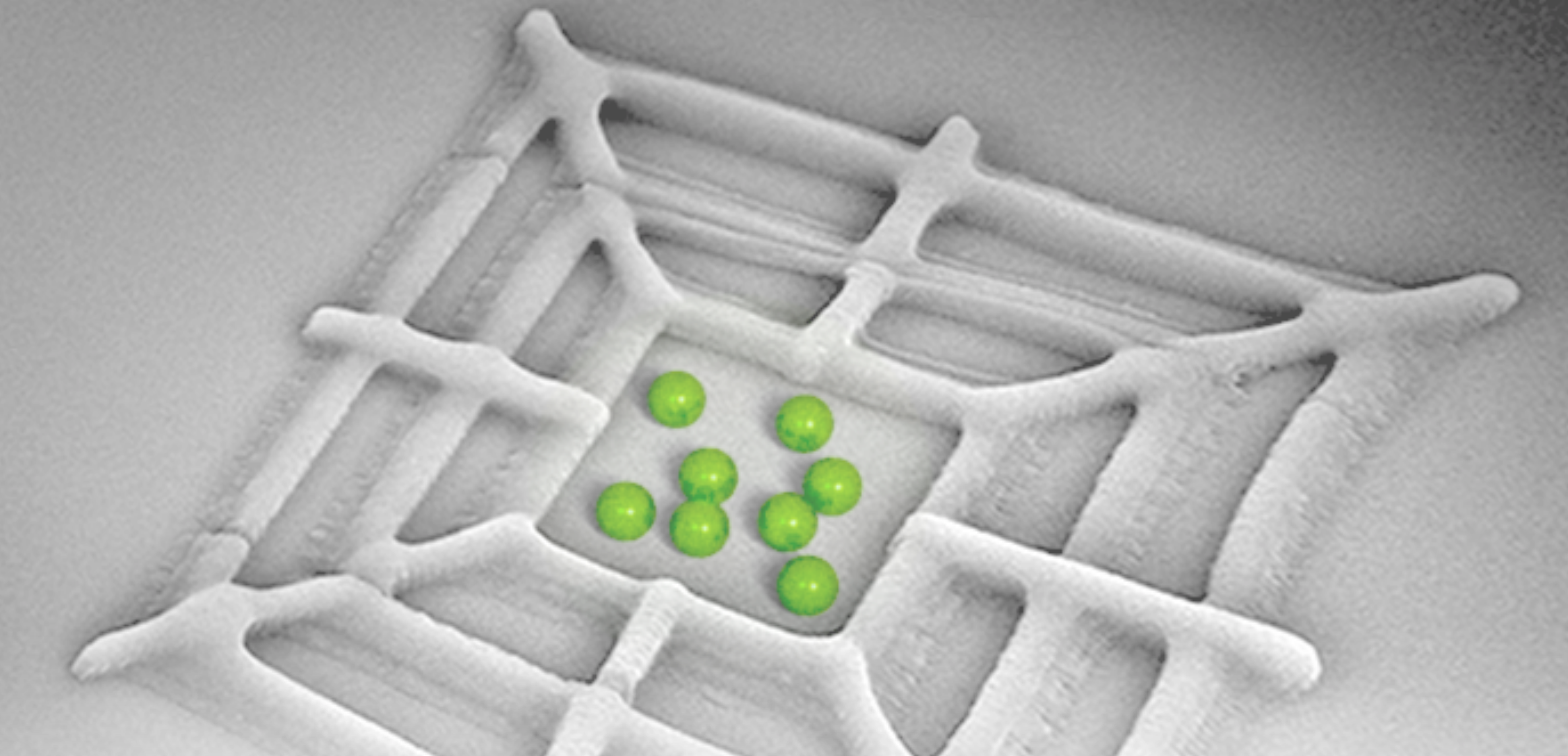
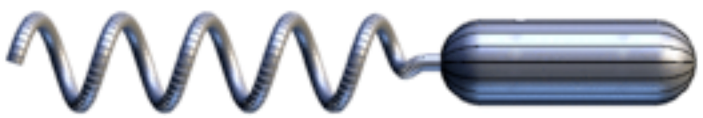


Swimming in complex environments: from biofilms to bacteria powered micro-devices

ROBERTO DI LEONARDO
Dip. Fisica, Sapienza Università di Roma, Italy
CNR-NANOTEC Soft and Living Matter Laboratory
School for Advanced Studies Sapienza

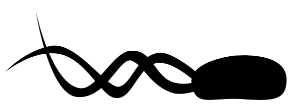
Outline

A SELF-PROPELLED MICRO-MACHINE

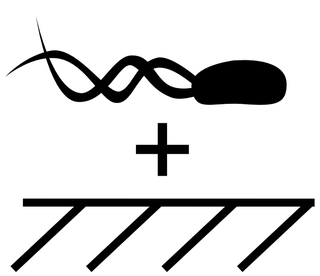


TUESDAY
Microhydrodynamics

a) SELF PROPELLING BACTERIA

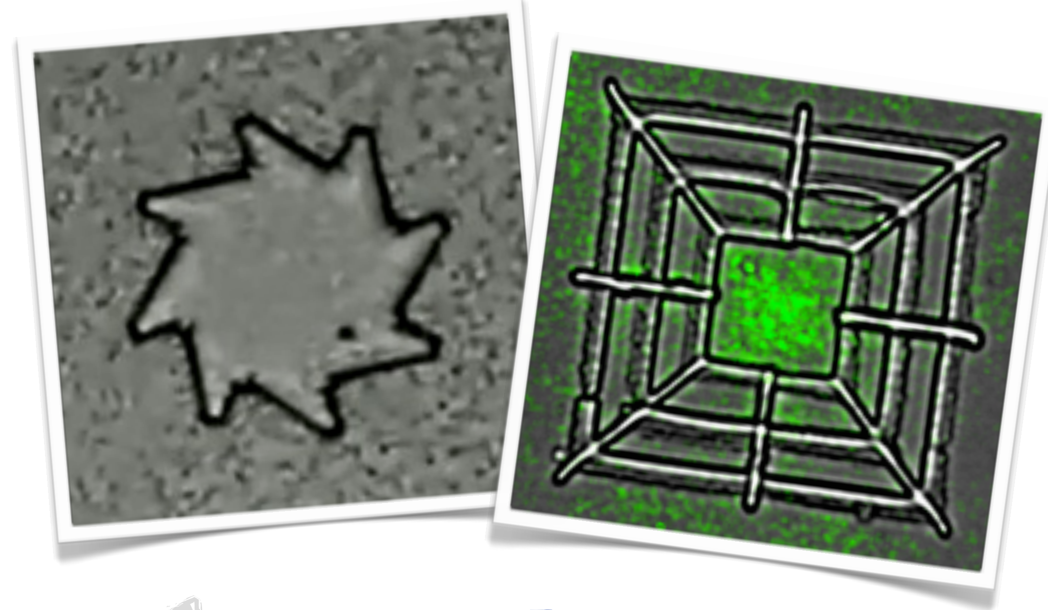


b) CONFINED SWIMMING

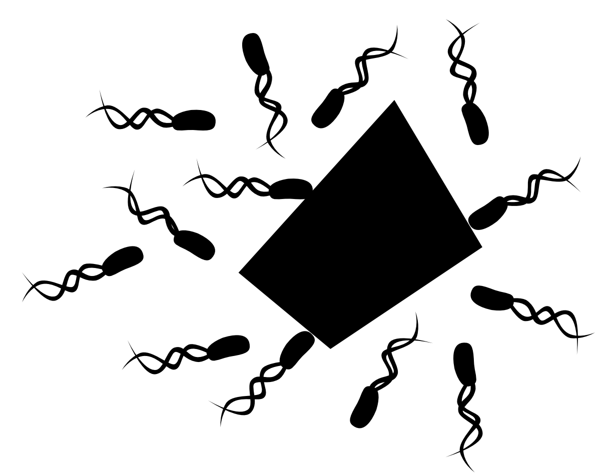


TODAY
Statistical Mechanics

d) BACTERIA POWERED MICRODEVICES



c) STOCHASTIC DYNAMICS IN ACTIVE BATHS



STOCHASTIC DYNAMICS IN ACTIVE BATHS I

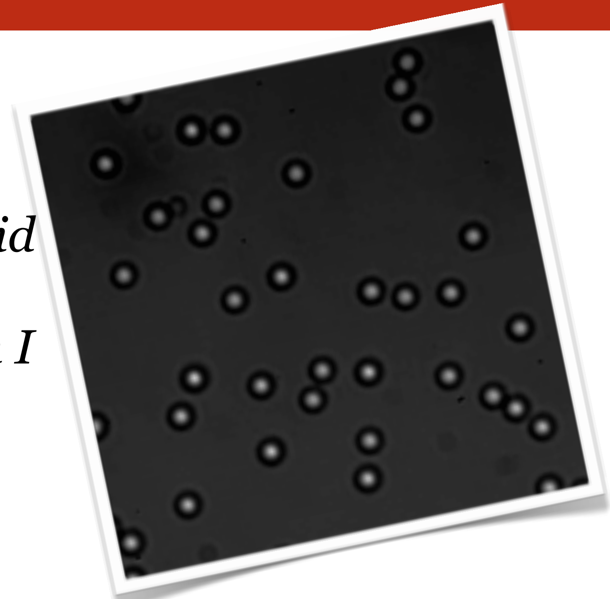
targeted delivery of colloidal cargos

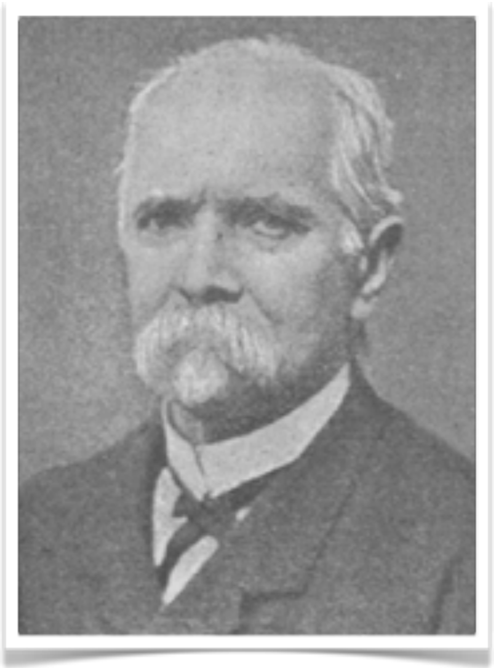
Brownian motion: thermal motion at equilibrium

1827

"Extremely minute particles of solid matter, when suspended in pure water ... exhibit motions for which I am unable to account."

ROBERT BROWN





1867

"Brownian motion [...] provides us with one of the most beautiful and direct experimental demonstrations of the fundamental principles of the mechanical theory of heat, making manifest the assiduous vibrational state that must exist both in liquids and solids"

GIOVANNI CANTONI

1905

A. EINSTEIN

W. SUTHERLAND

MEAN-SQUARE DISPLACEMENT

$$\langle \Delta r^2(t) \rangle = 6Dt$$

DIFFUSION COEFFICIENT

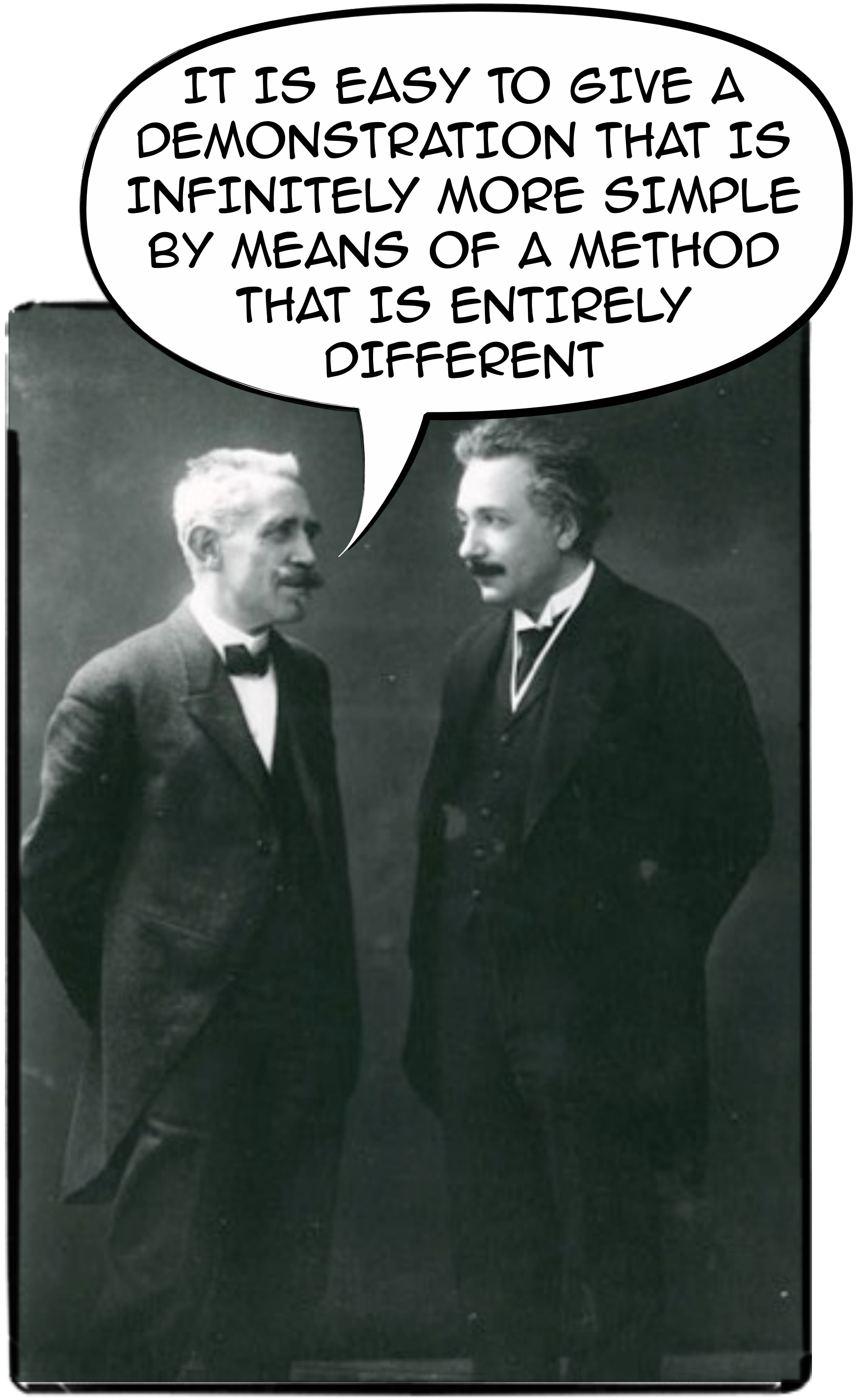
$$D = k_B T/\gamma$$

STOKES DRAG

$$\gamma = 6\pi\mu a$$

Langevin equation

1908 **PAUL LANGEVIN:**



LANGEVIN EQUATION

$$m\ddot{x} \sim 0 = \underbrace{f(x)}_{\text{EXTERNAL}} \underbrace{- \overbrace{\gamma \dot{x}(t)}^{\text{FRICTION}} + \overbrace{\eta(t)}^{\text{RANDOM FORCE}}}_{\text{INTERACTION WITH SOLVENT}}$$

UNBIASED $\langle \eta(t) \rangle = 0$

WHITE NOISE $\langle \eta(t)\eta(t') \rangle = k_B T \; \underbrace{2\gamma\delta(t-t')}_{\text{FLUCTUATION}}$

FRICTION $\gamma \dot{x}(t) = \int_0^t \overbrace{2\gamma\delta(t-t')}^{\text{DISSIPATION}} \; \dot{x}(t') dt'$

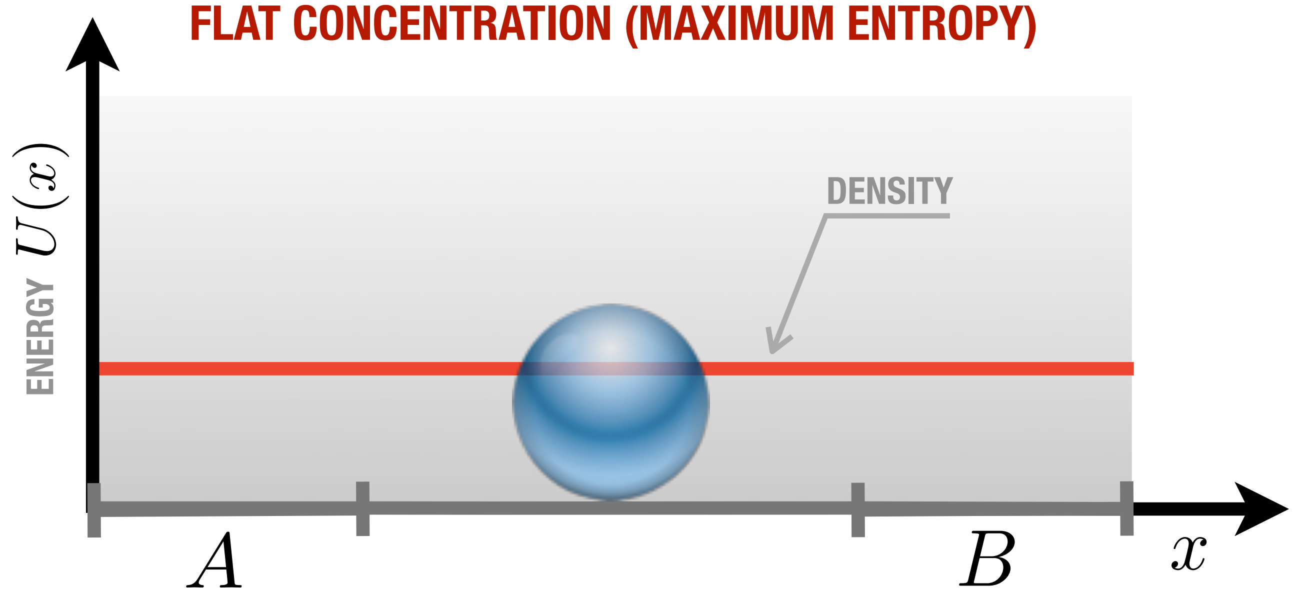
$$\Downarrow$$

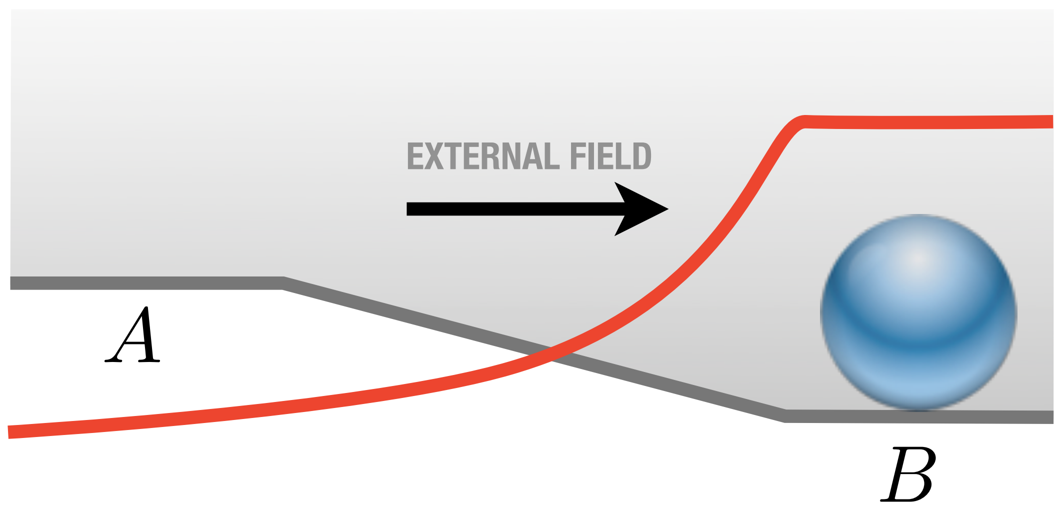
$$\frac{\rho_B}{\rho_A} = \exp\left[\int_A^B \frac{f(x)}{k_B T} dx\right]$$

