3D-tracking reveals: How do sperm find the egg?

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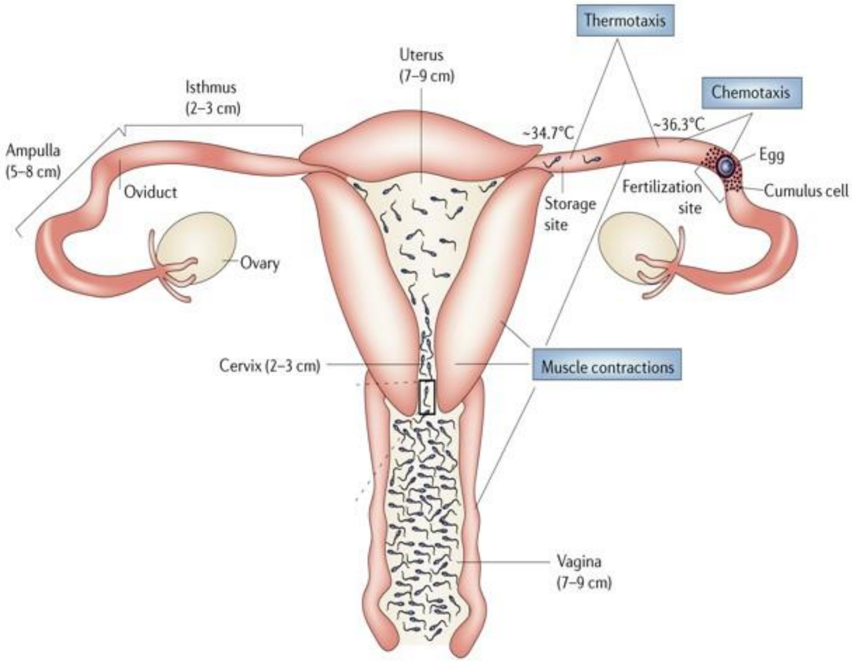
How do sperm find the egg?