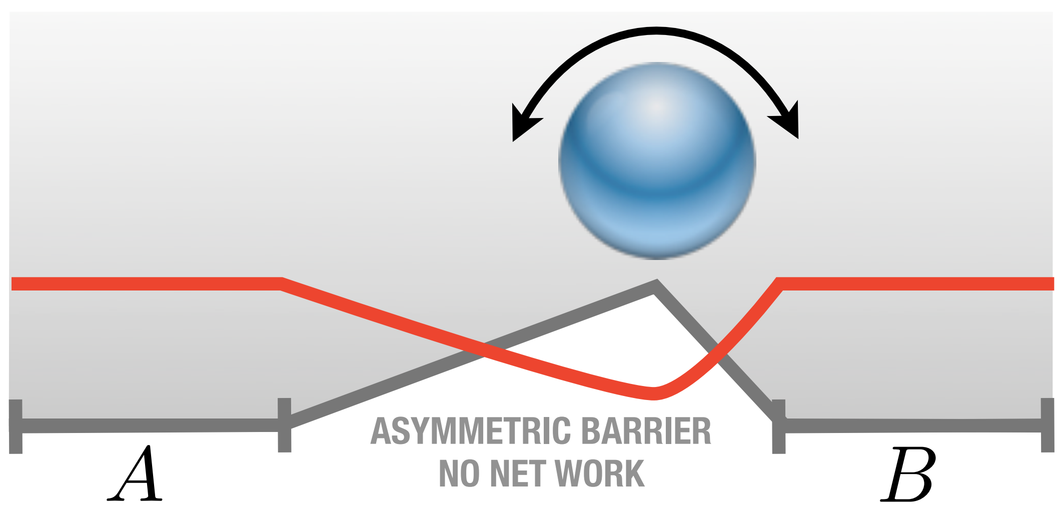
$$\|$$

BOLTZMANN DISTRIBUTION $\exp\left[-\frac{U_B - U_A}{k_B T}\right]$

Colloidal delivery at equilibrium







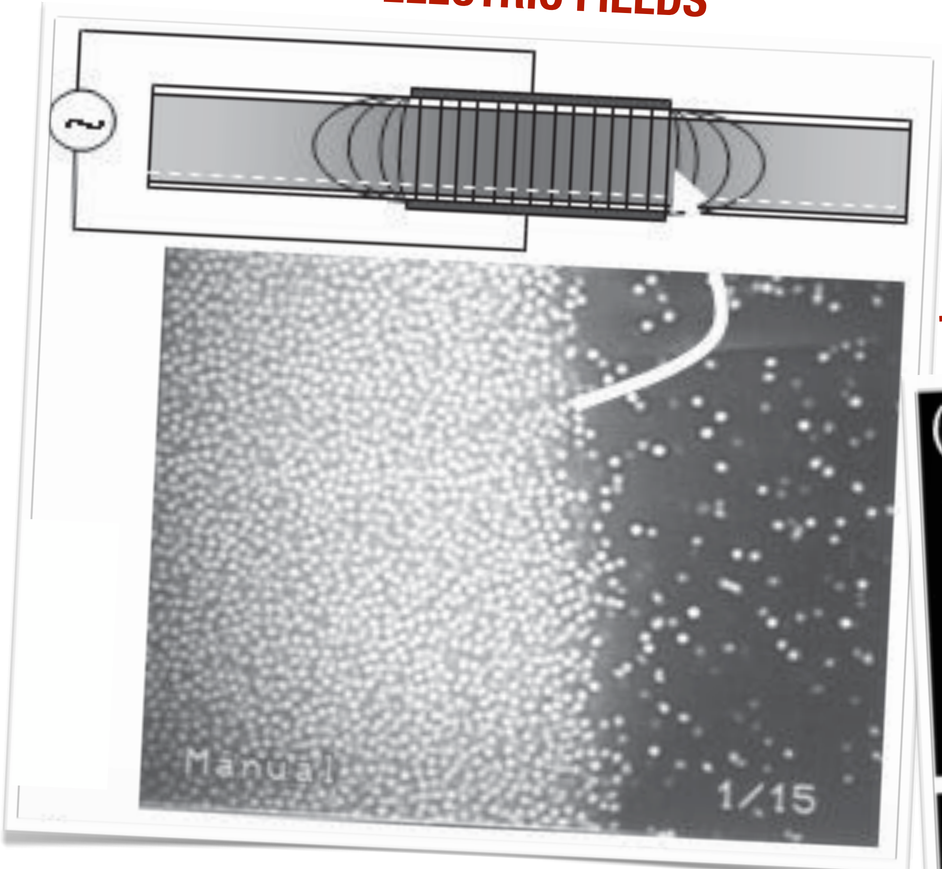
$$\frac{\rho_B}{\rho_A} = \exp\left[\int_A^B \frac{f(x)}{k_B T} dx\right]$$

$$\parallel$$

BOLTZMANN DISTRIBUTION $\exp\left[-\frac{U_B - U_A}{k_B T}\right]$

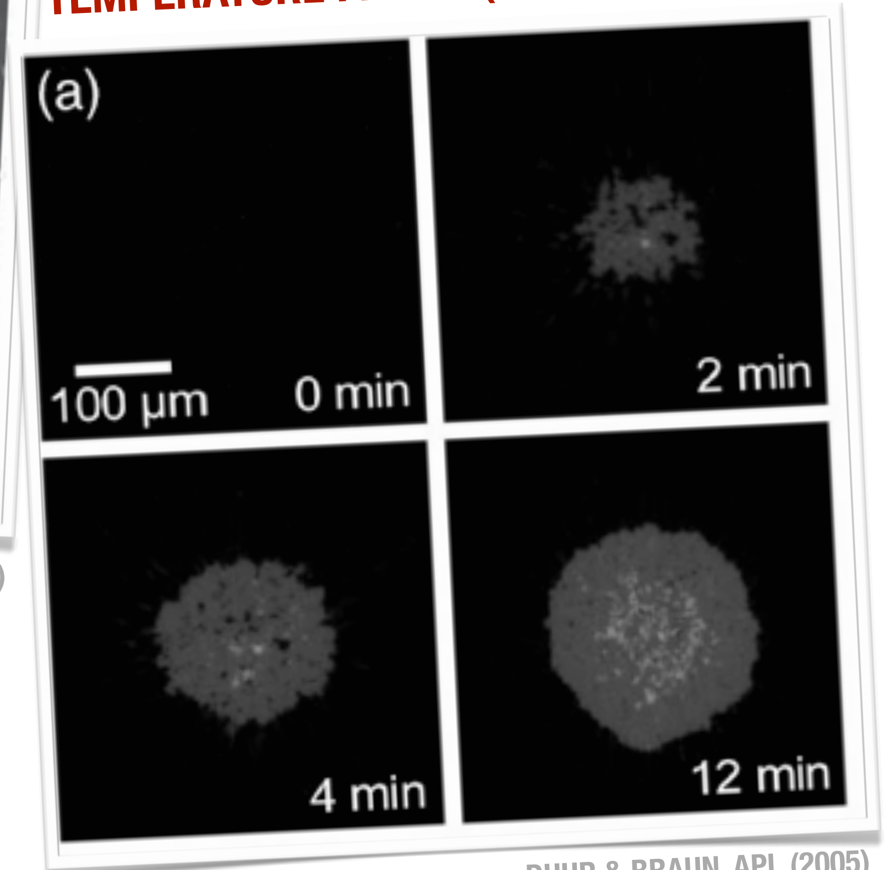
Transport with external fields

ELECTRIC FIELDS



SULLIVAN et al. PRL (2006)

TEMPERATURE FIELDS (LASER HEATING)

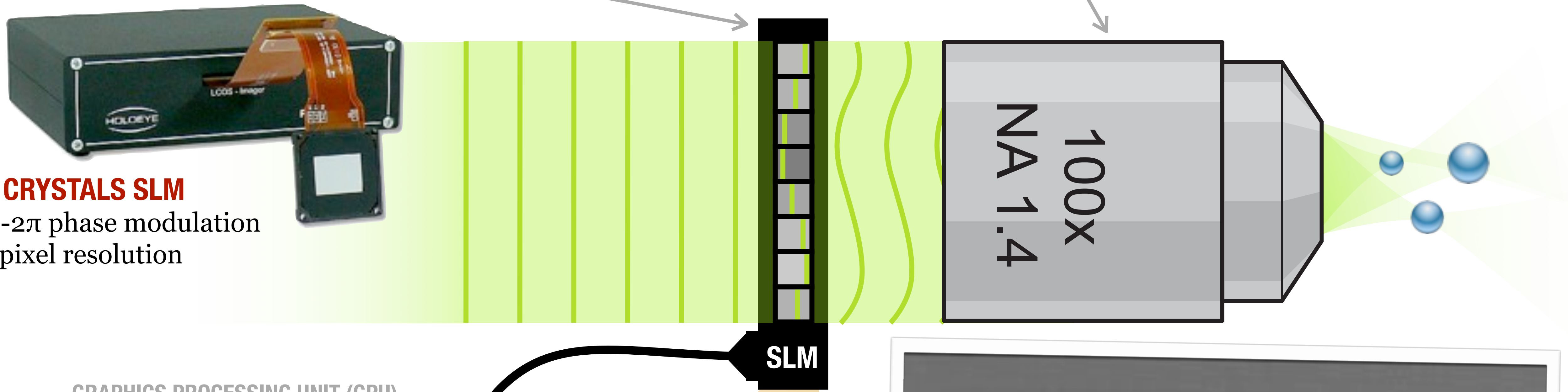


DUHR & BRAUN, APL (2005)

MAGNETIC, FLOW ...

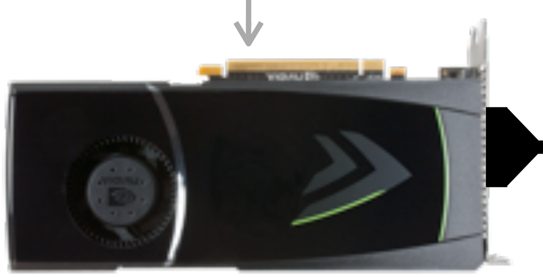
Optical micromanipulation: Holographic Tweezers

GRIER, NATURE (2003)
PADGETT & DI LEONARDO, Lab Chip (2011)



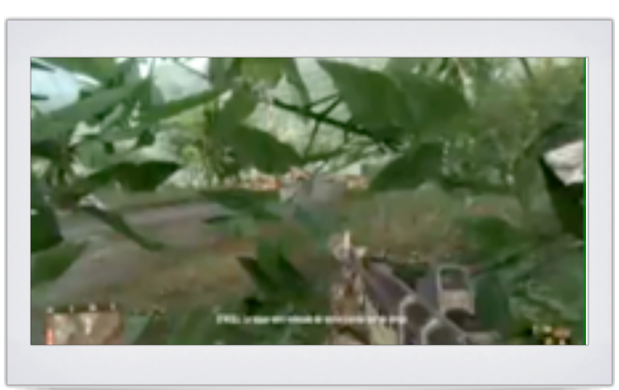
LIQUID CRYSTALS SLM
8 bit, 0-2π phase modulation
1 Megapixel resolution

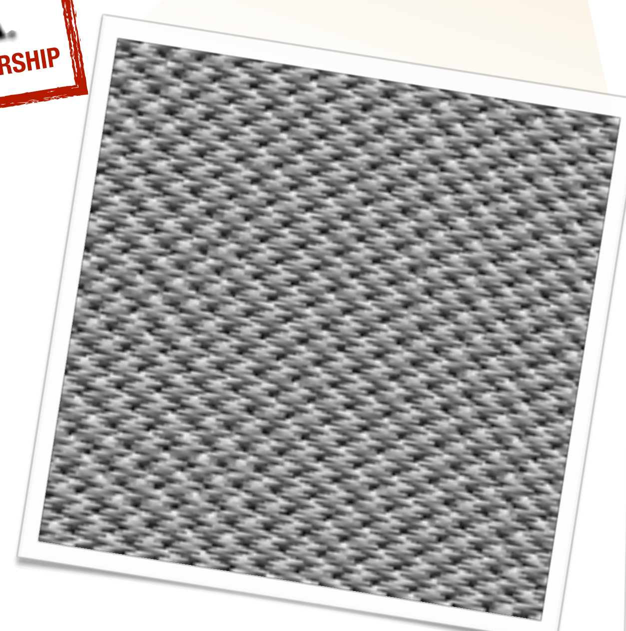
GRAPHICS PROCESSING UNIT (GPU)

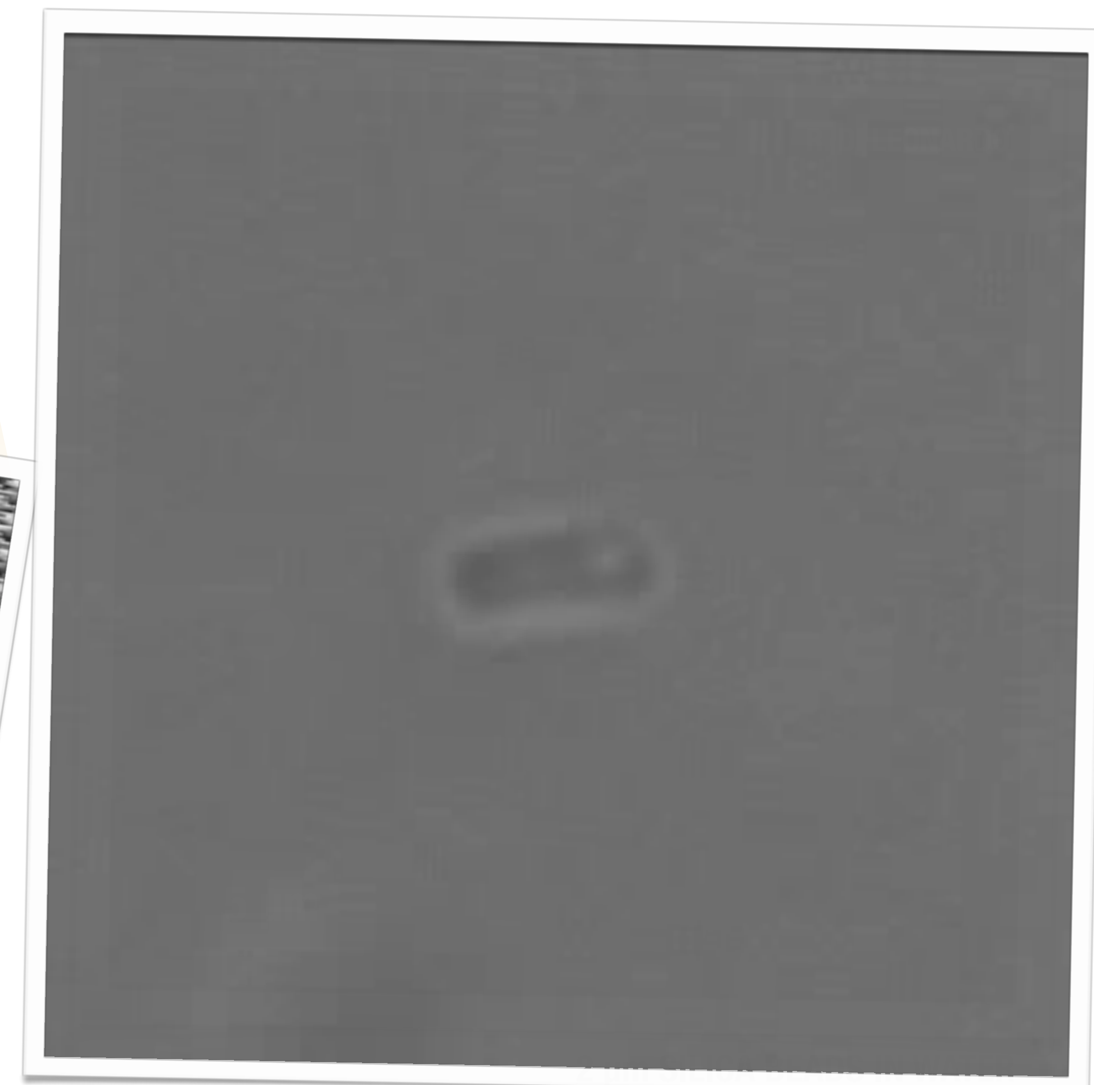


SPONSORED BY NVIDIA ACADEMIC PARTNERSHIP

DIGITAL PARALLEL HOLOGRAPHY
Highly optimized holograms in real time
DI LEONARDO et al., Opt. Express (2006)
BIANCHI & DI LEONARDO Comp. Phys. Comm. (2010)





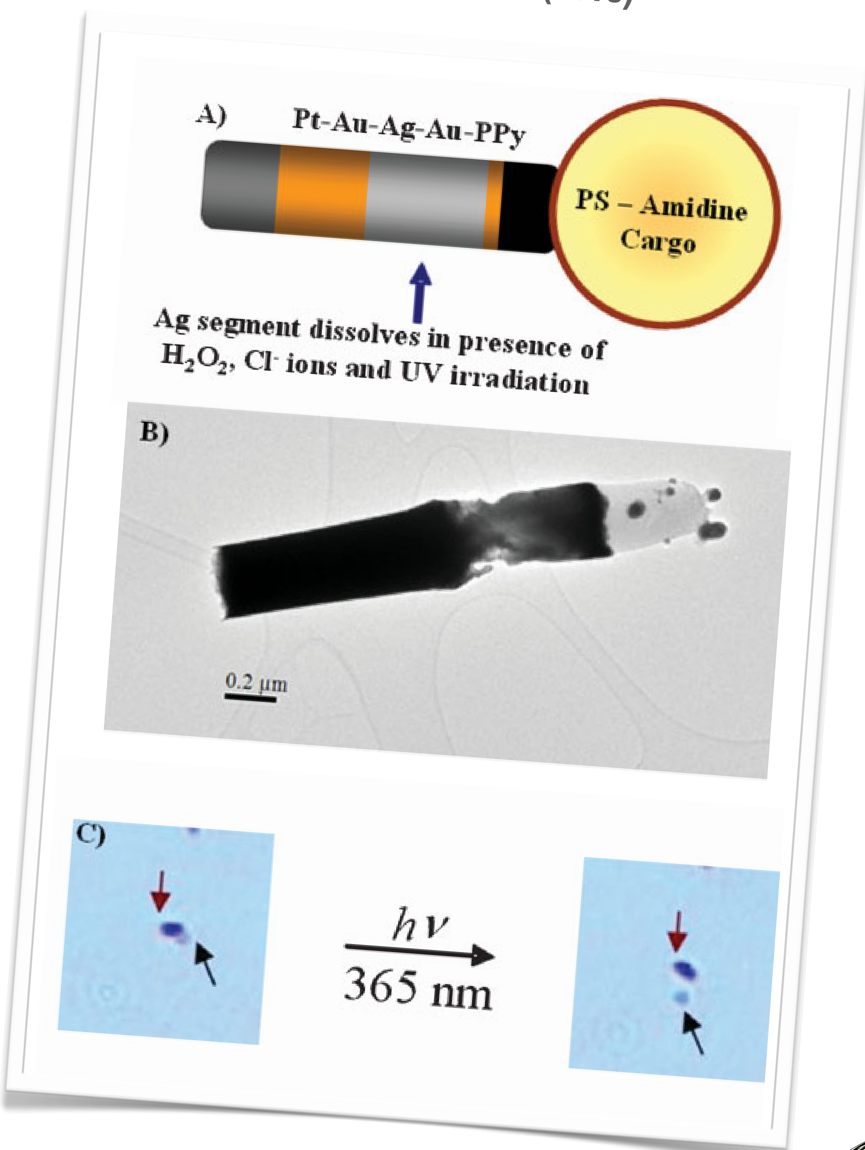


Using active particles as micro-oxen

SYNTHETIC SWIMMERS

CATALYTIC Pt-Au NANOMOTOR

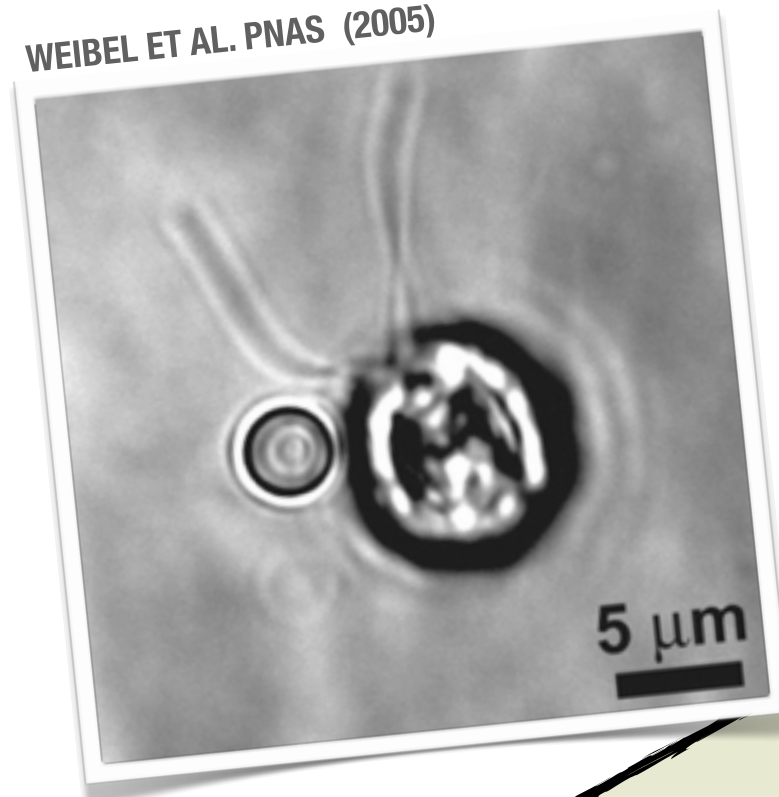
SUNDARARAJAN et al. SMALL (2010)

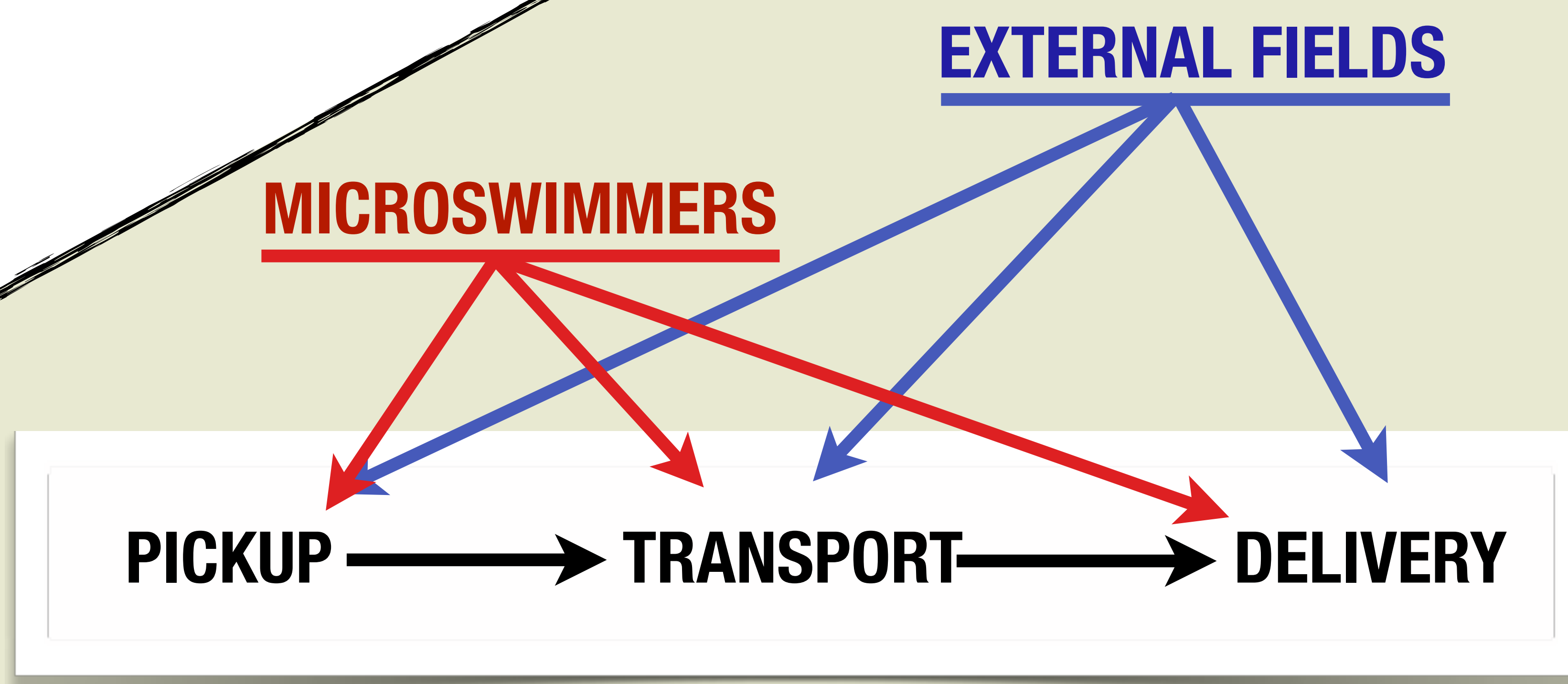


SWIMMING CELLS

C. reinhardtii

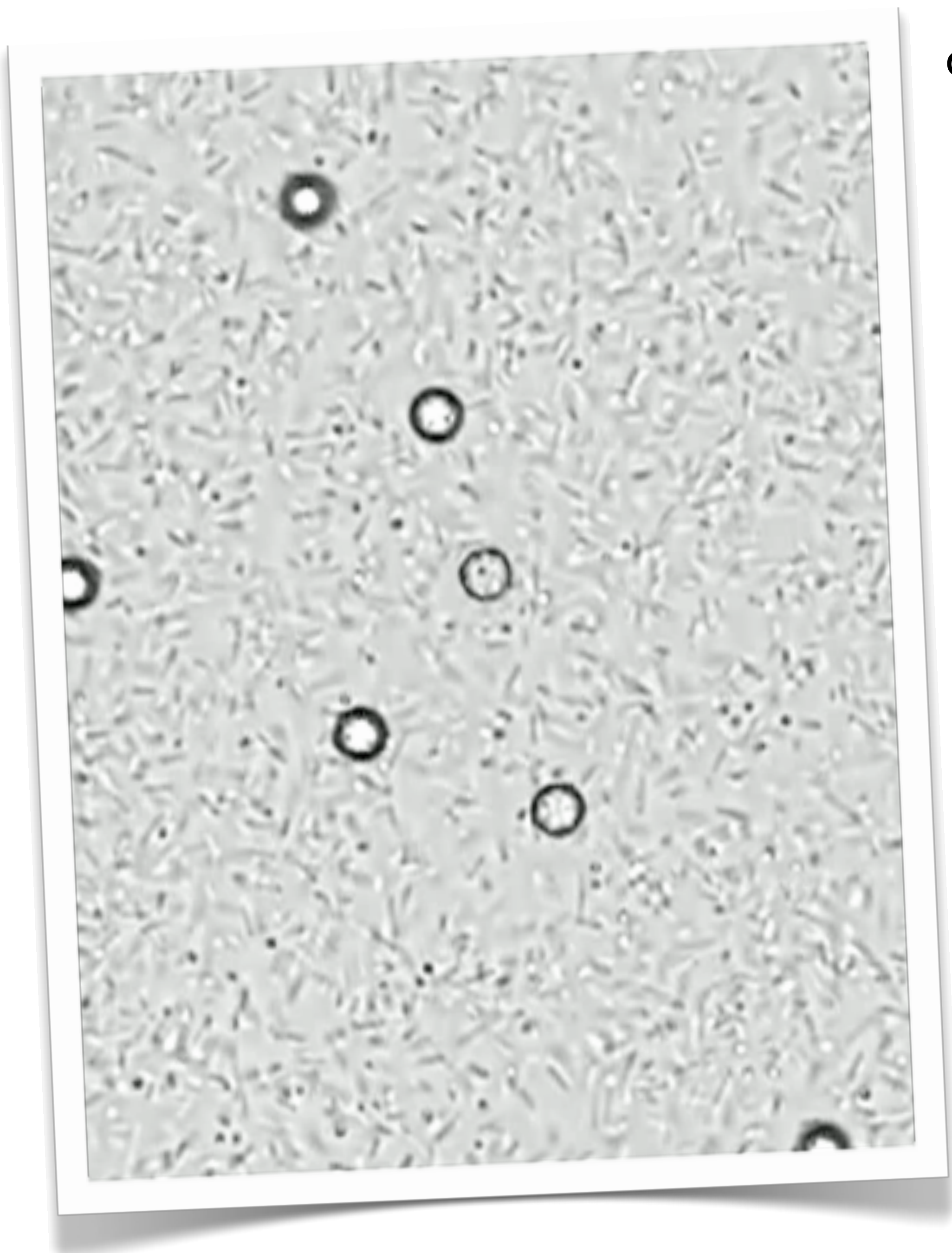
WEIBEL ET AL. PNAS (2005)

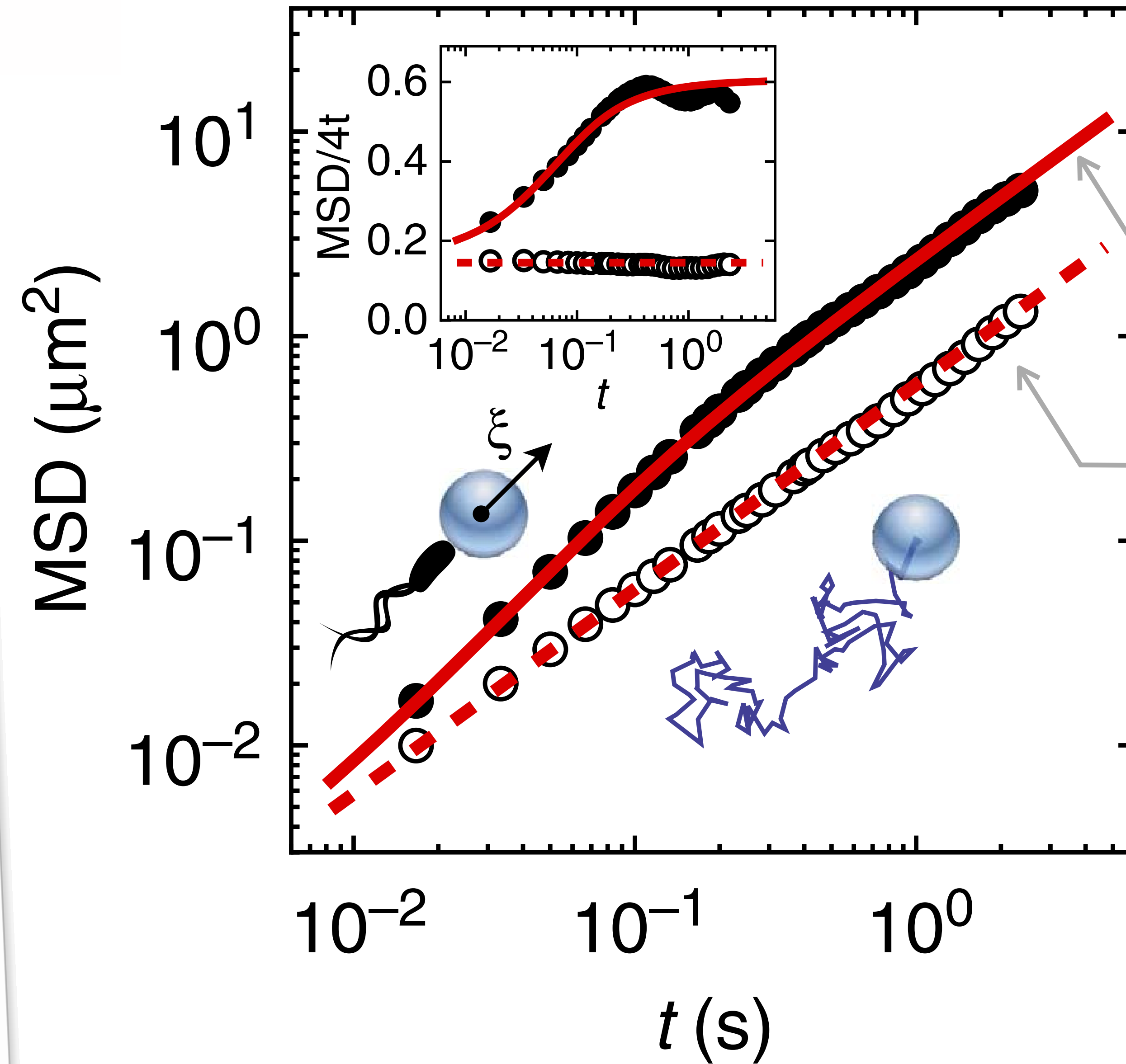




Colloids in active baths

5 µm LATEX BEADS IN E.coli





$$D^* = \frac{k_B T^*}{\gamma}$$

$$D = \frac{k_B T}{\gamma}$$

ACTIVE NOISE

$$0 = f(x) - \gamma \dot{x}(t) + \eta(t) + \xi(t)$$

$$\langle \xi(t) \rangle = 0$$

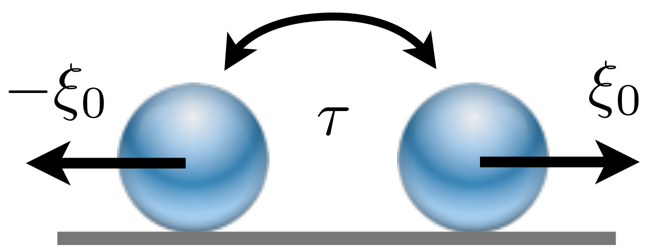
$$\langle \xi(0)\xi(t) \rangle = \langle \xi^2 \rangle e^{-t/\tau}$$

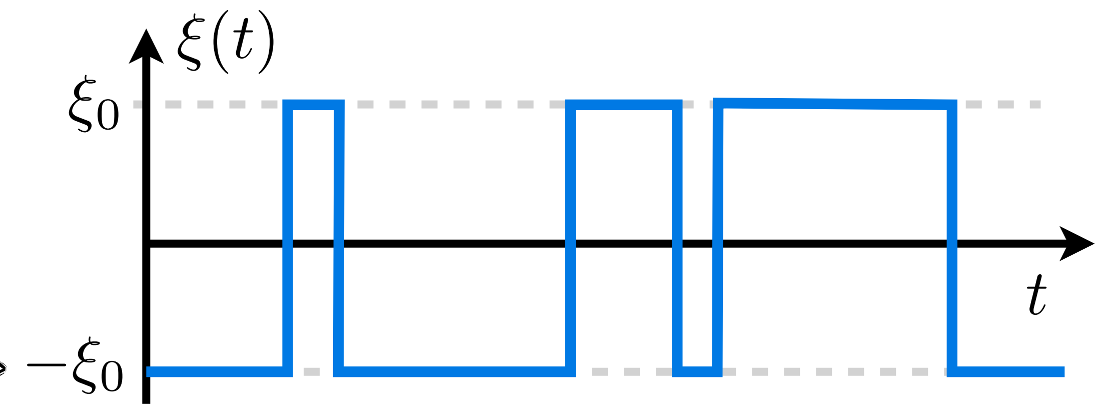
COLORED NOISE

Non-equilibrium random walks

1D RUN AND TUMBLE

SCHNITZER, PRE (1993)
TAILLEUR & CATES, PRL (2008)
ANGELANI, COSTANZO, RDL, EPL (2011)





COLORED DICOTOMOUS(1D) NOISE

$$\langle \xi(t) \rangle = 0$$

$$\langle \xi(0)\xi(t) \rangle = \xi_0^2 e^{-t/\tau}$$

RUN LENGTH

FREE PARTICLE

MOBILITY

$$\dot{x}(t) = \xi(t)/\gamma$$

$$v_0 = \xi_0/\gamma$$

$$\langle \Delta r(t)^2 \rangle = \frac{2v_0^2}{\lambda^2}(\lambda t - 1 + e^{-\lambda t})$$

$t \ll \tau$ → $v_0^2 t^2$ **BALLISTIC**

$t \gg \tau$ → $2D^* t$ **DIFFUSIVE**

$$D^* = \frac{v_0^2}{\lambda} = K_B T^*/\gamma$$

$$f_0 v_0 \lambda^{-1}$$

RUN & TUMBLE IN EXTERNAL FIELD (J=0)

$$\frac{\rho(x)}{\rho(0)} = \frac{T^*(0)}{T^*(x)} \exp\left[\int_0^x \frac{f(x)}{k_B T^*(x)} dx\right]$$