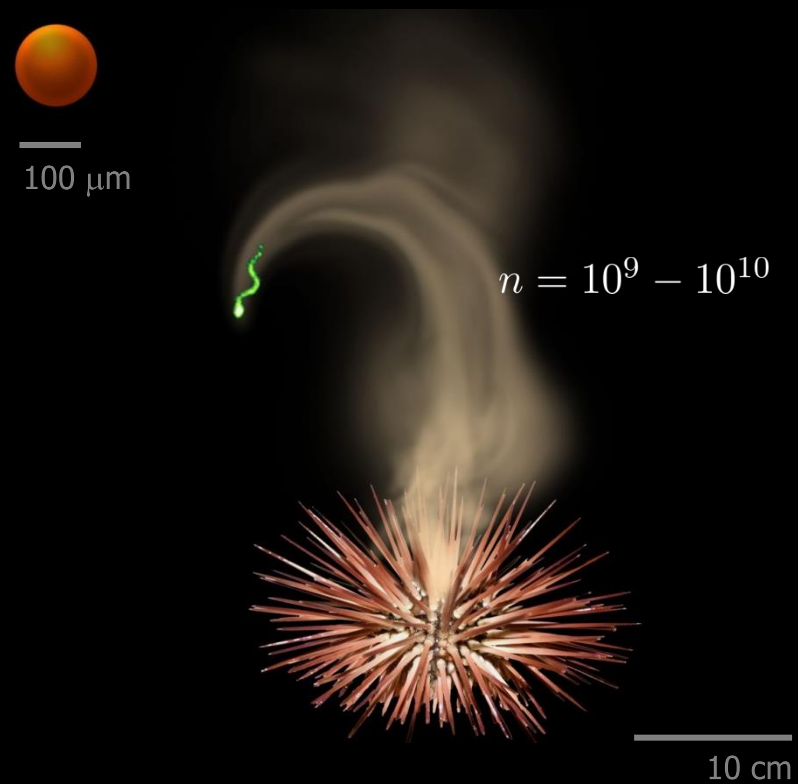
The search environment matters

Internal fertilization



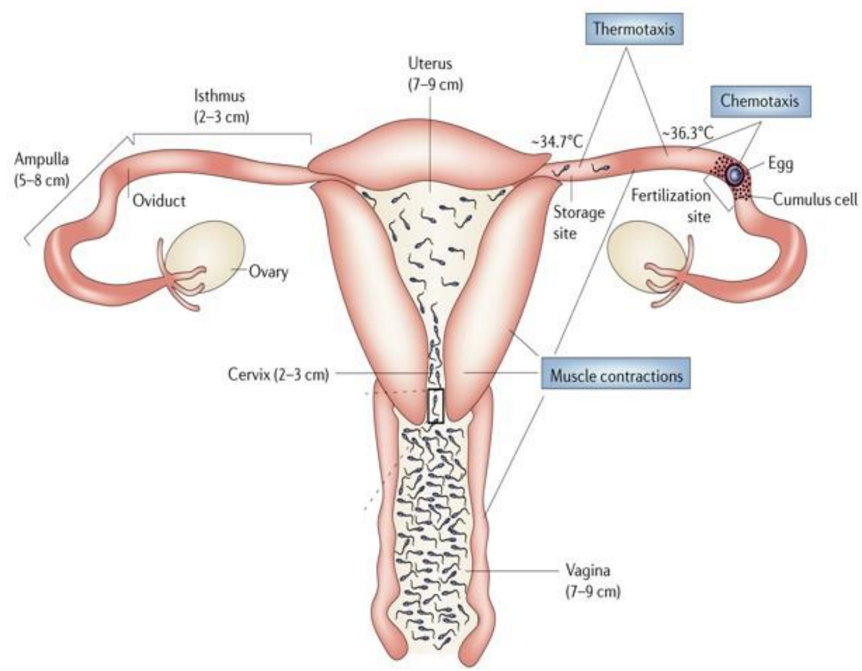
The search environment matters

External fertilization



$n = 10^9 - 10^{10}$

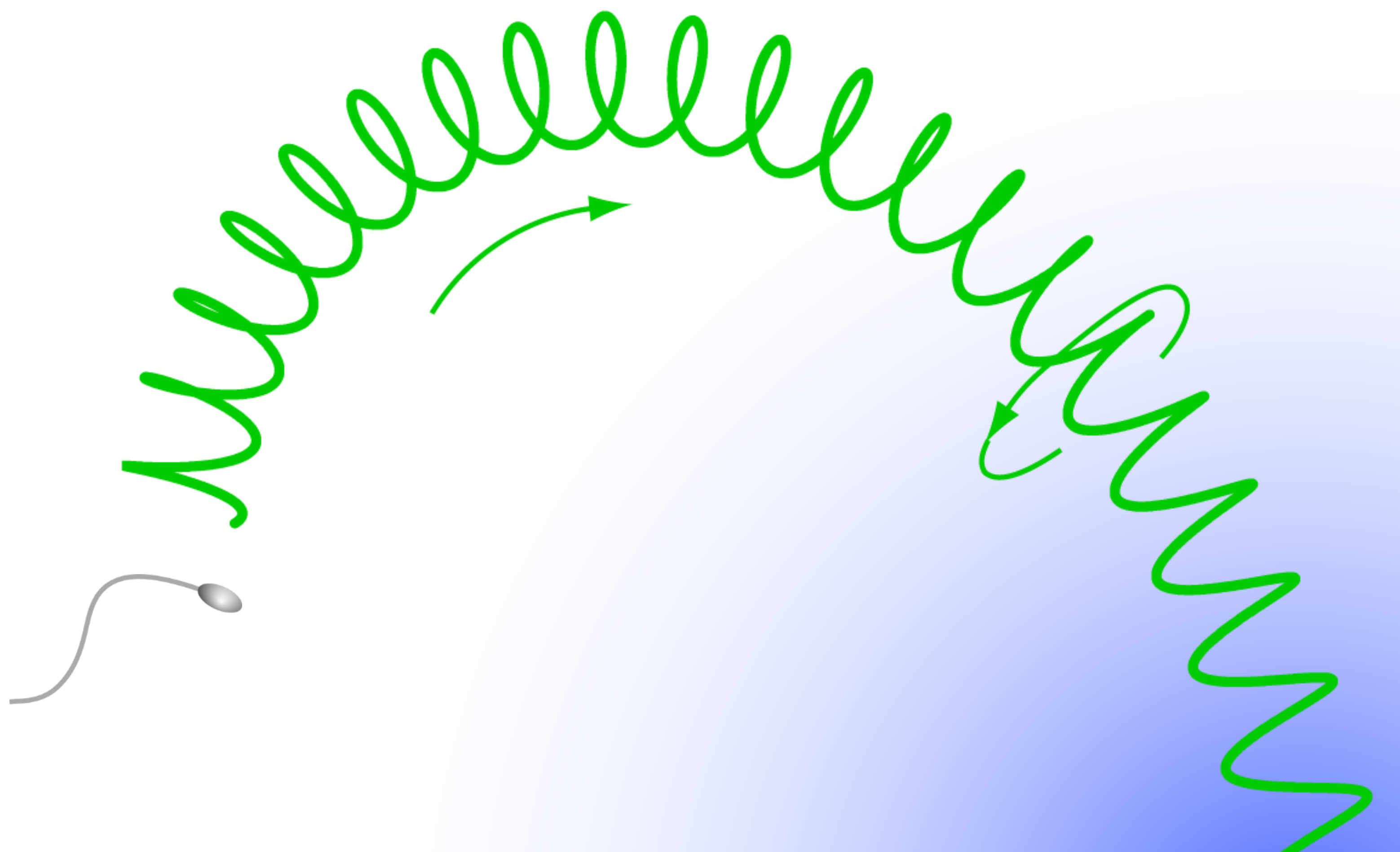
Internal fertilization



$n = 10^7 - 10^9$

The egg releases chemical guidance cues

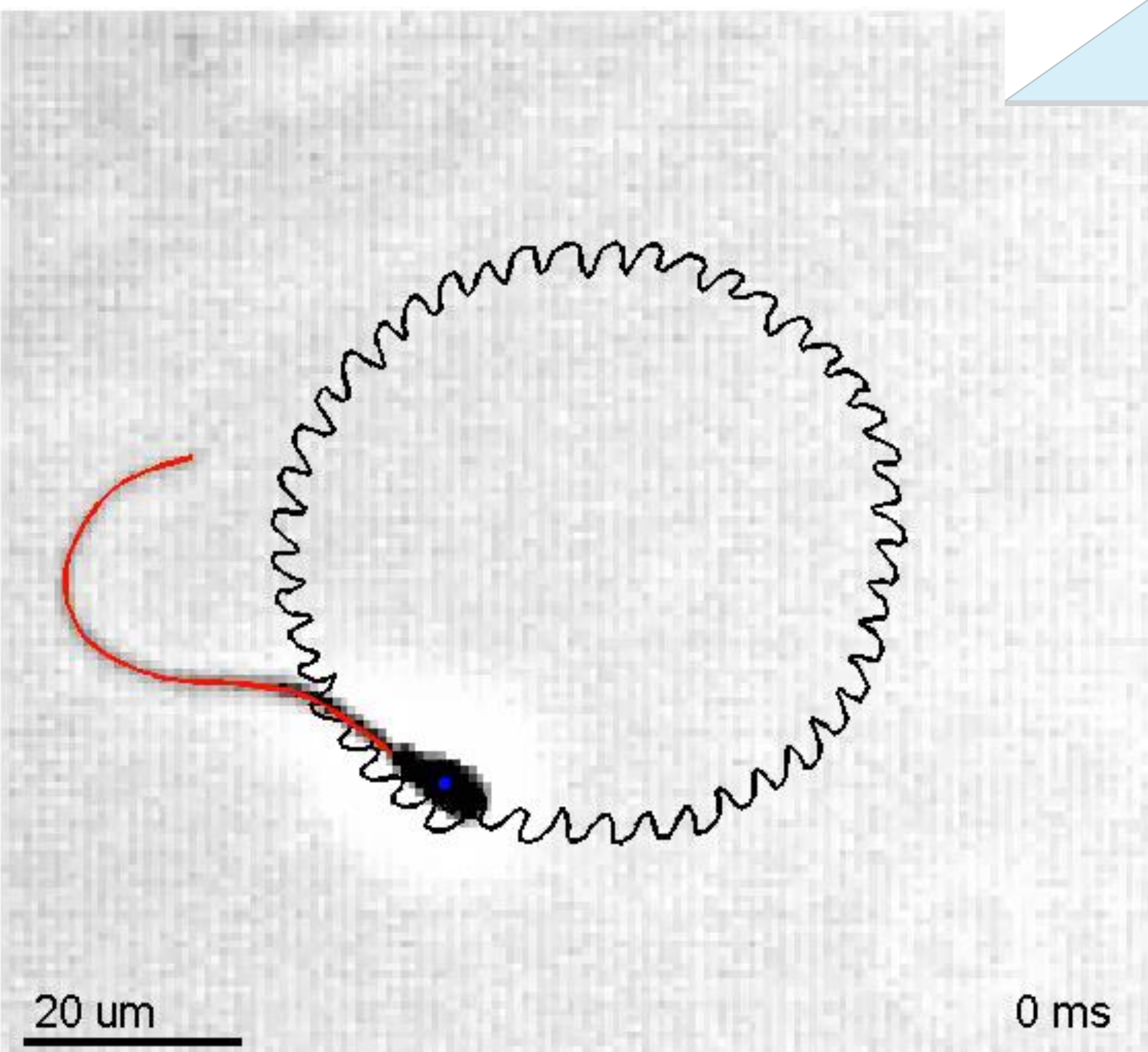
Theory: Sperm from marine species steer along helical paths

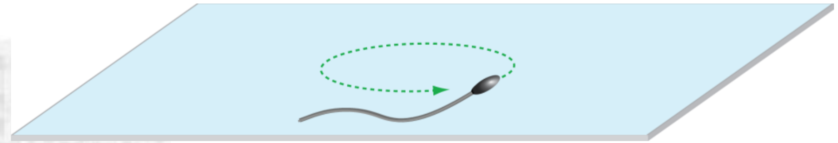


Friedrich et al.: PNAS (2007)
Friedrich et al.: NJP (2008)
Friedrich et al.: PRL (2009)

Let’s consider the simpler 2d case

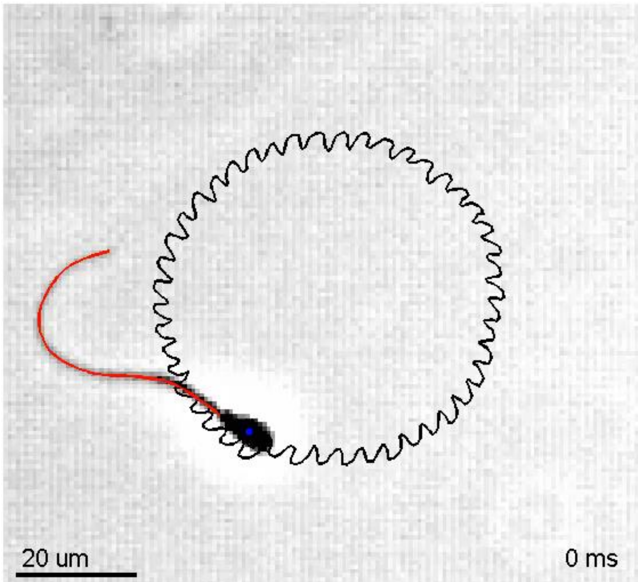
Sperm swim along circular paths close to boundaries