$$T^*(x) = T^* - f(x)^2 \tau/\gamma$$

SPACE DEPENDENT TEMPERATURE

WHITE NOISE LIMIT

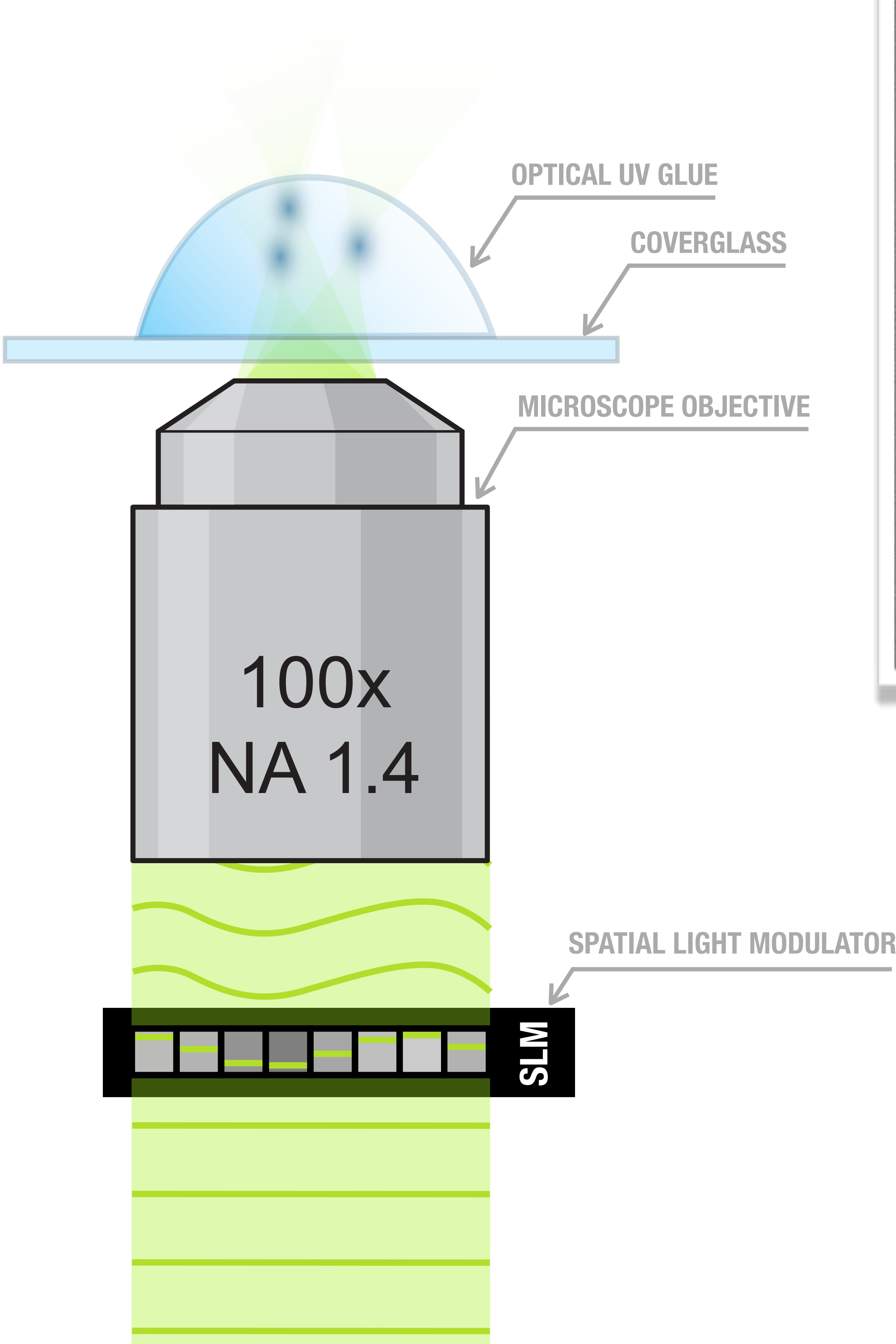
$$\tau \to 0$$

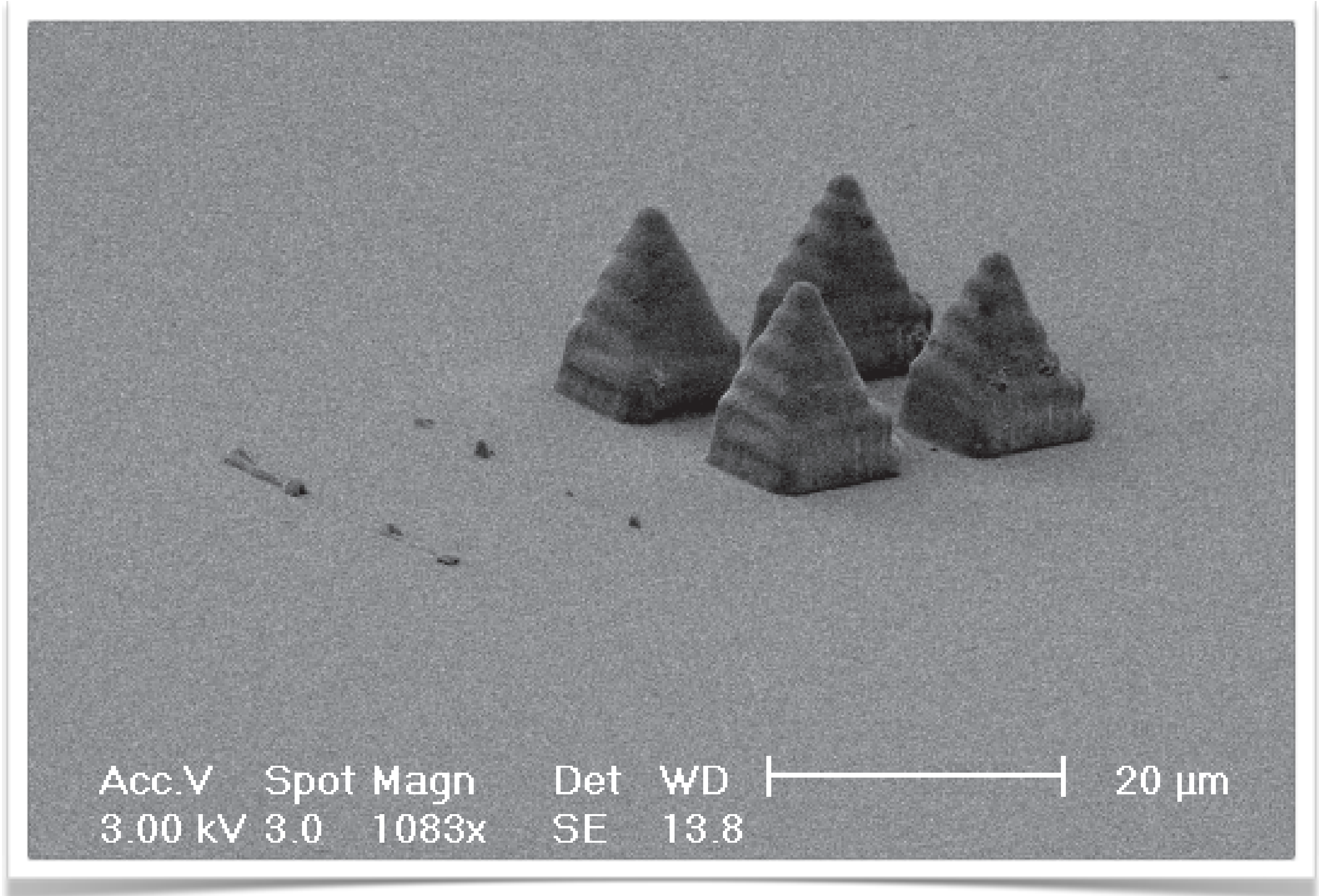
$$T(x) \to T^*$$

$$\rho(x) \propto \exp\left[-\frac{U(x)}{K_B T^*}\right]$$

BOLTZMANN-LIKE STATISTICS

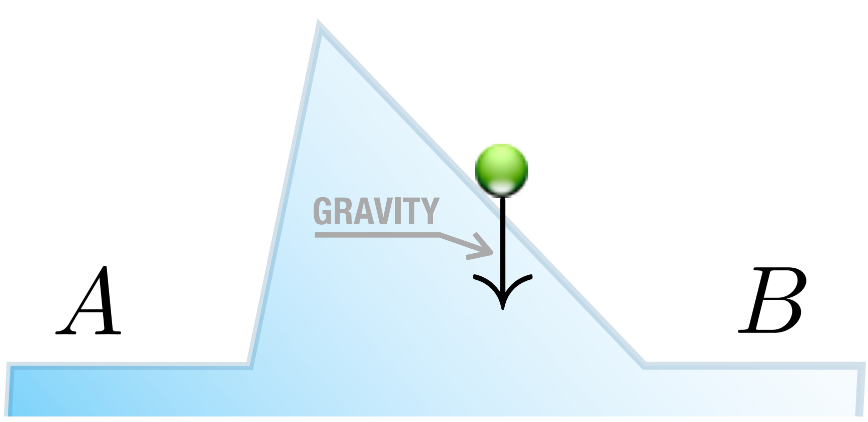
Holographic microfabrication





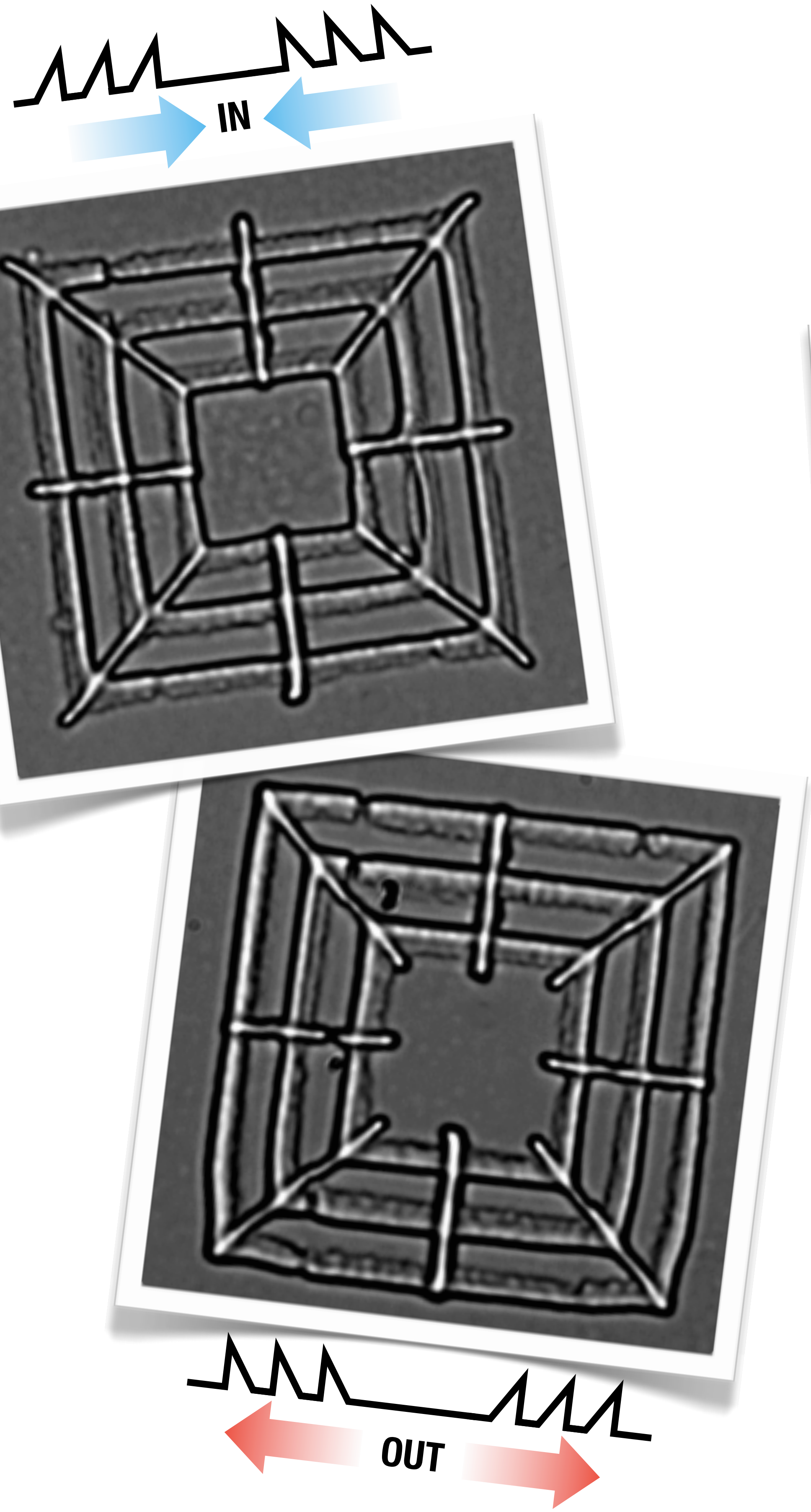
N. J. JENNESS, ET AL. OPT. EXPRESS 16, 15942 (2008).

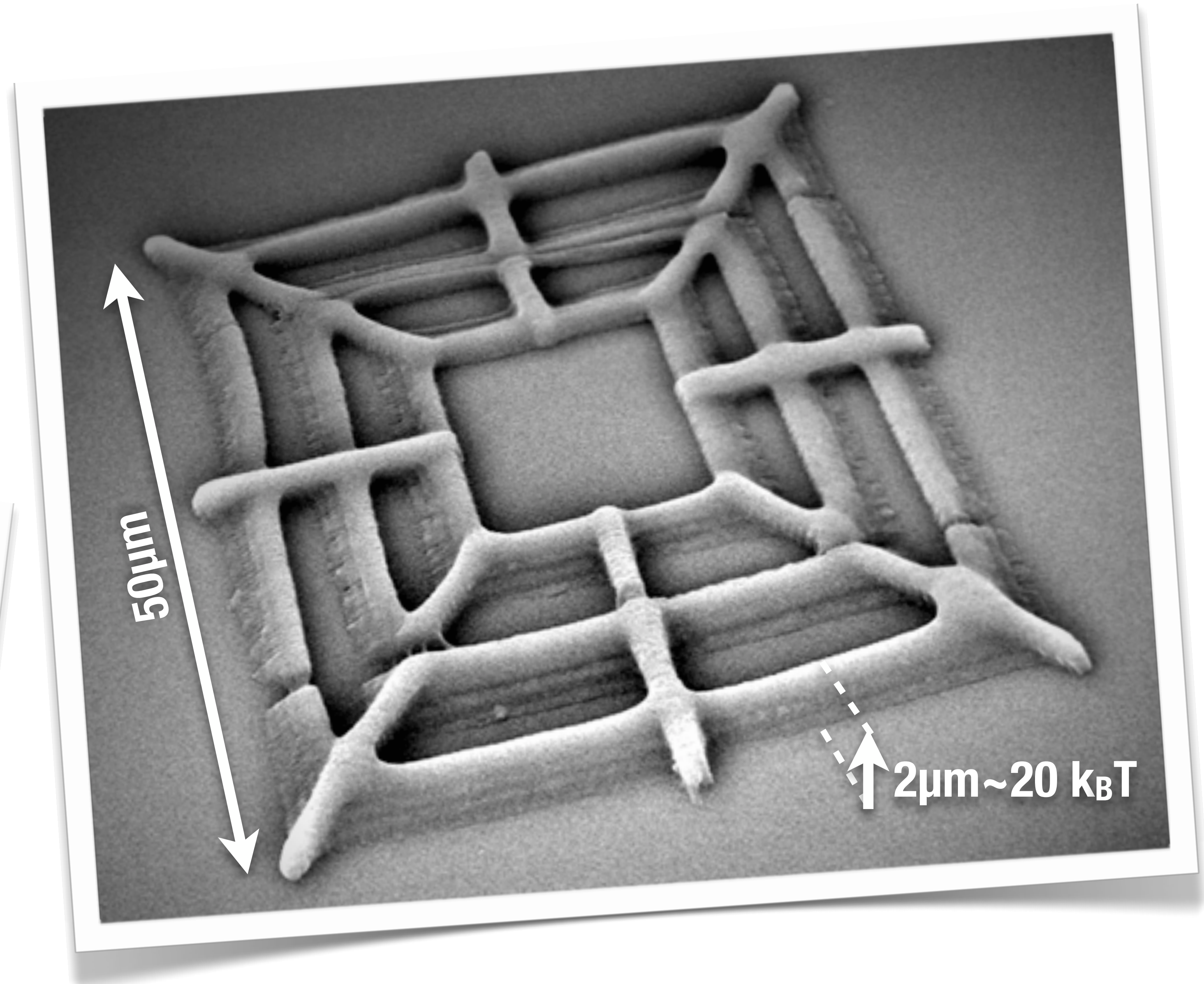
A MICROPATTERNED SURFACE WITH A 3D TOPOGRAPHY ACTS AS A STATIC (GRAVITATIONAL) ENERGY LANDSCAPE



Collecting and ejecting structures

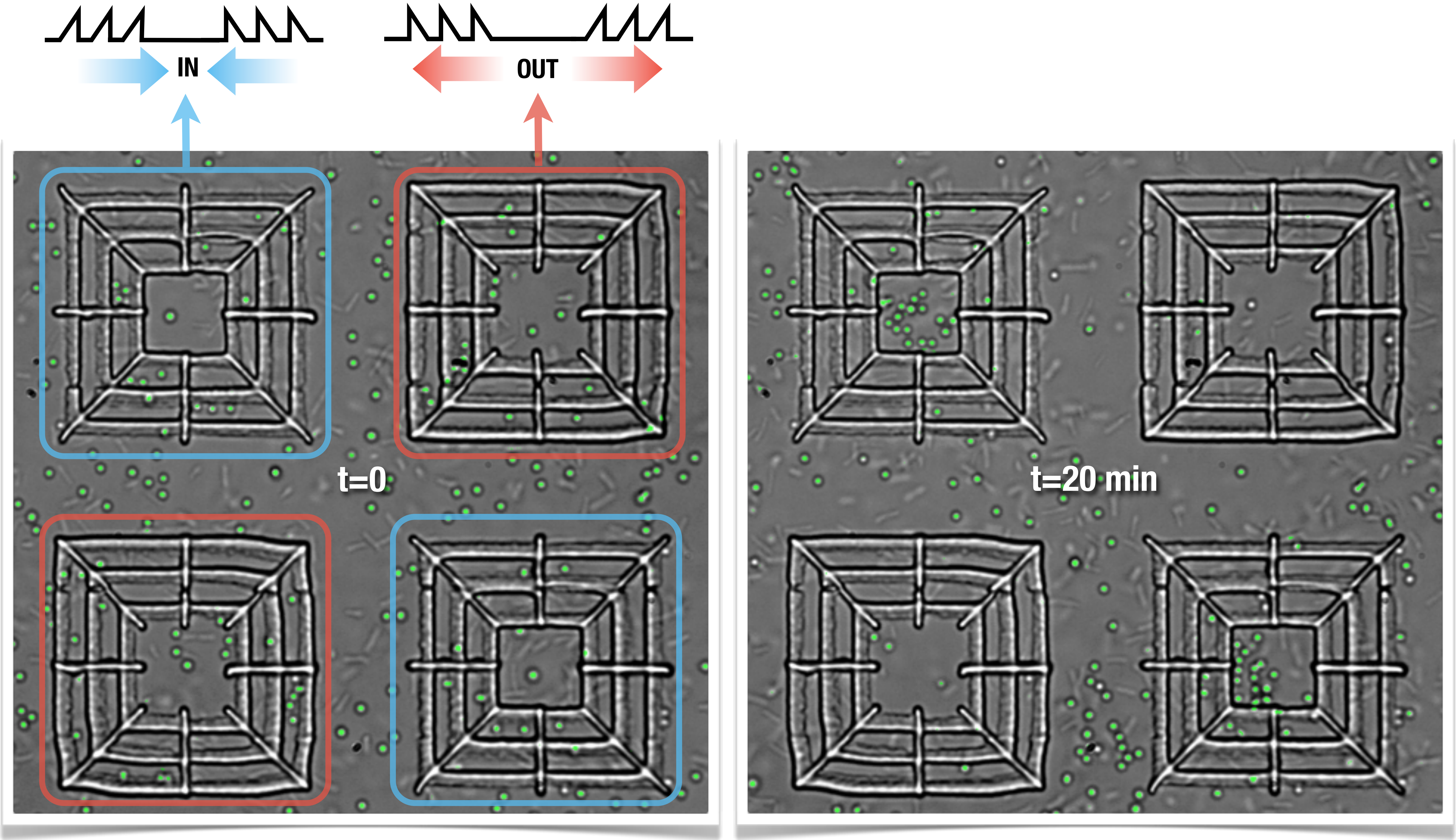
KOUMAKIS, LEPORE, MAGGI, RDL, Nature Comm. (2013)