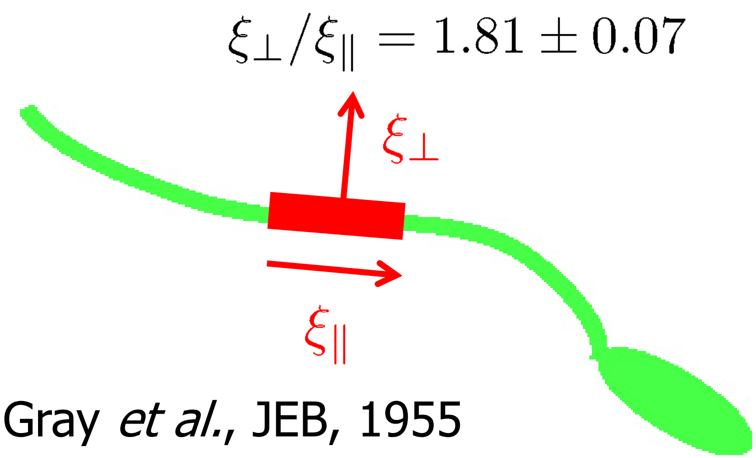




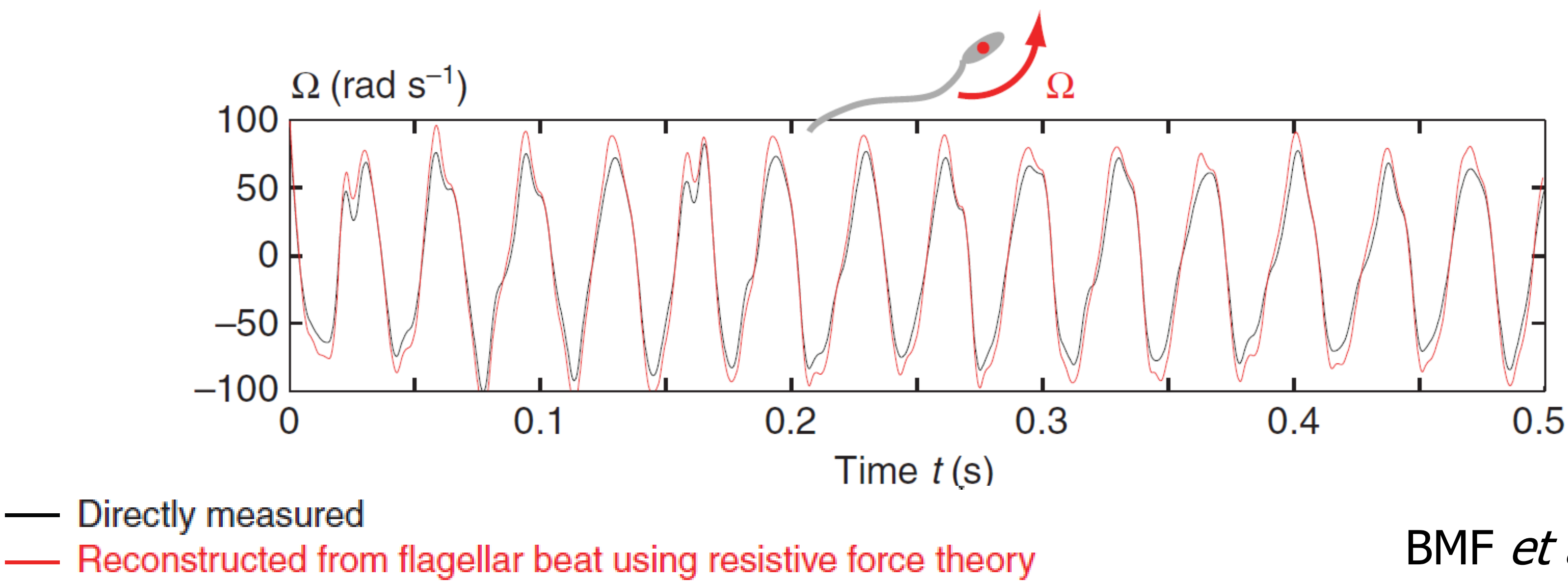
BMF, I Riedel-Kruse, J Howard, F Jülicher, J exp Biol **213**, 2010