Targeted delivery of colloids

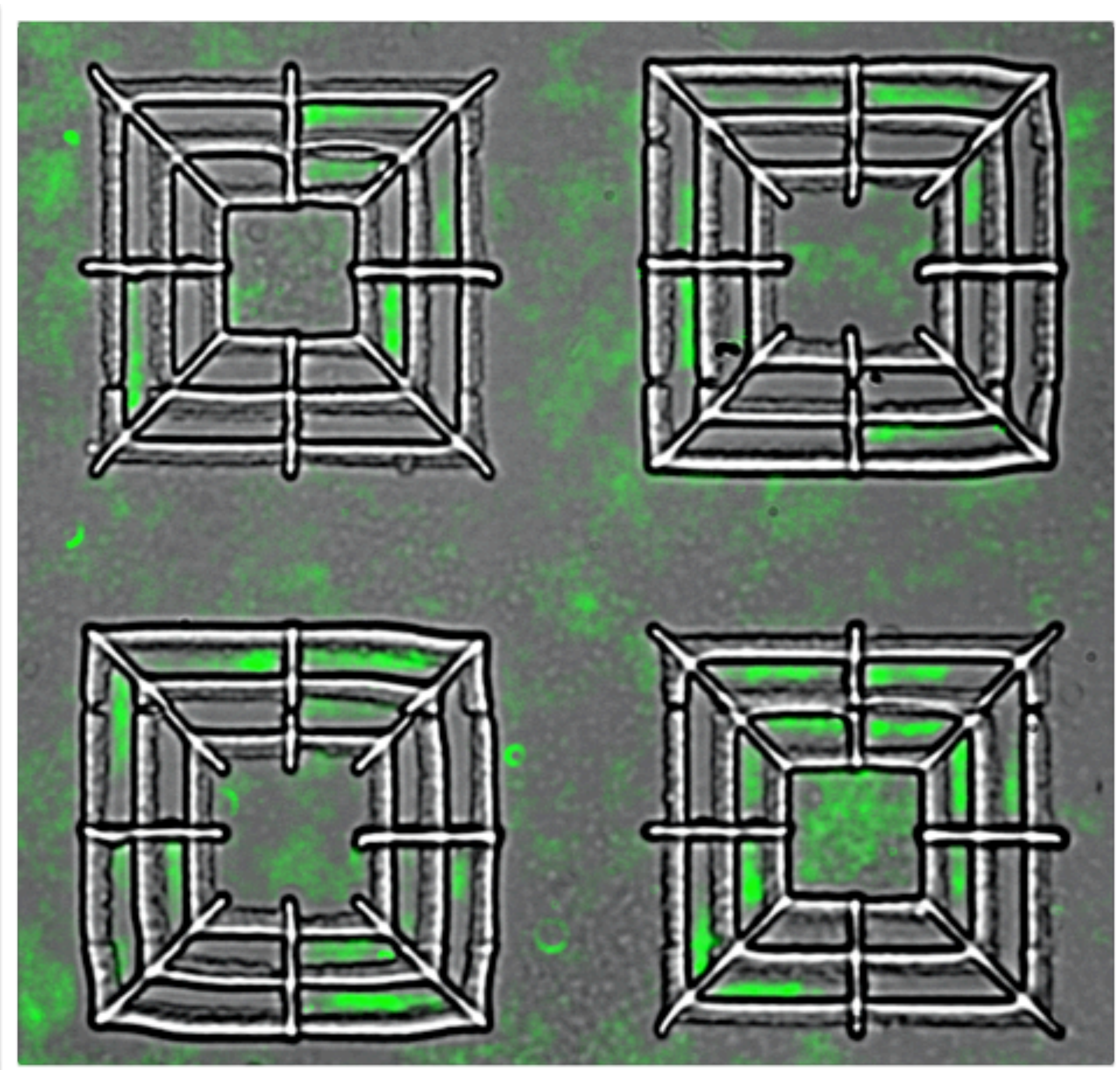
KOUMAKIS, LEPORE, MAGGI, RDL, Nature Comm. (2013)



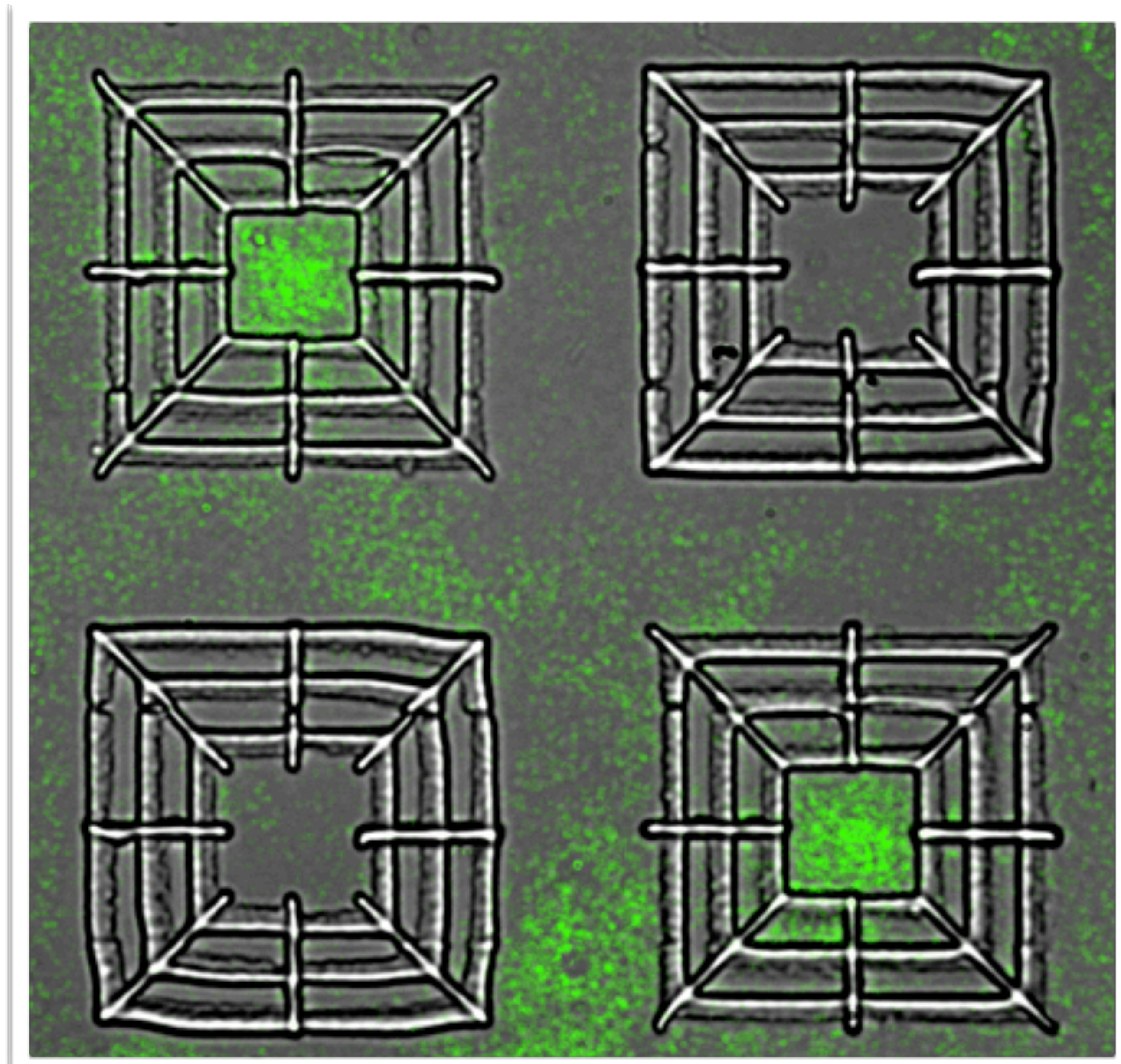
Average particle densities

KOUMAKIS, LEPORE, MAGGI, RDL, Nature Comm. (2013)

THERMAL BATH

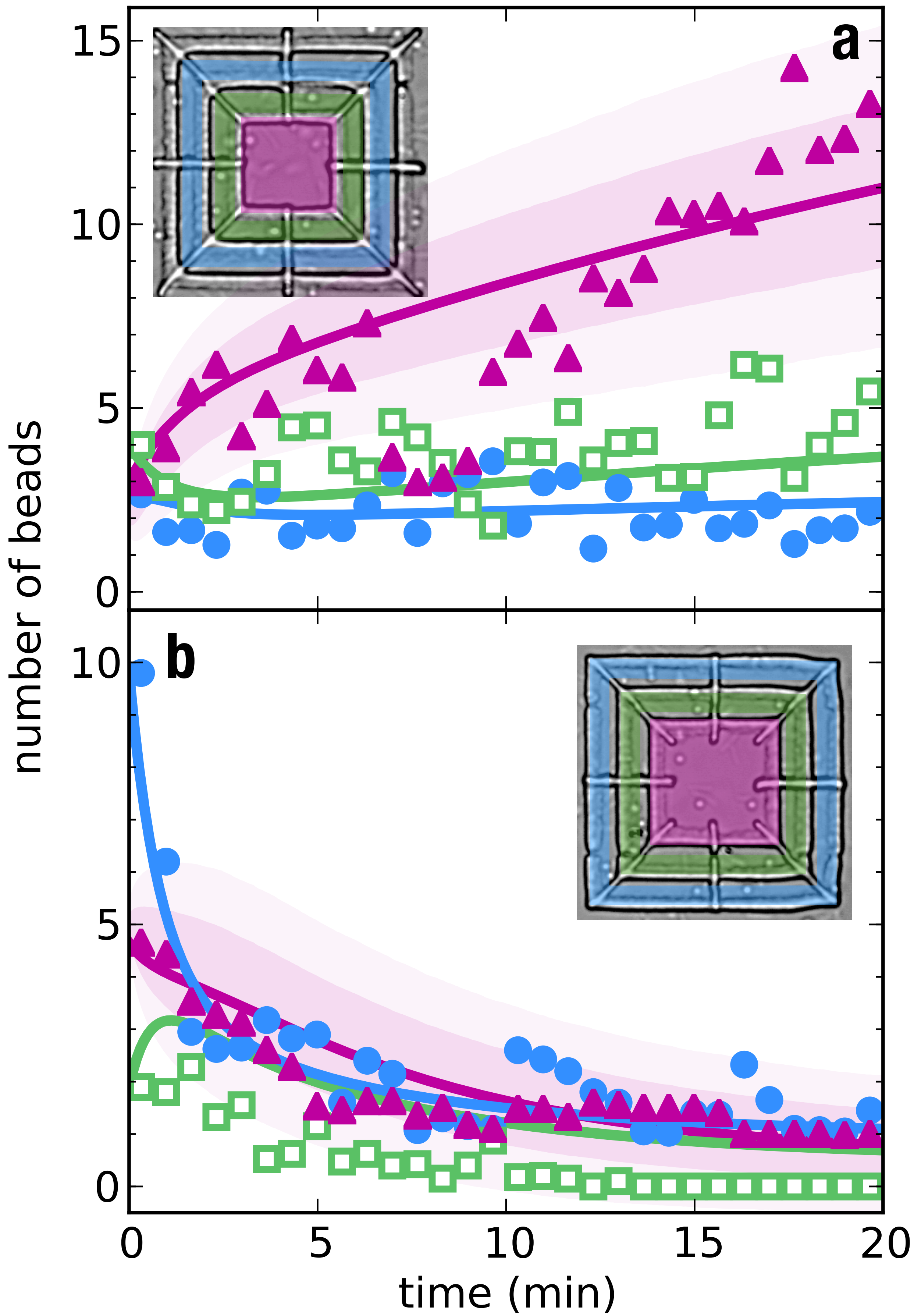


ACTIVE BATH



Fitting transition rates

KOUMAKIS, LEPORE, MAGGI, RDL, Nature Comm. (2013)

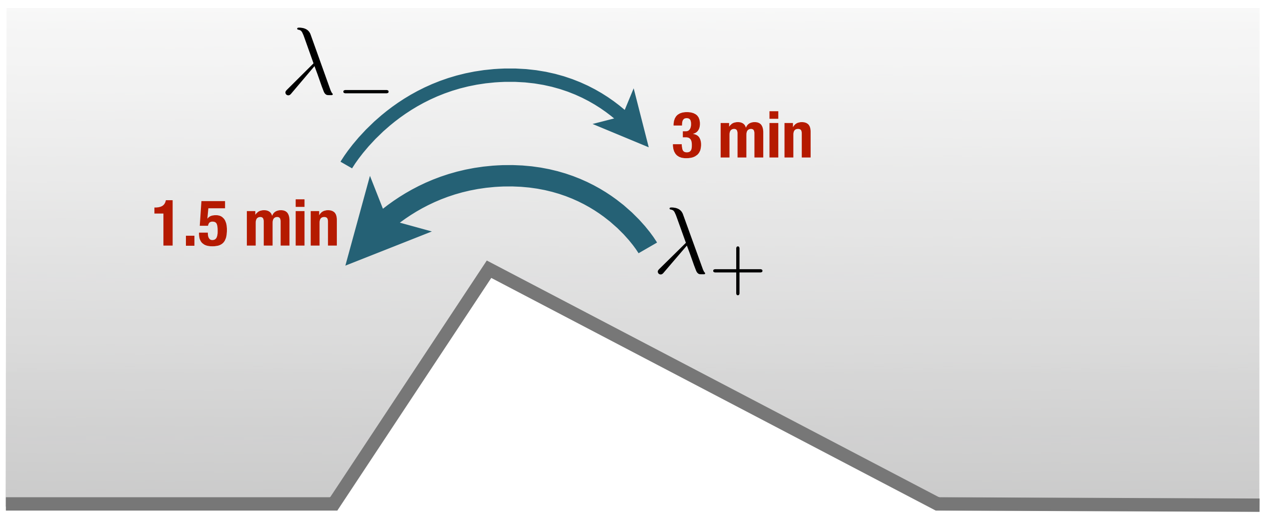


$$\dot{\mathbf{N}}(t) = -\mathbf{\Lambda} \cdot \mathbf{N}(t) + \mathbf{S}$$

$$\mathbf{N} = (n_0, n_1, n_2) \qquad \mathbf{S} = (0, 0, s)$$

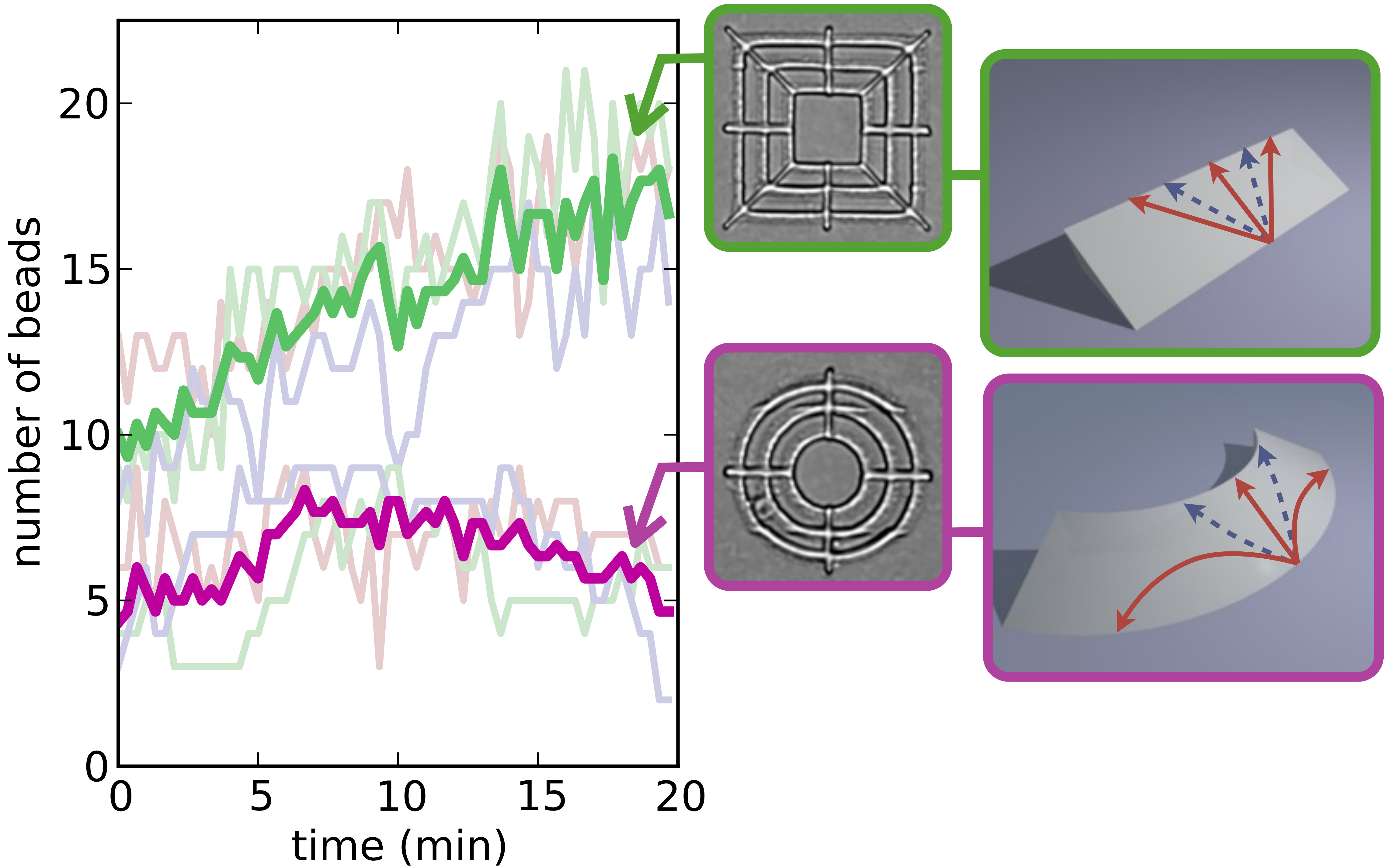
$$\lambda_+ = 0.66 \text{ min}^{-1}$$

$$\lambda_- = 0.36 \text{ min}^{-1}$$



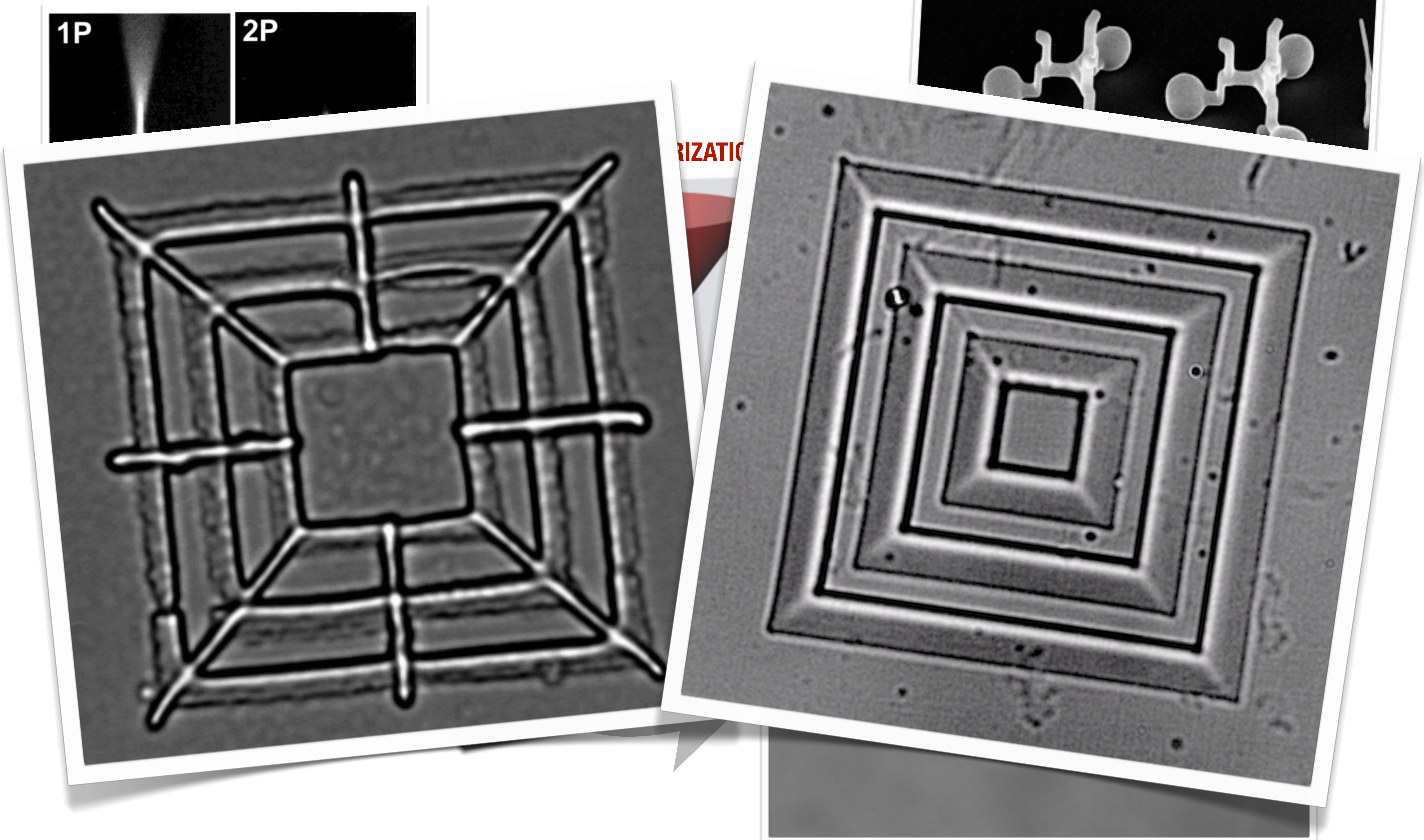
Curvature effect

KOUMAKIS, LEPORE, MAGGI, RDL, Nature Comm. (2013)