Anisotropic friction allows self-propulsion



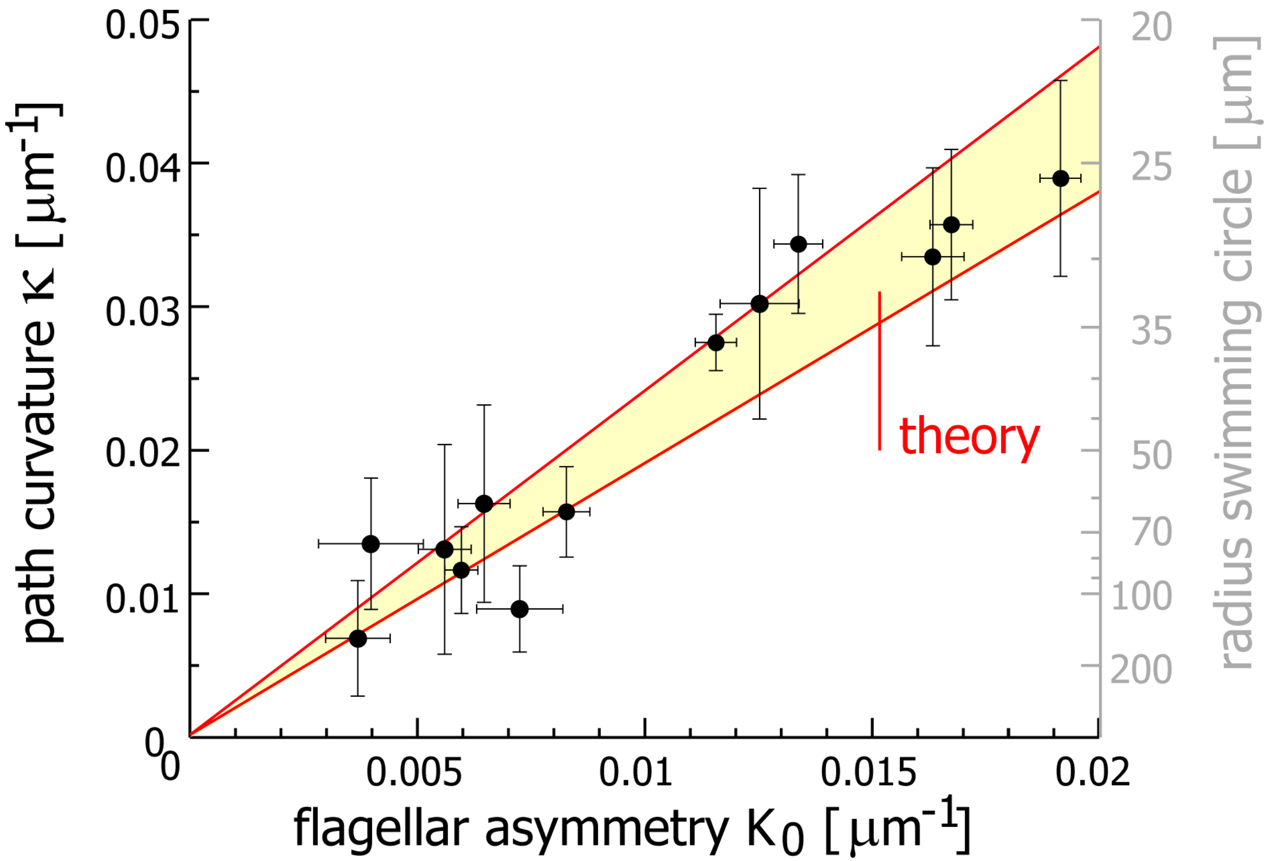


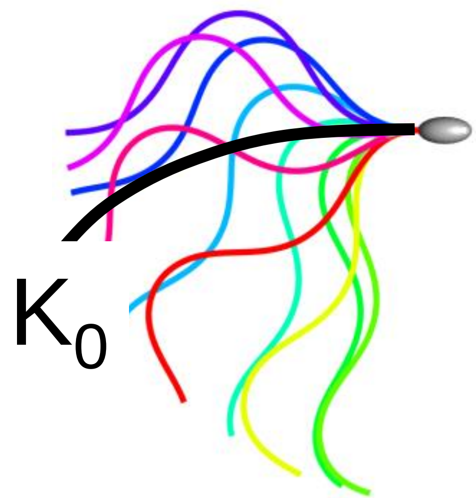
Gray *et al.*, JEB, 1955



BMF *et al.*, JEB, 2010

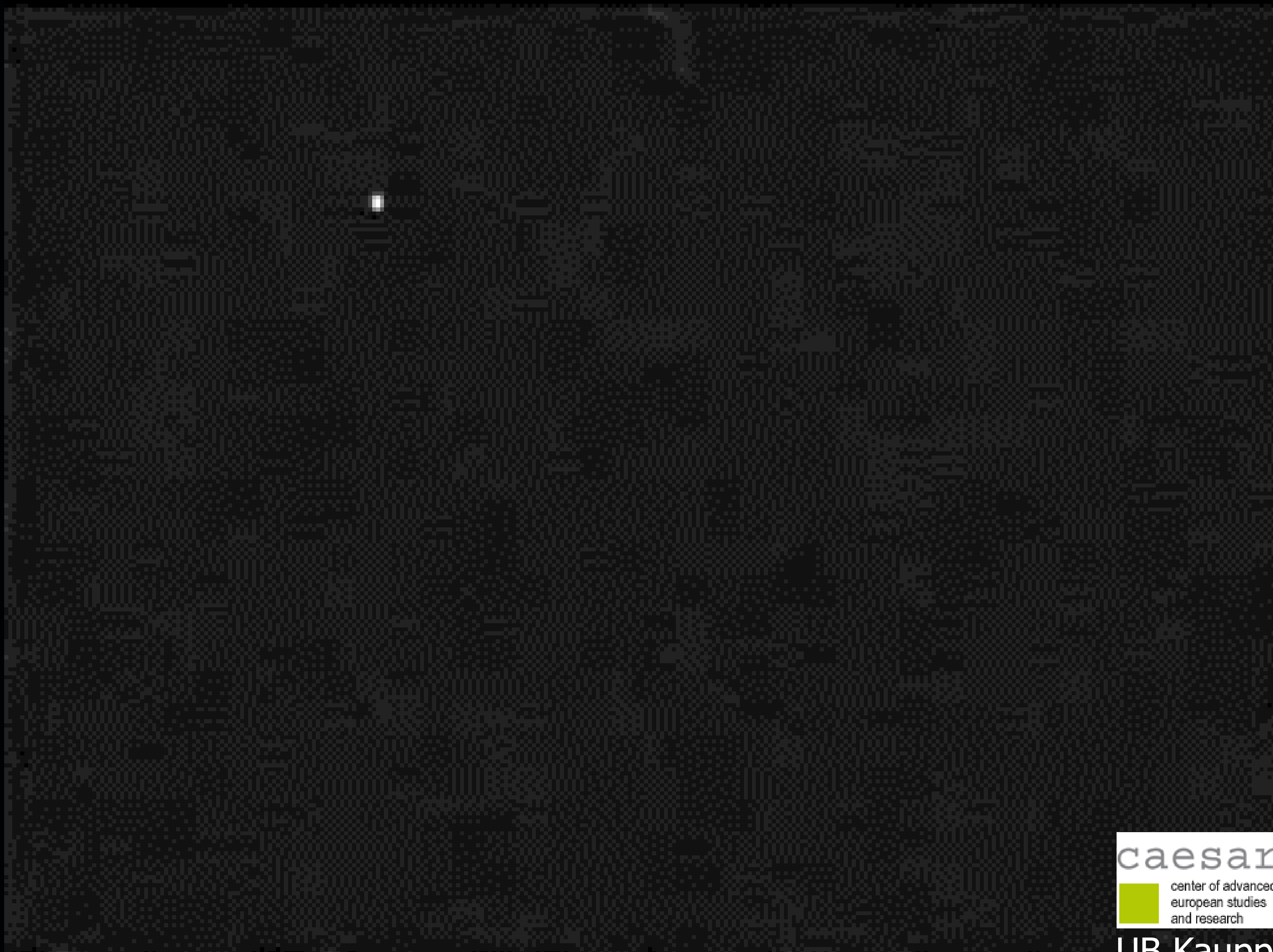
Flagellar asymmetry controls path curvature





BMF, I Riedel-Kruse, J Howard, F Jülicher, J exp Biol **213**, 2010

Testing chemotaxis in a shallow observation chamber



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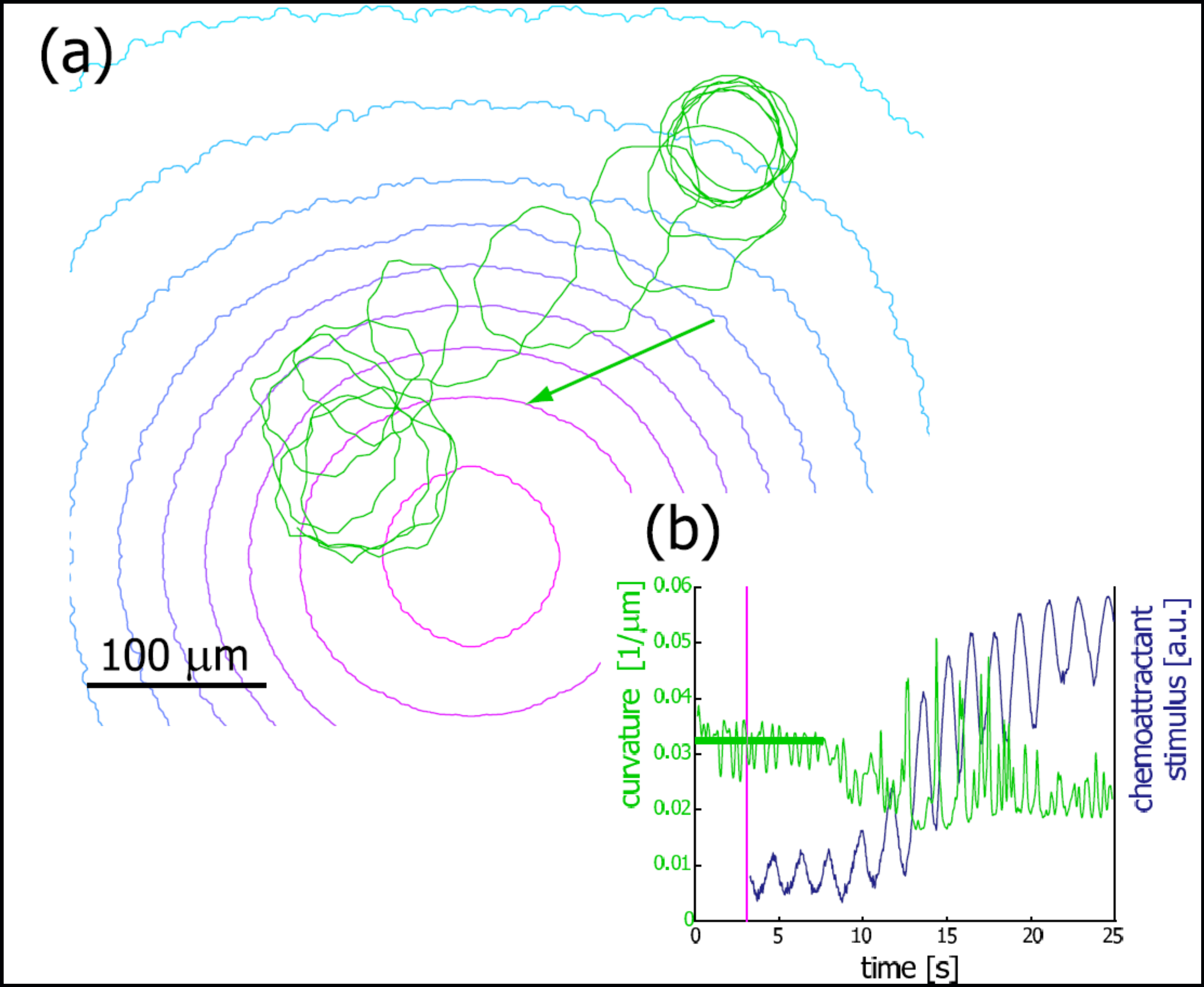
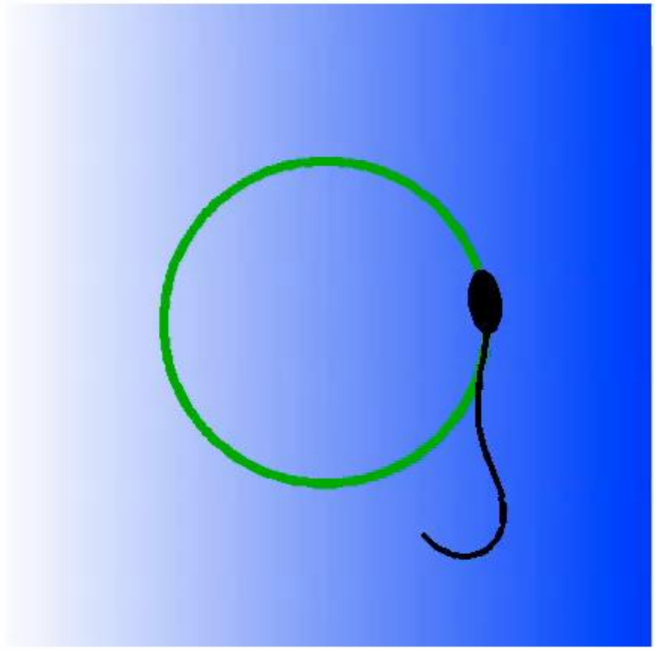
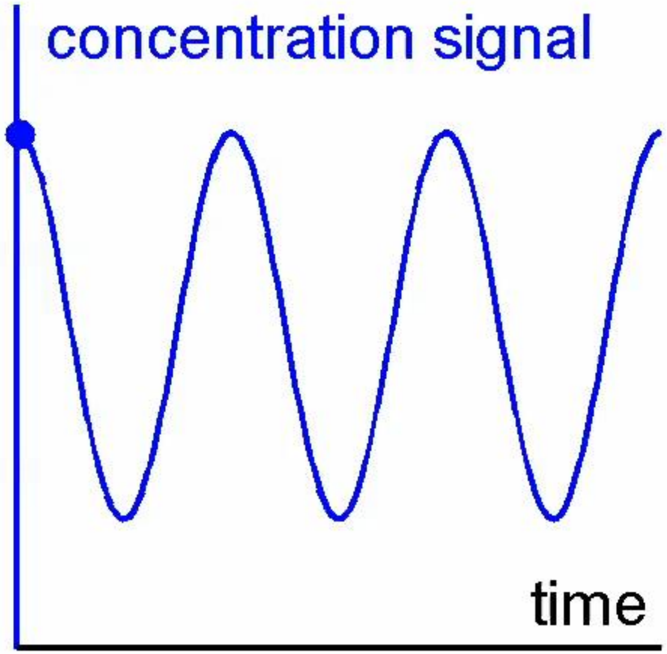
Testing chemotaxis in a shallow observation chamber