Two-photon lithography

TWO PHOTON ABSORPTION



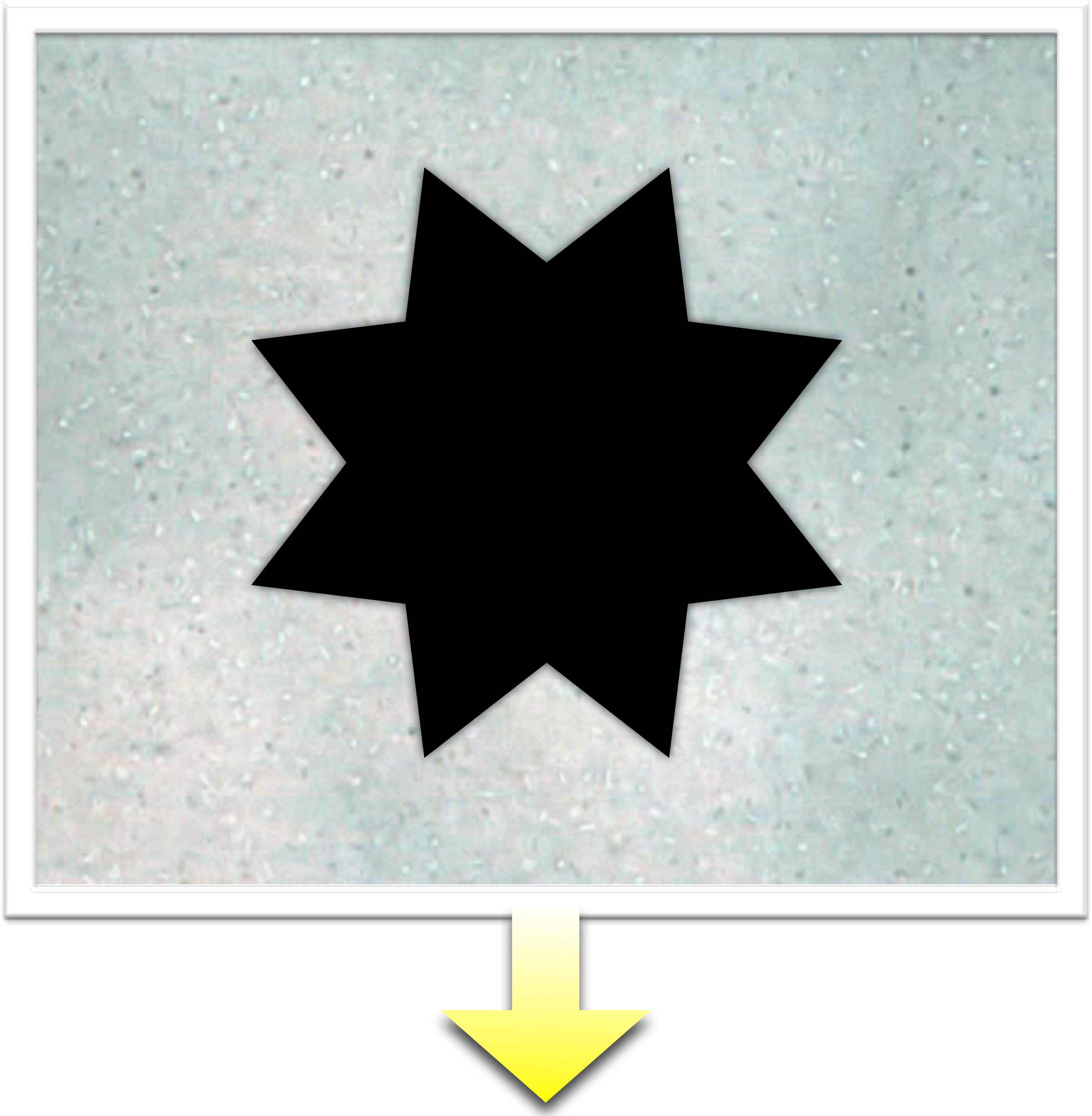
G. VIZSNYICZAI, UNPUBLISHED

STOCHASTIC DYNAMICS IN ACTIVE BATHS II

a bacterial ratchet motor

Work from fluctuations

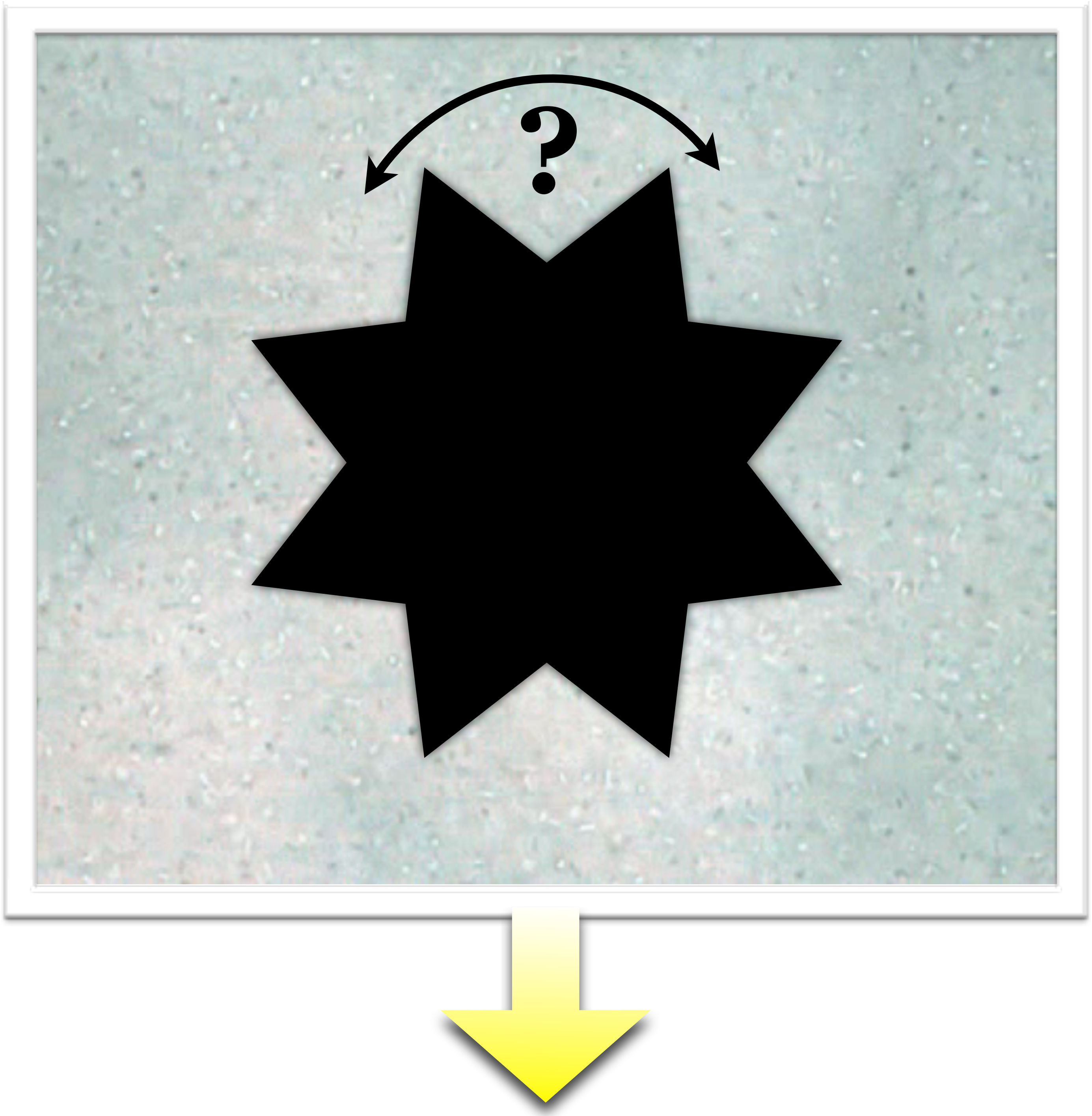
UNBIASED RANDOM FLUCTUATIONS



WORK?

Work from fluctuations

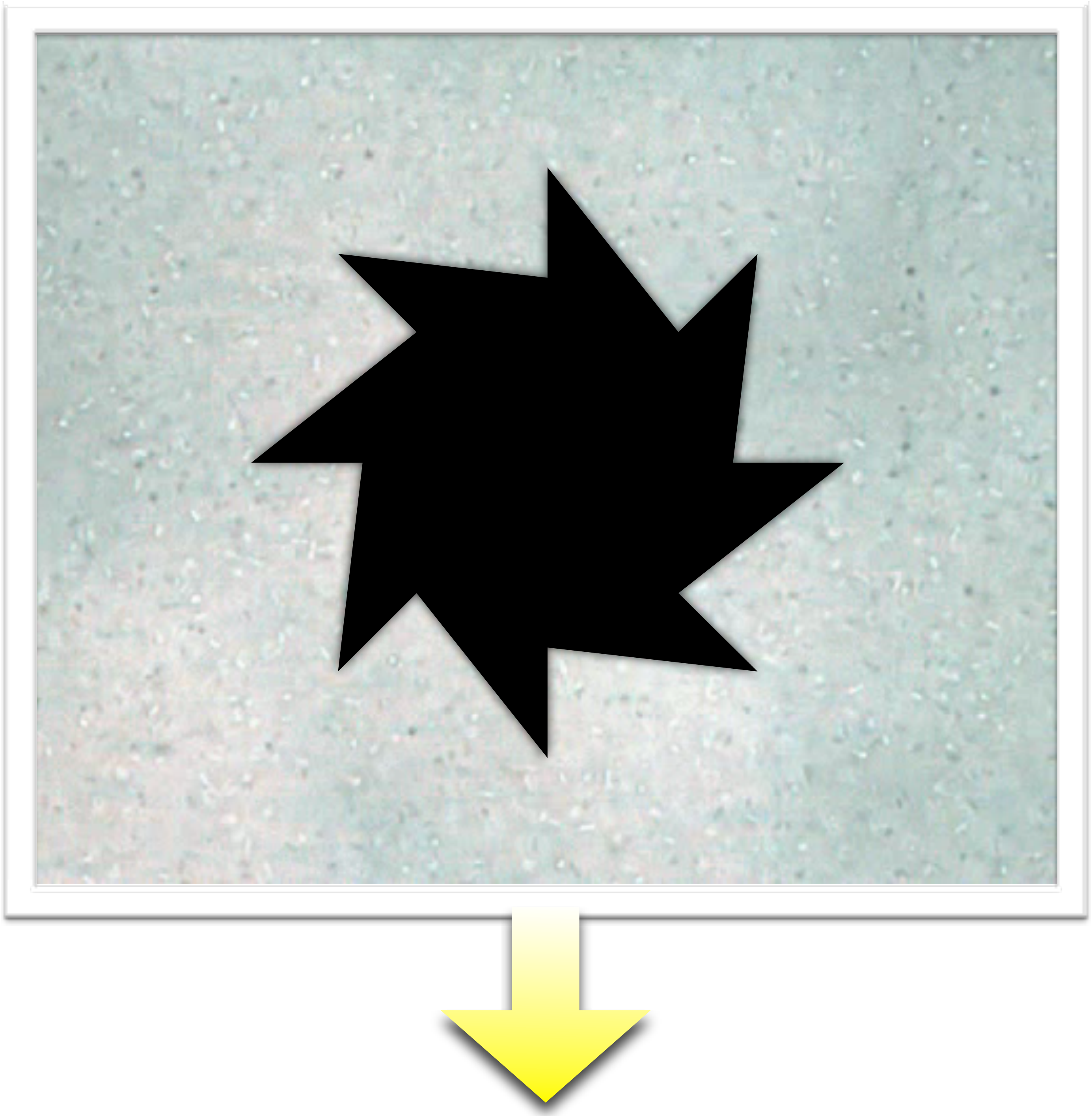
UNBIASED RANDOM FLUCTUATIONS



WORK?

Work from fluctuations

UNBIASED RANDOM FLUCTUATIONS



WORK?

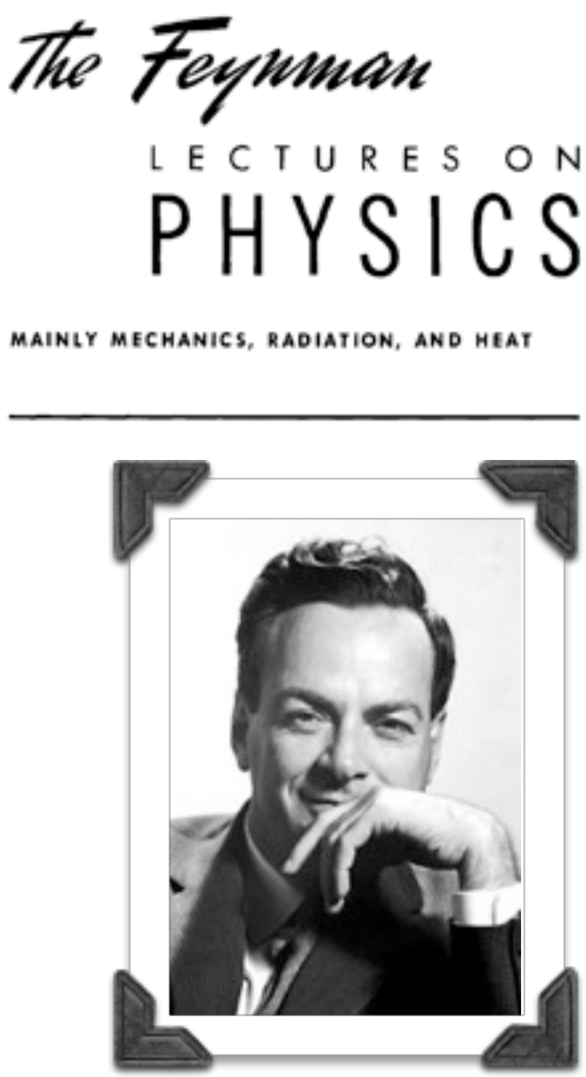
"C'est la dissymétrie qui crée le phénomène" P. CURIE, J. PHYS 3, 393, (1894)

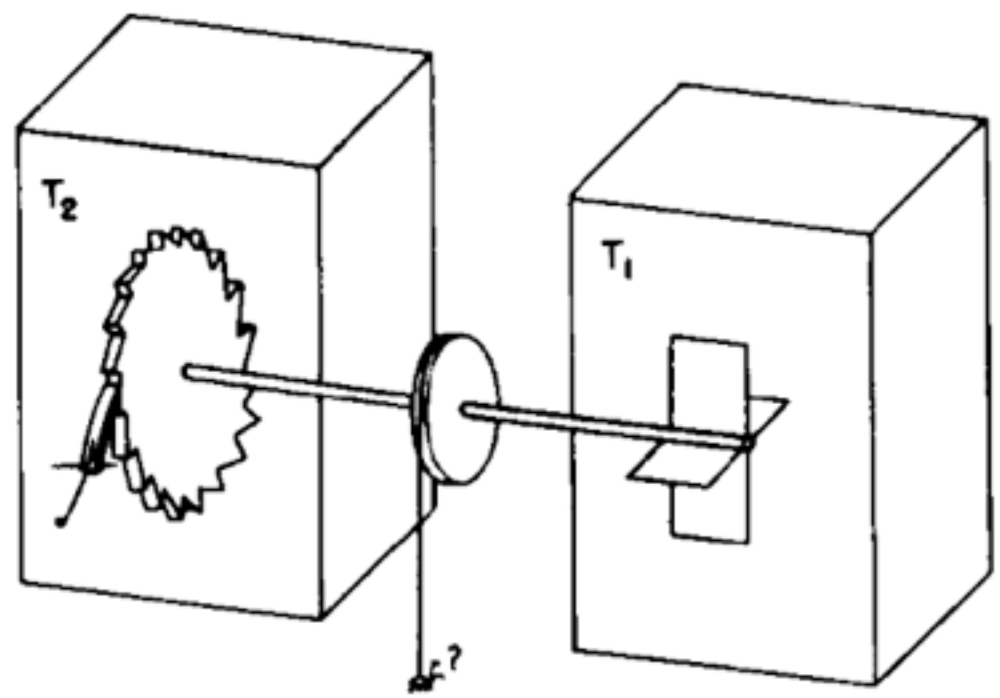
Brownian ratchets

XXII. EXPERIMENTELL NACHWEISBARE, DER ÜBLICHEN THERMODYNAMIK WIDERSPRECHENDE MOLEKULAR-PHÄNOMENE.

Physikalische Zeitschrift, XIII. Jahrgang, pp. 1069—1080. 1912. Vortrag vor der 84. Naturforscherversammlung zu Münster (Westfalen).

M. SMOLUCHOWSKI

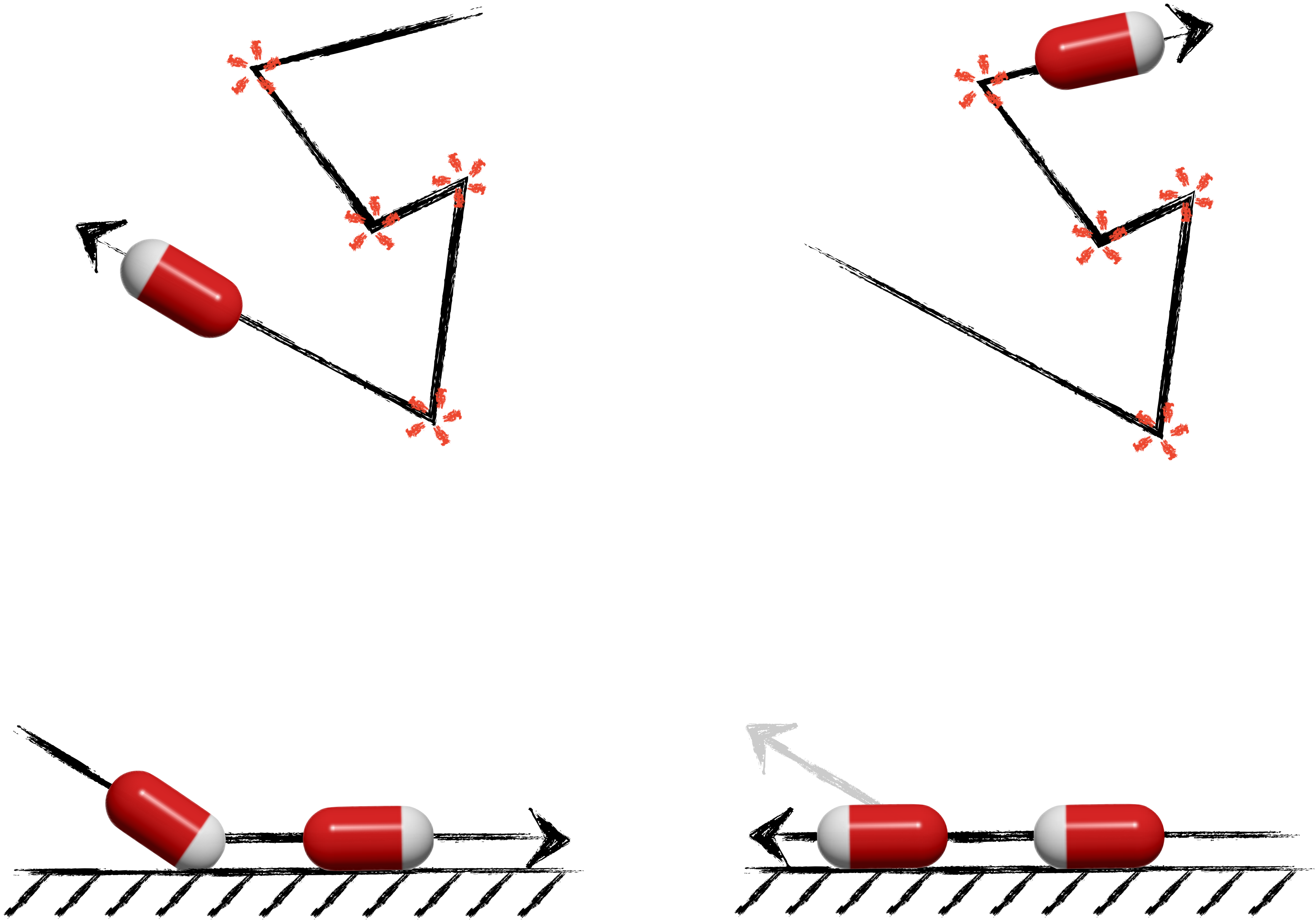




“So it is impossible to design a machine which, in the long run, is more likely to be going one way than the other, if the machine is sufficiently complicated”