Theory: Sperm measure concentration along circular paths

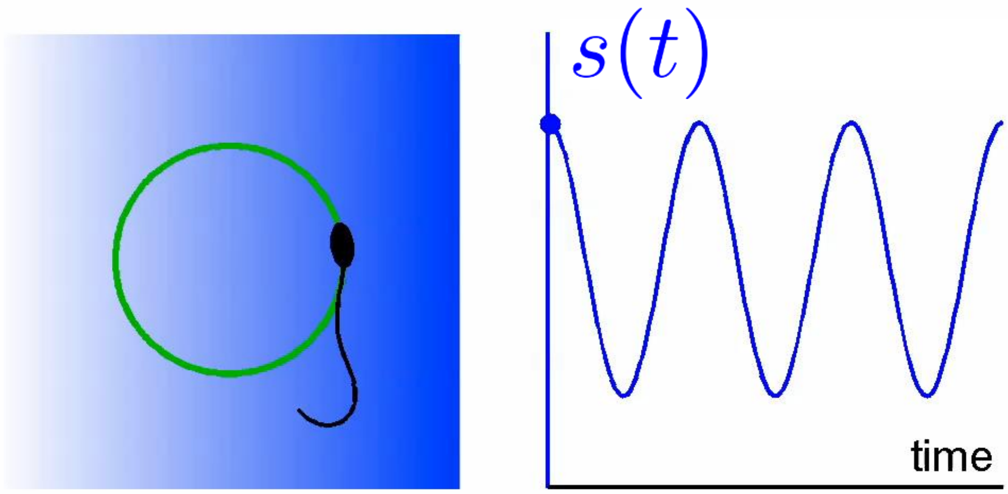




Theory: Sperm measure concentration along circular paths

swimming path $\mathbf{r}(t)$

concentration stimulus $s(t) = c(\mathbf{r}(t))$



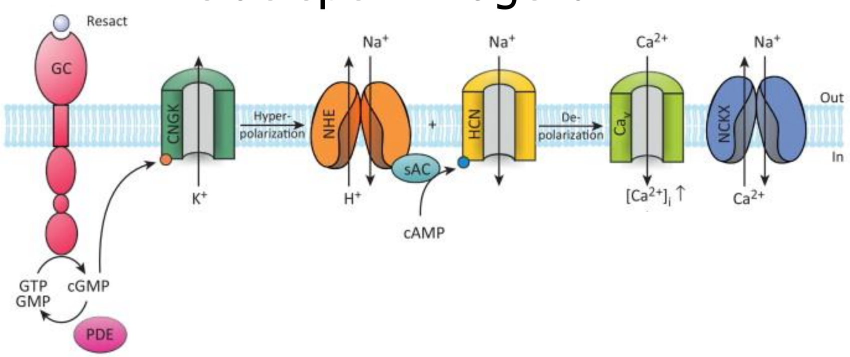
A signalling system transfers the stimulus into steering

swimming path $\mathbf{r}(t)$

concentration stimulus $s(t)$

path curvature $\kappa(t)$

signalling system
inside sperm flagellum



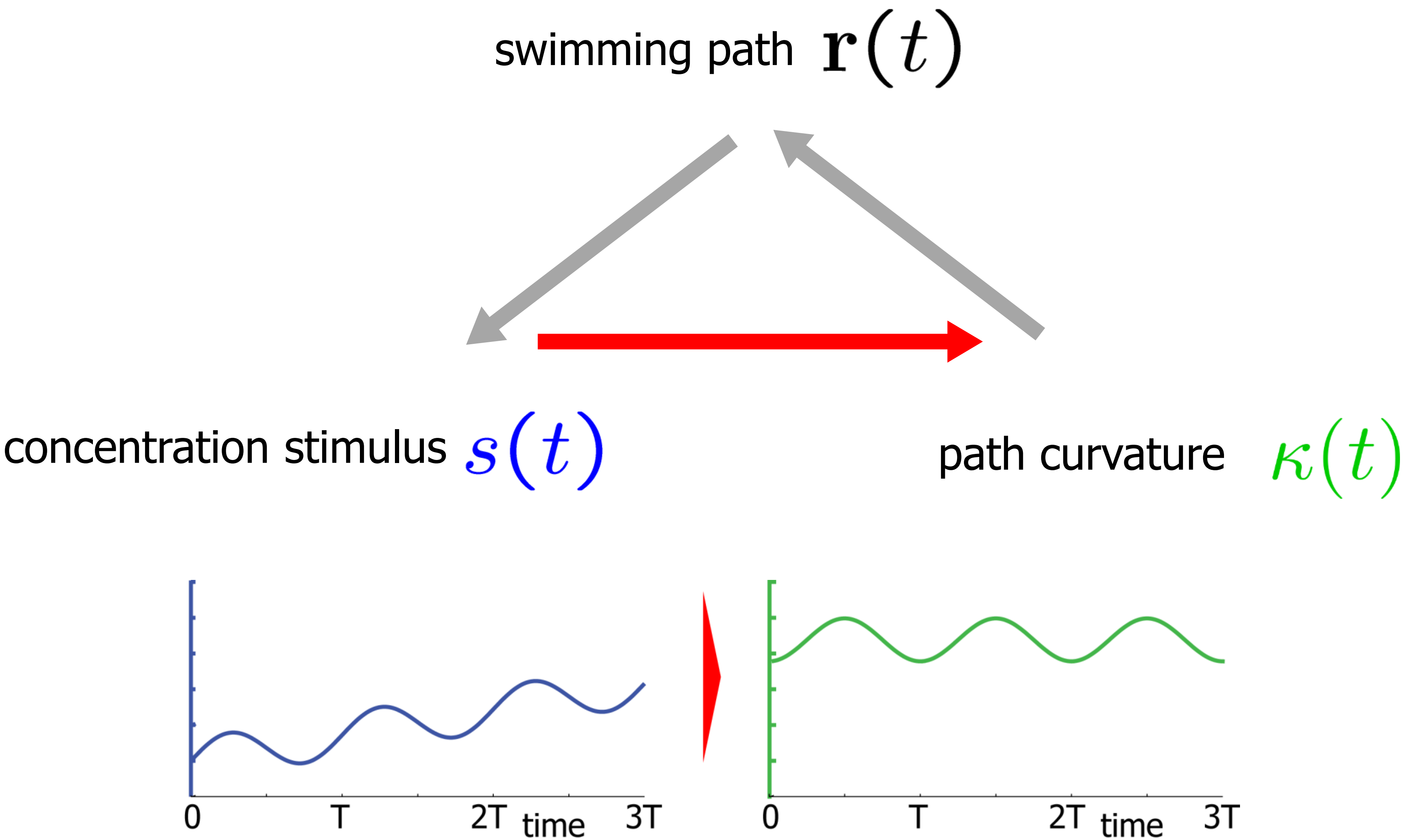
minimal description
as adaptation module

$$\tau_a \dot{a} = ps - a$$

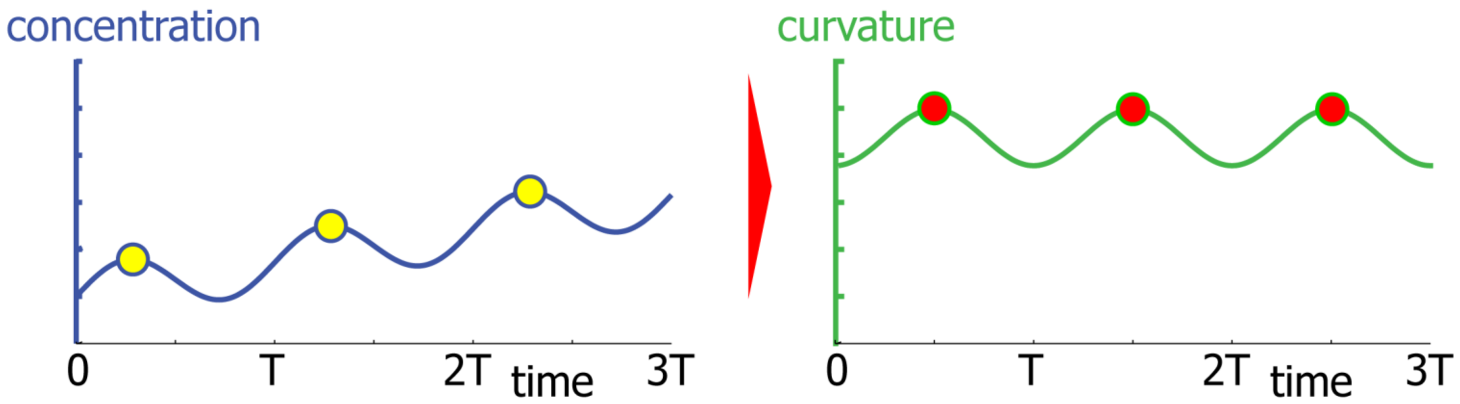
$$\tau_p \dot{p} = p(1-a)$$

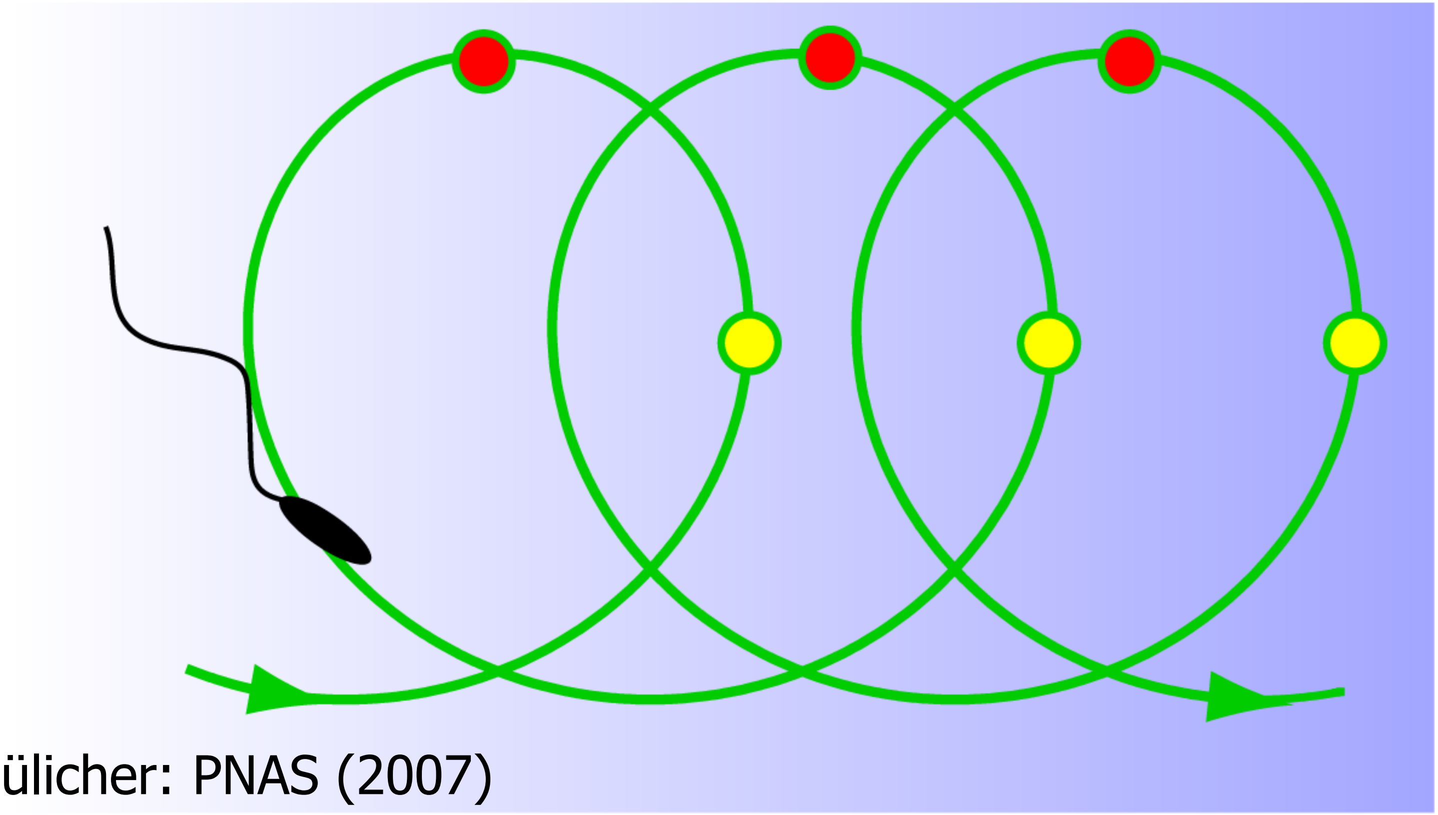
$$\kappa = \kappa_0 + \chi(a-1)$$

Stimulus oscillations elicit curvature oscillations



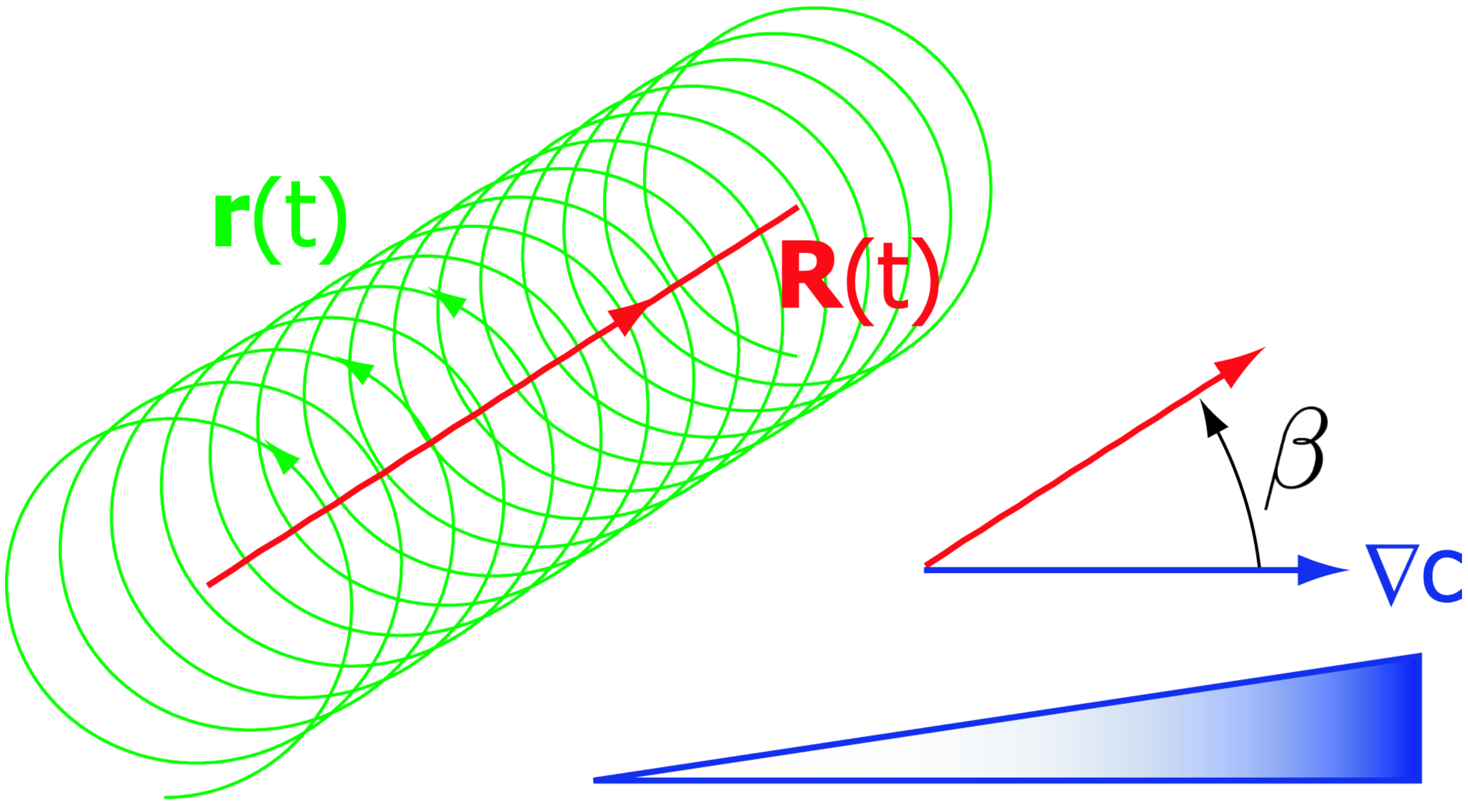
Theory of sperm chemotaxis





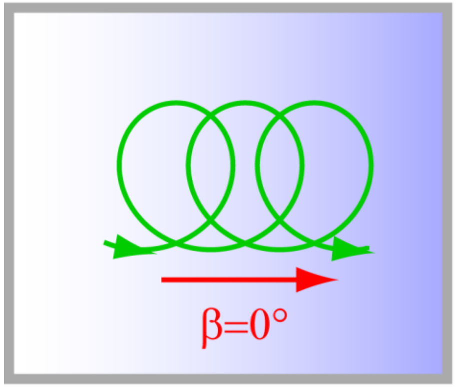
Friedrich, Jülicher: PNAS (2007)

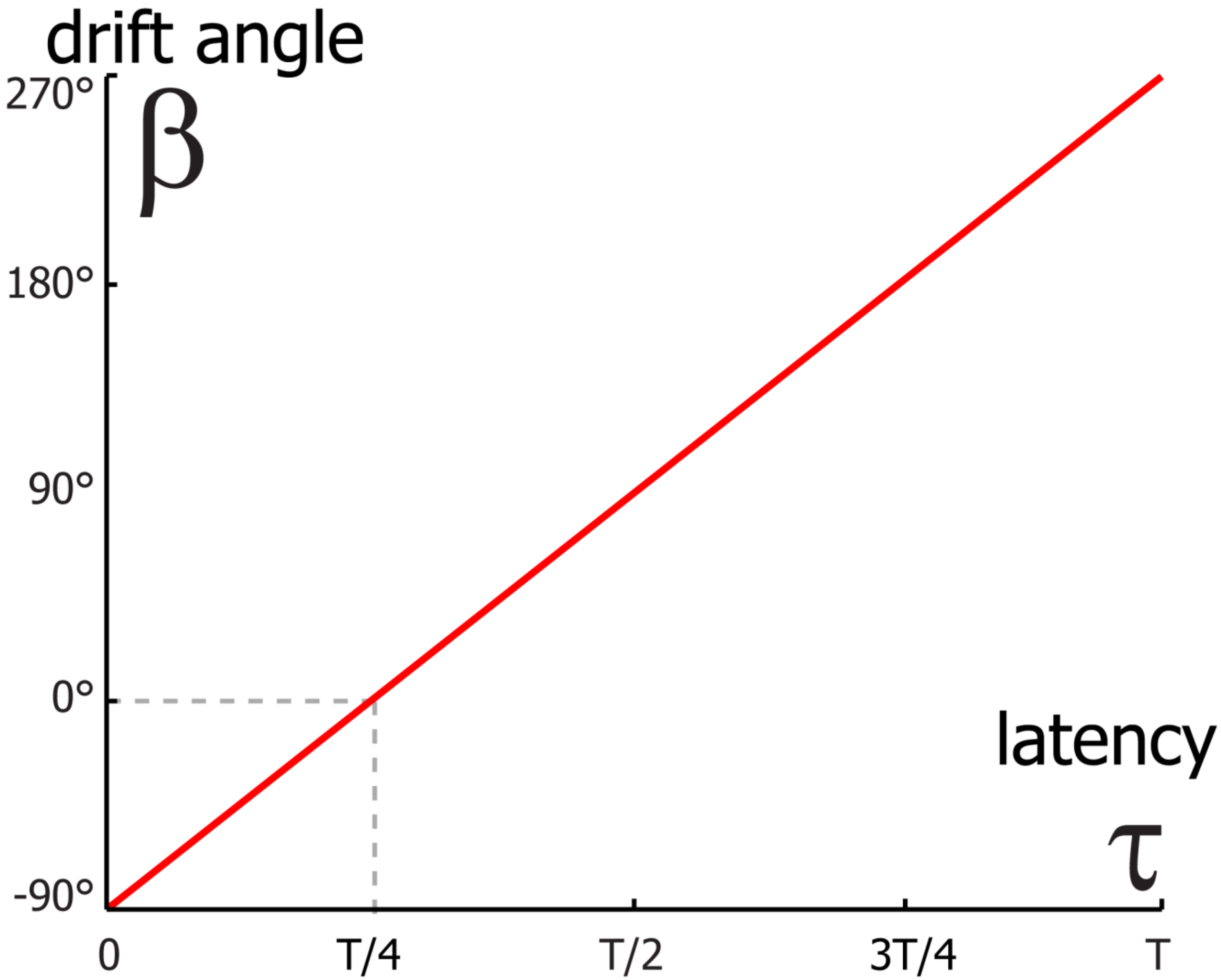
In general, there will be an angle between gradient and drift