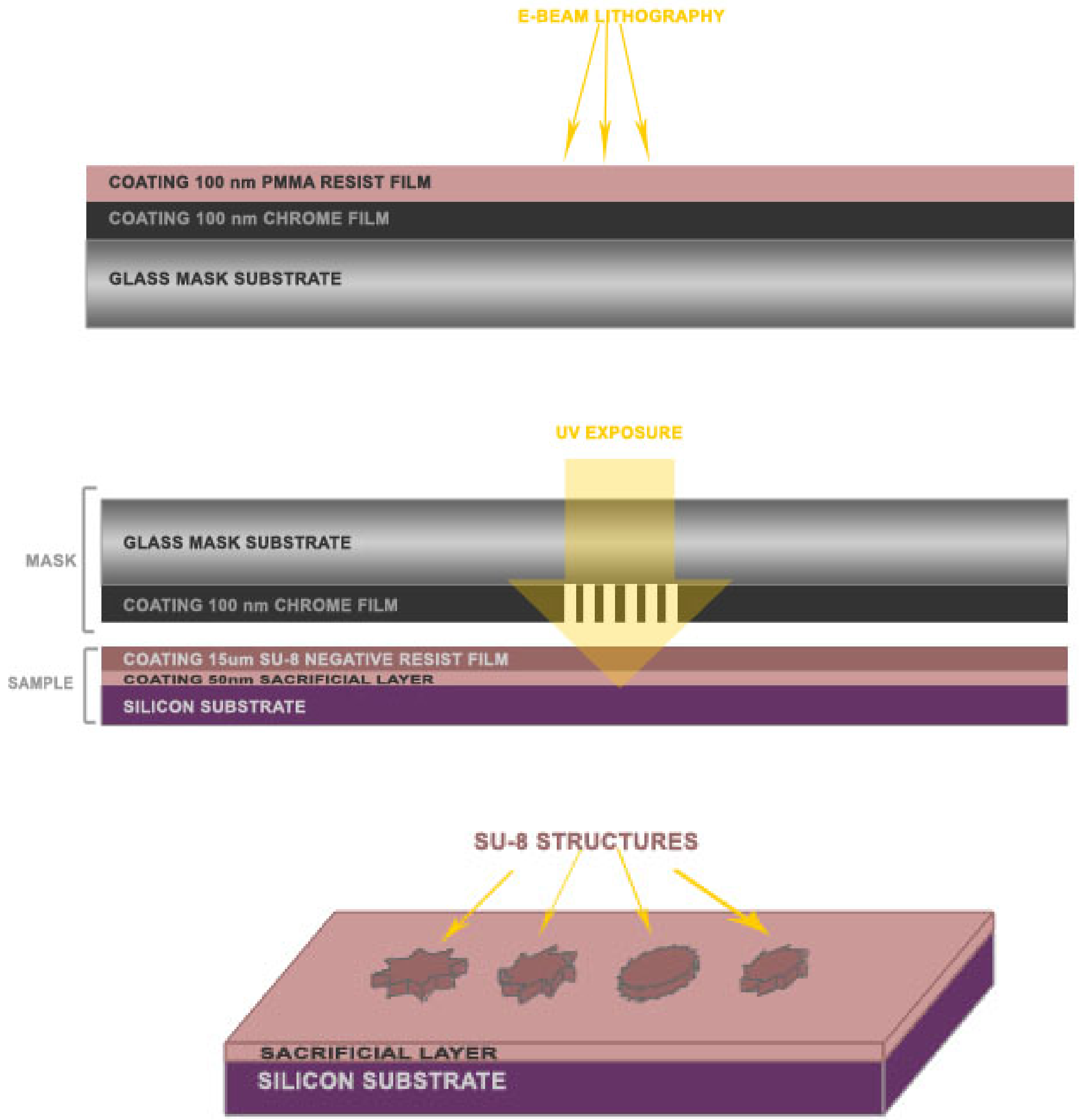
“It is based on the fact that the laws of mechanics are reversible”

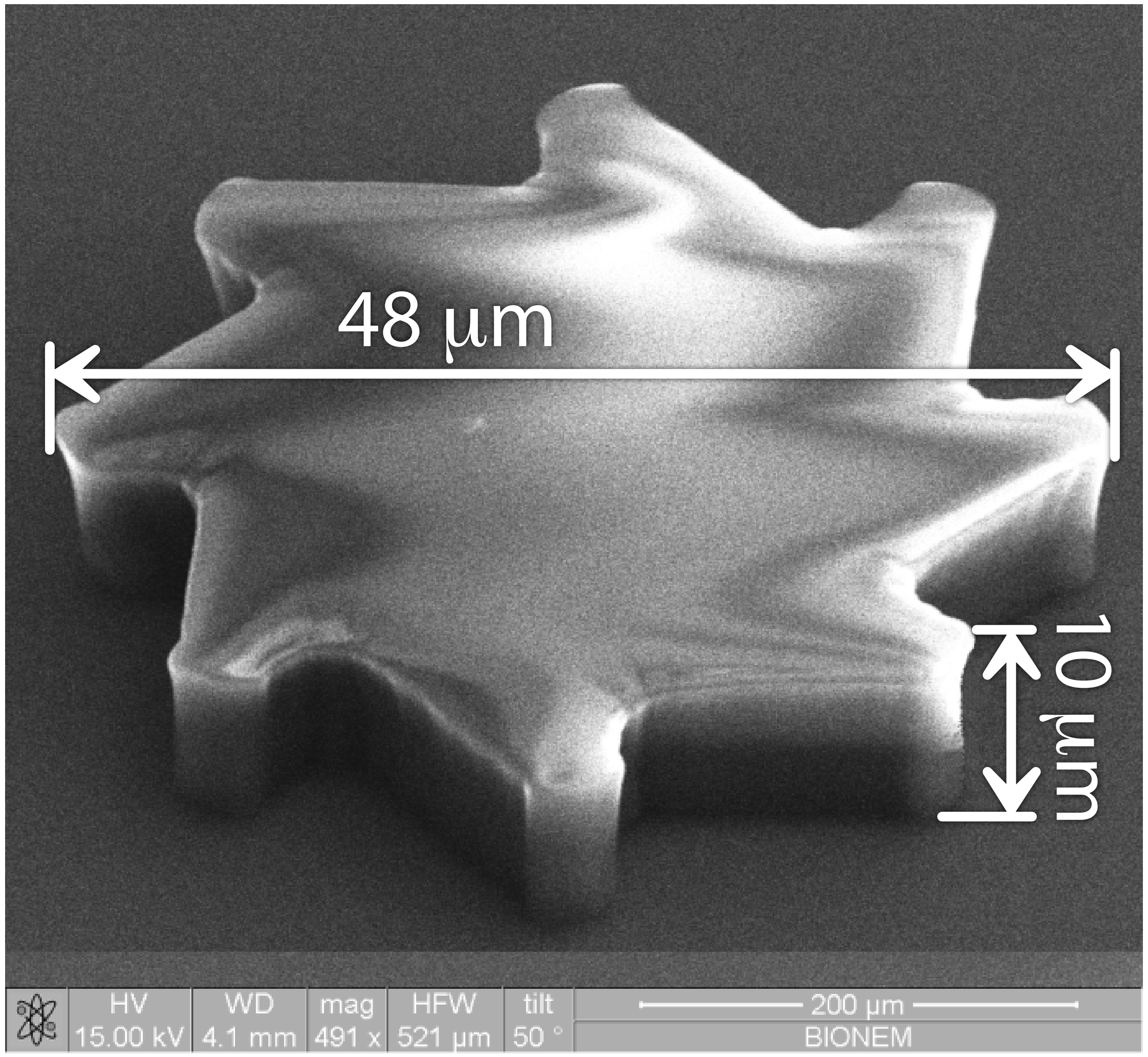
Bacterial dynamics violates detailed balance



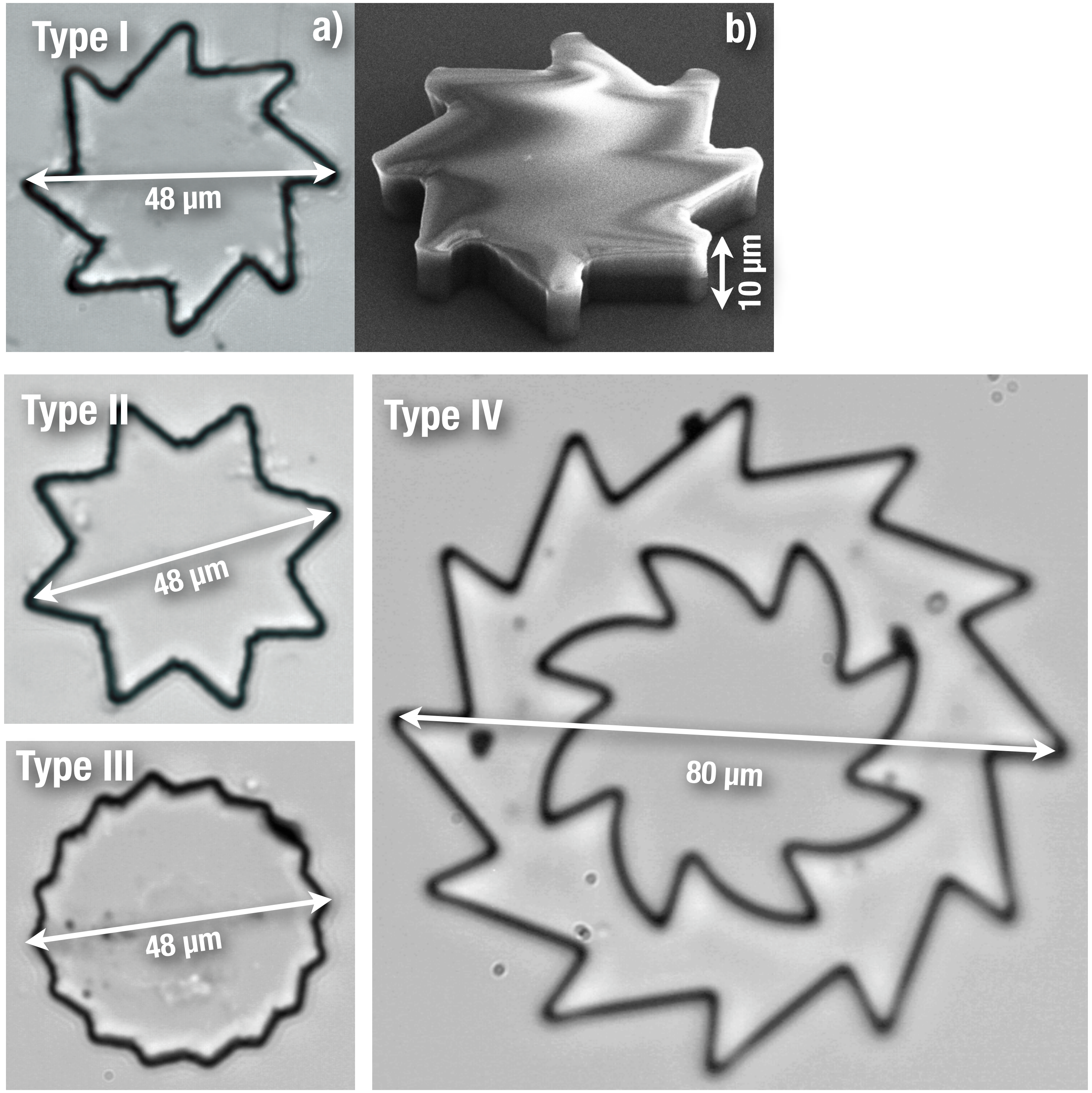
Micro-fabrication

E. Di FABRIZIO BIONEM LAB, CATANZARO

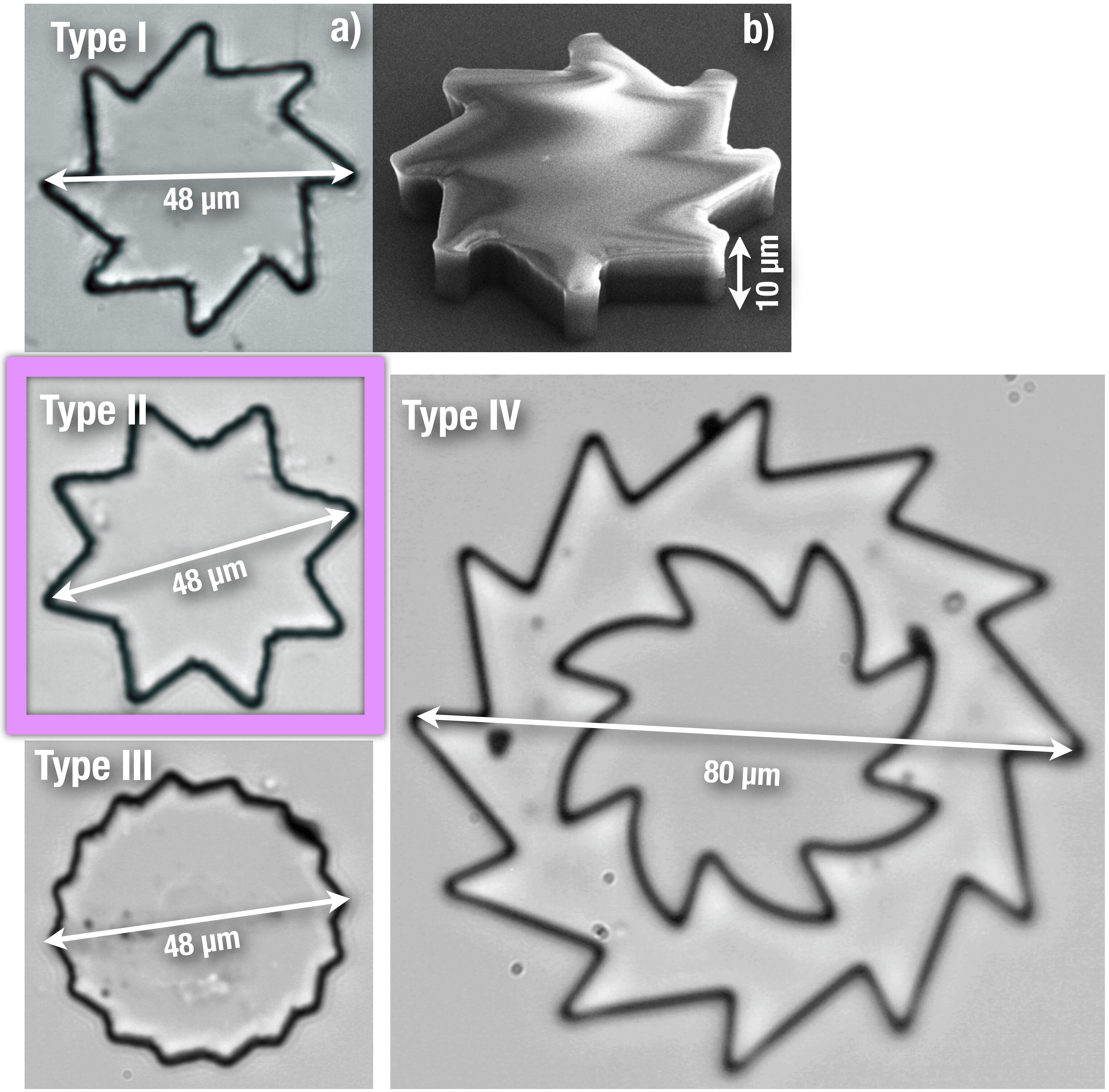




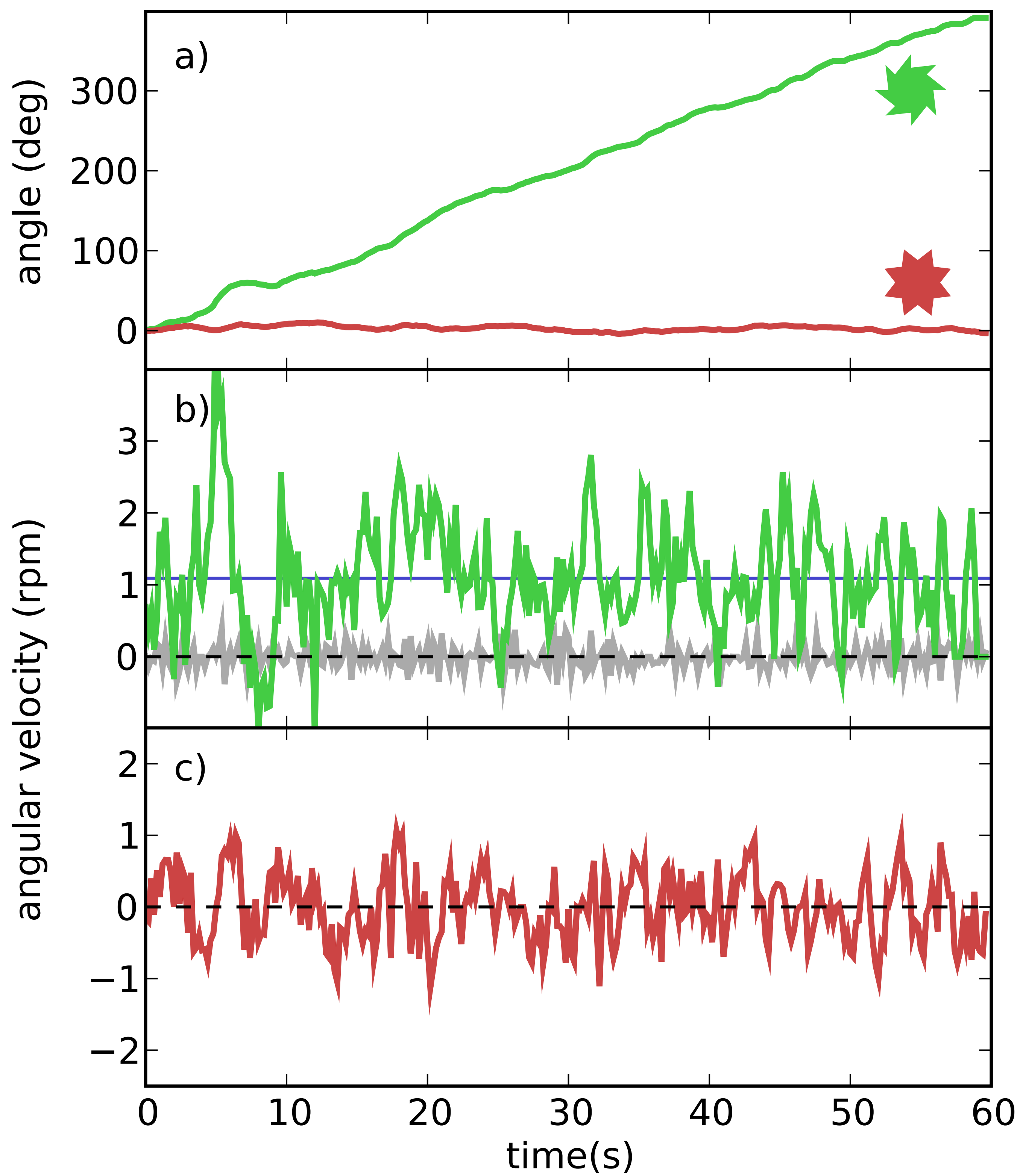
2D geometries



2D geometries



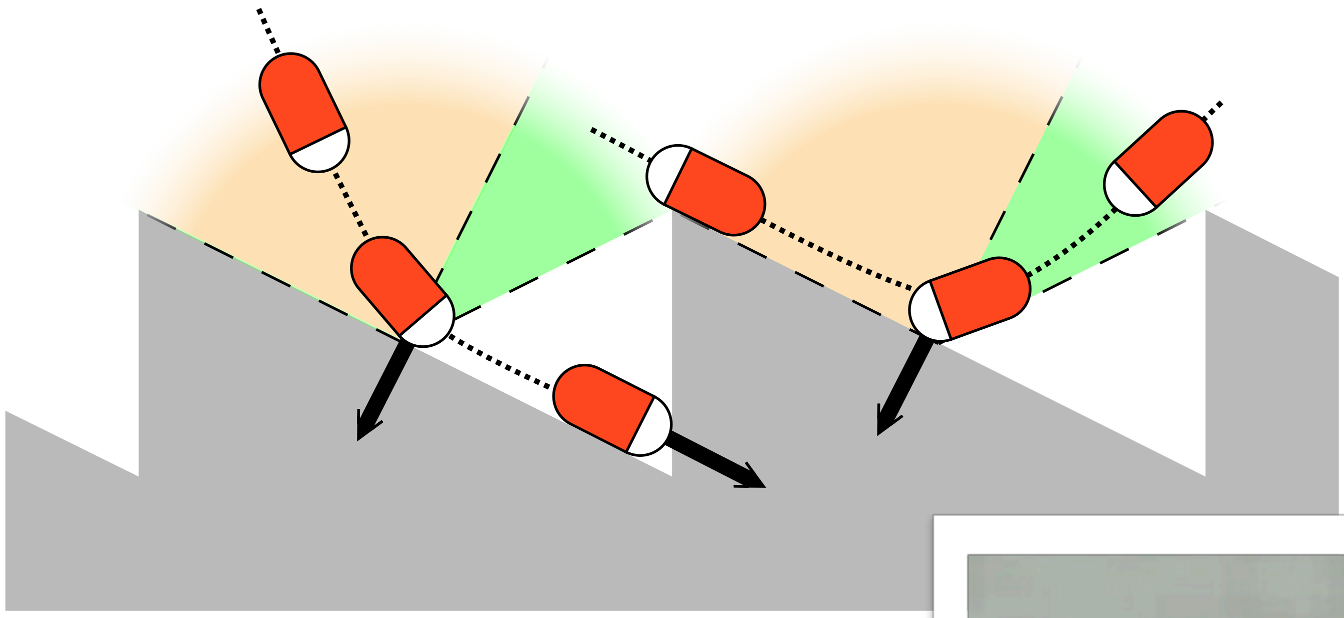
2D geometries

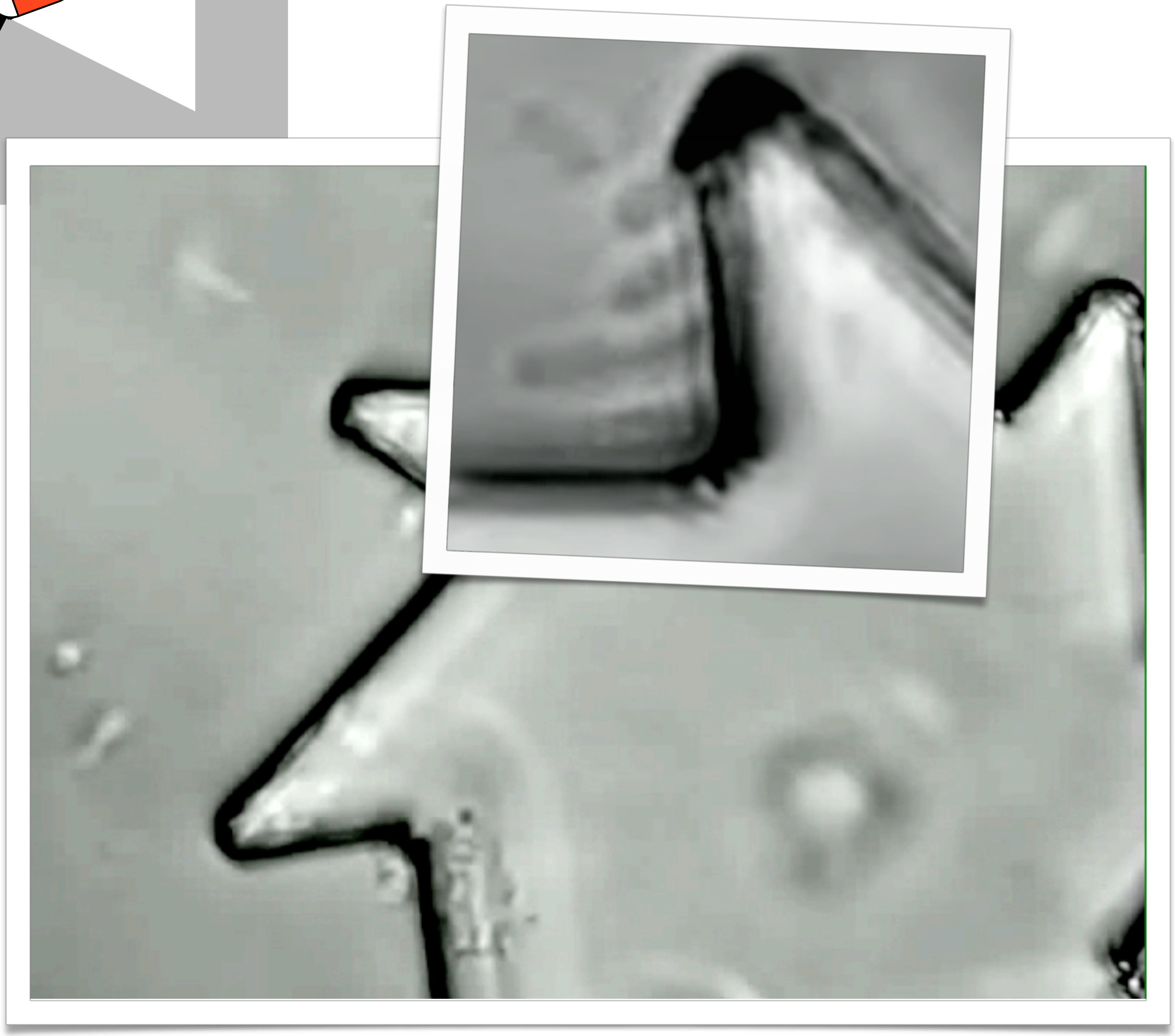


R. DI LEONARDO, et al. PNAS (2010)

nature RESEARCH HIGHLIGHTS

Bacteria-boundary interaction

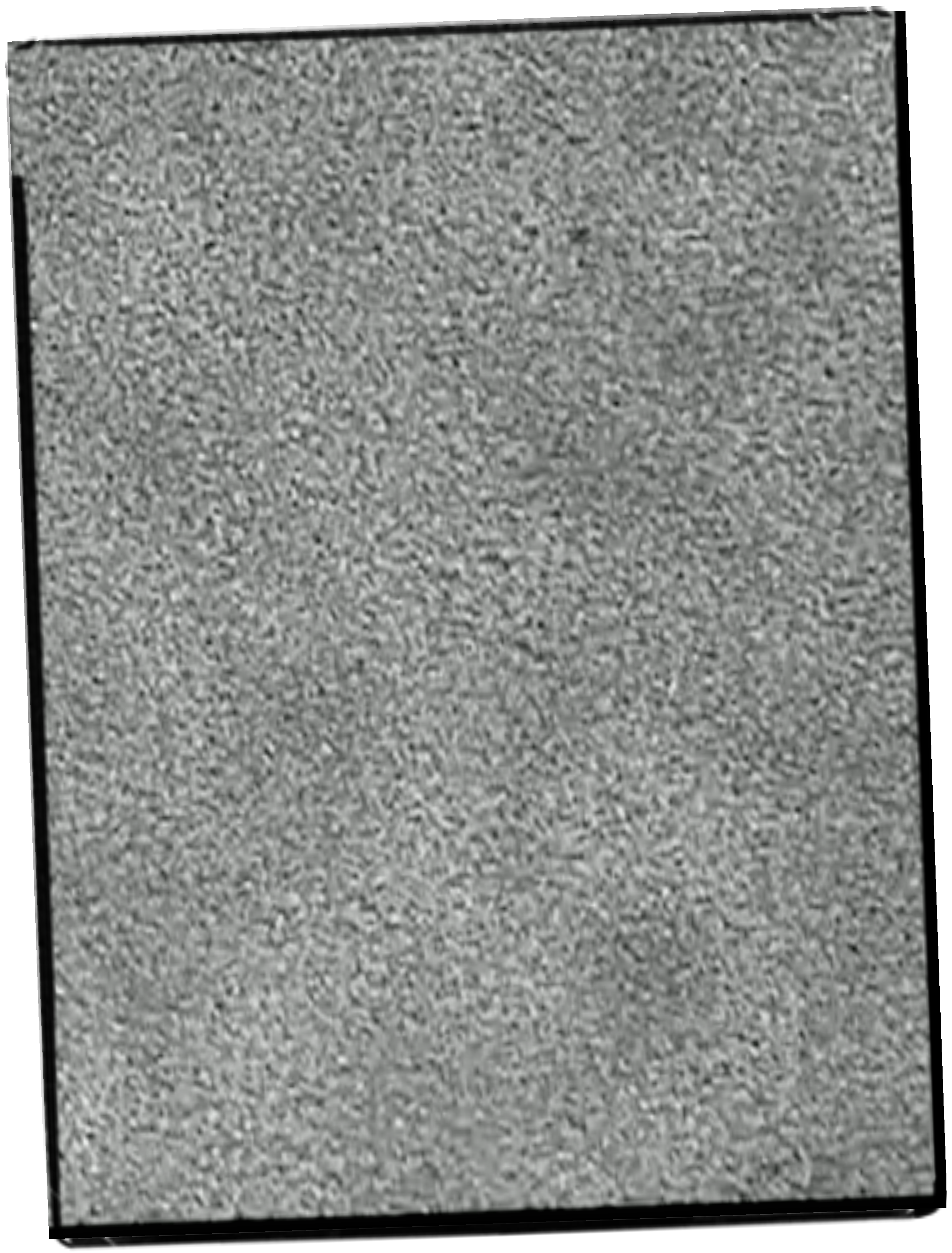


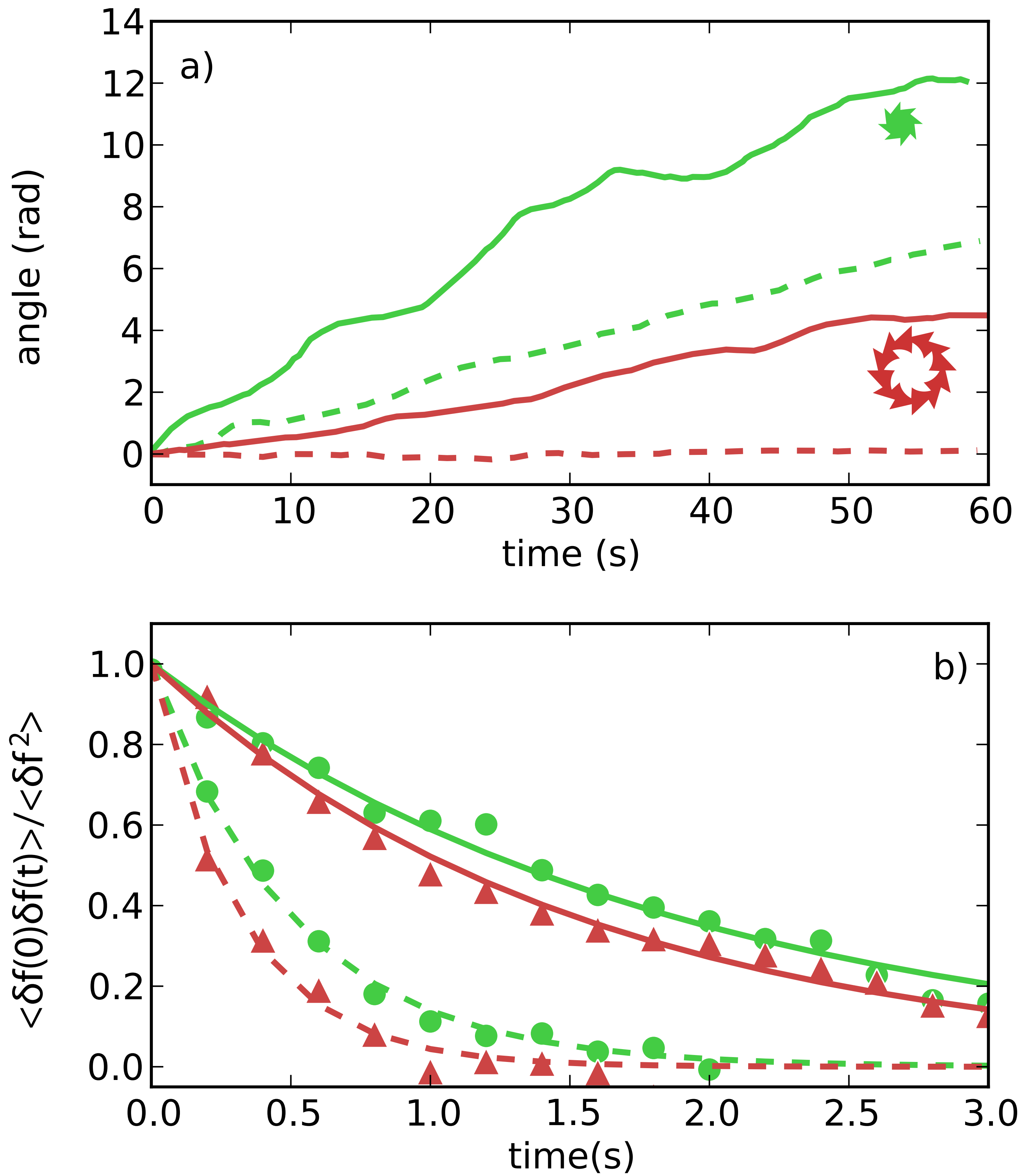


High concentration regime

$\sim 10^{11}$

BACTERIA/ML





STOCHASTIC DYNAMICS IN ACTIVE BATHS

- persistent (non FDT) forces due to bacteria generate stationary states characterized by probability distributions that strongly deviate from Boltzmann
- these stationary states are also microscopically not invariant under time reversal
- these peculiar properties of active matter allow to exploit bacteria as a workforce in miniaturized environments

microfisica

CONSIGLIO NAZIONALE DELLE RICERCHE - NANOTEC
SOFT AND LIVING MATTER LABORATORY
DIPARTIMENTO DI FISICA SAPIENZA
P.le A. Moro 2, 00185 ROMA, ITALY

PHYSICS AT THE MICRON SCALE

PEOPLE


R. DI LEONARDO


C. MAGGI


N. KOUMAKIS


M. PAOLUZZI


S. BIANCHI


A. LEPORE


F. SAGLIMBENI


G. VIZSNYICZAI

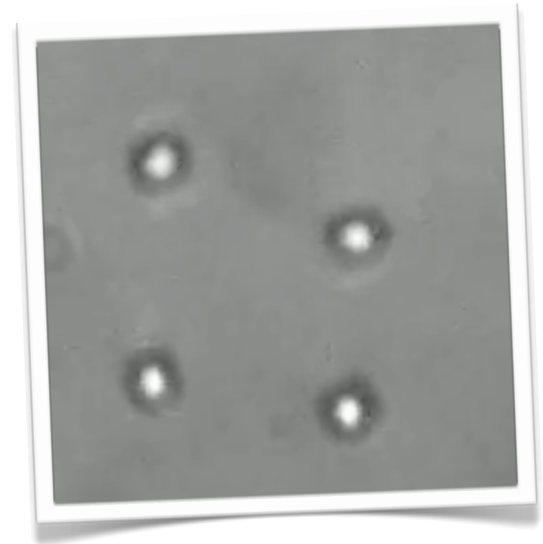
COLLABORATIONS

L. ANGELANI, CNR-IPCF SAPIENZA
E DI FABRIZIO, C. LIBERALE, KAUST, SAUDI ARABIA

FUNDING

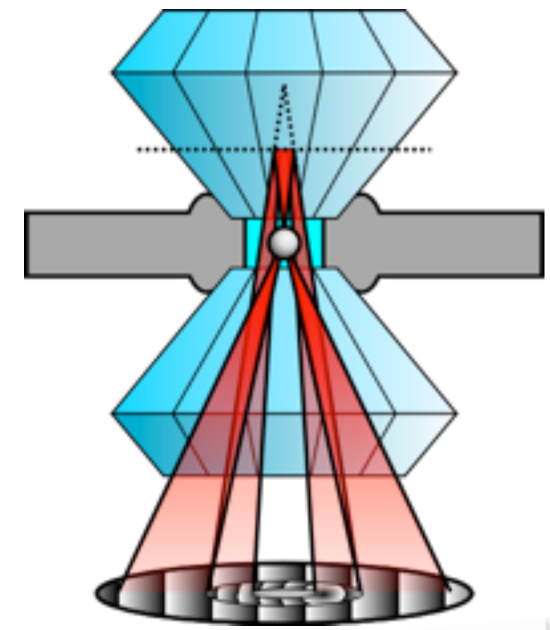
HYDRO SYNC IN ROTATING LANDSCAPES

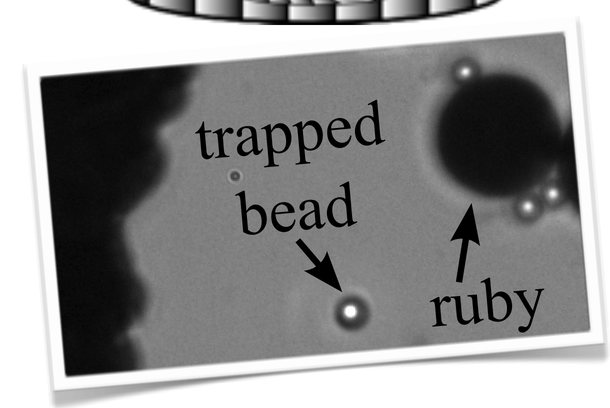
KOUMAKIS & RDL, PRL (2013)



TRAPPING AT GPa

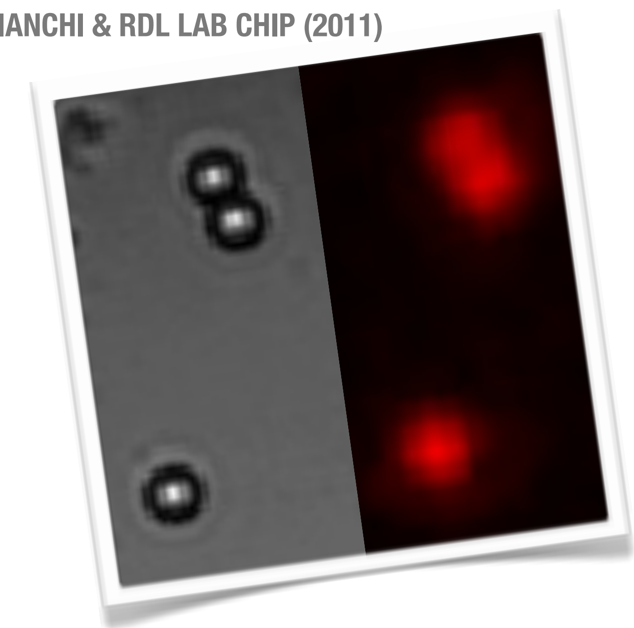
BOWMAN, GIBSON, PADGETT, SAGLIMBENI, RDL PRL (2013).





IMAGING THROUGH OPTICAL FIBERS

BIANCHI & RDL LAB CHIP (2011)



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