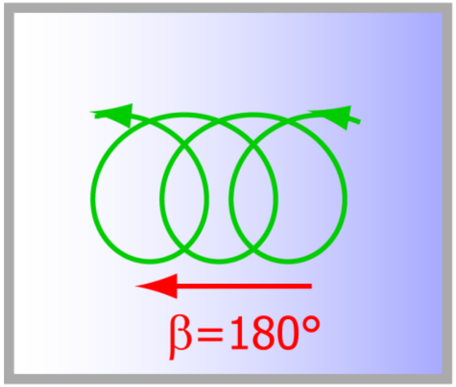
$$\frac{\beta}{2\pi} = \frac{\tau}{T} - \frac{1}{4}$$

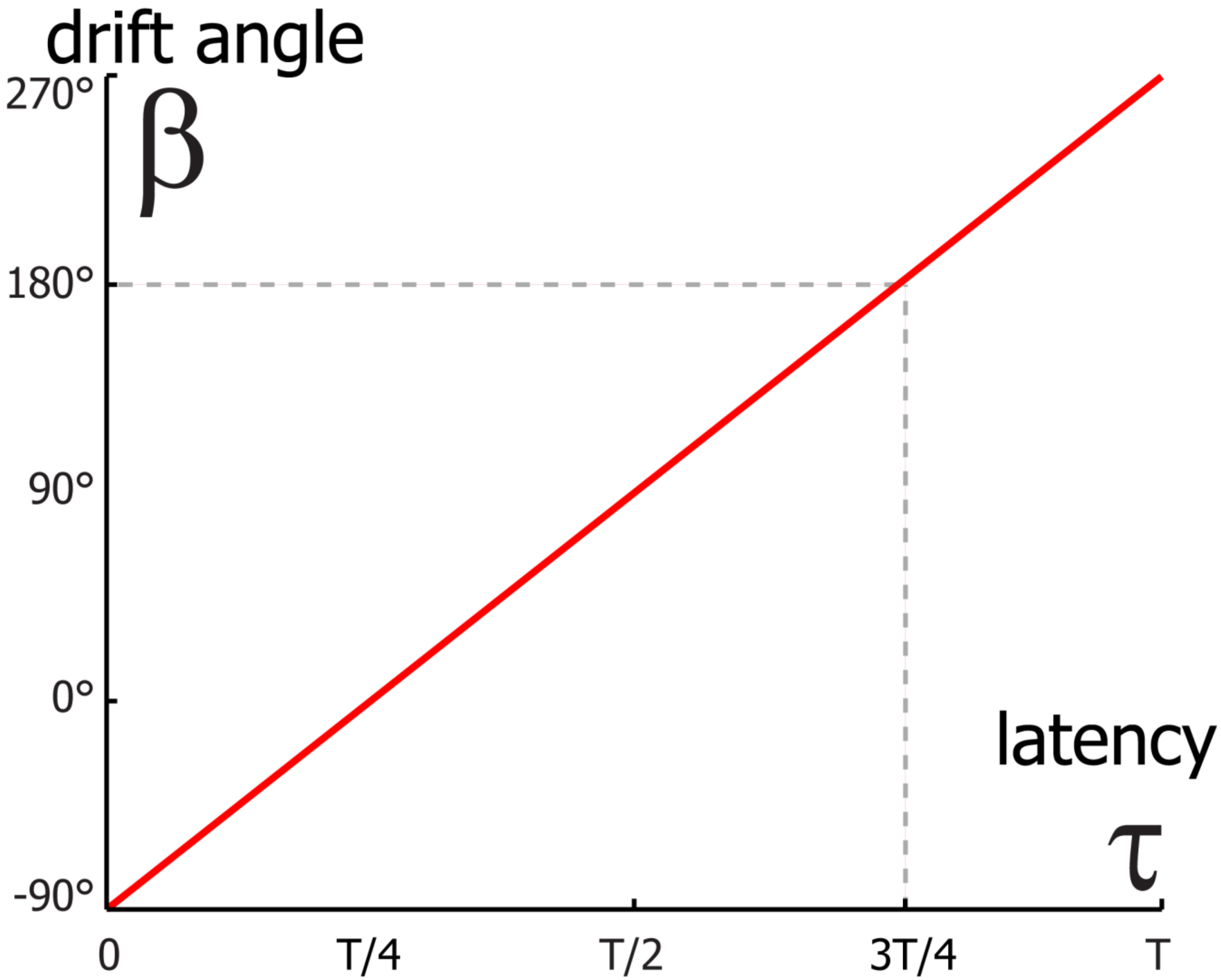
The latency sets the drift direction



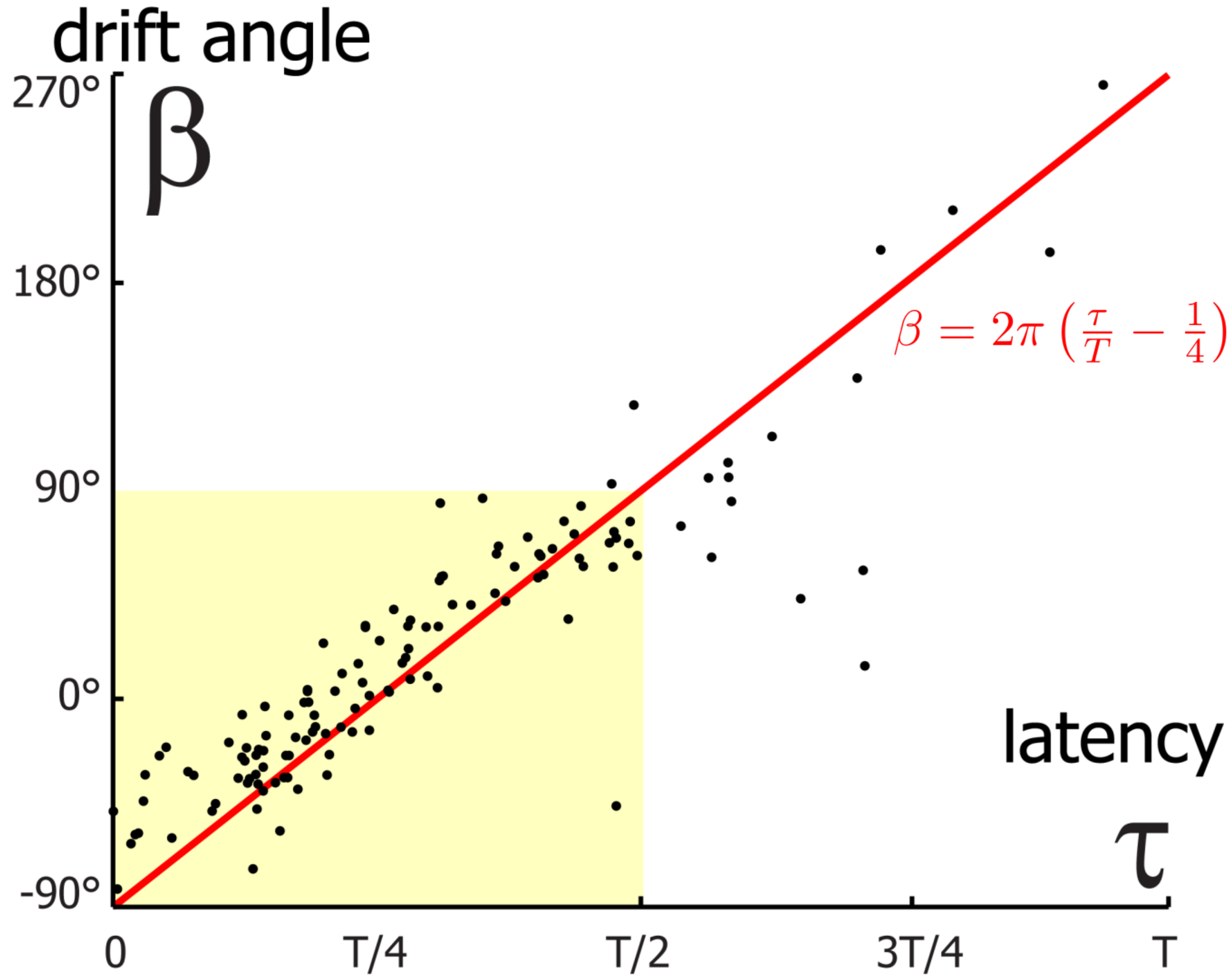


Chemotaxis down the gradient for mistuned latency



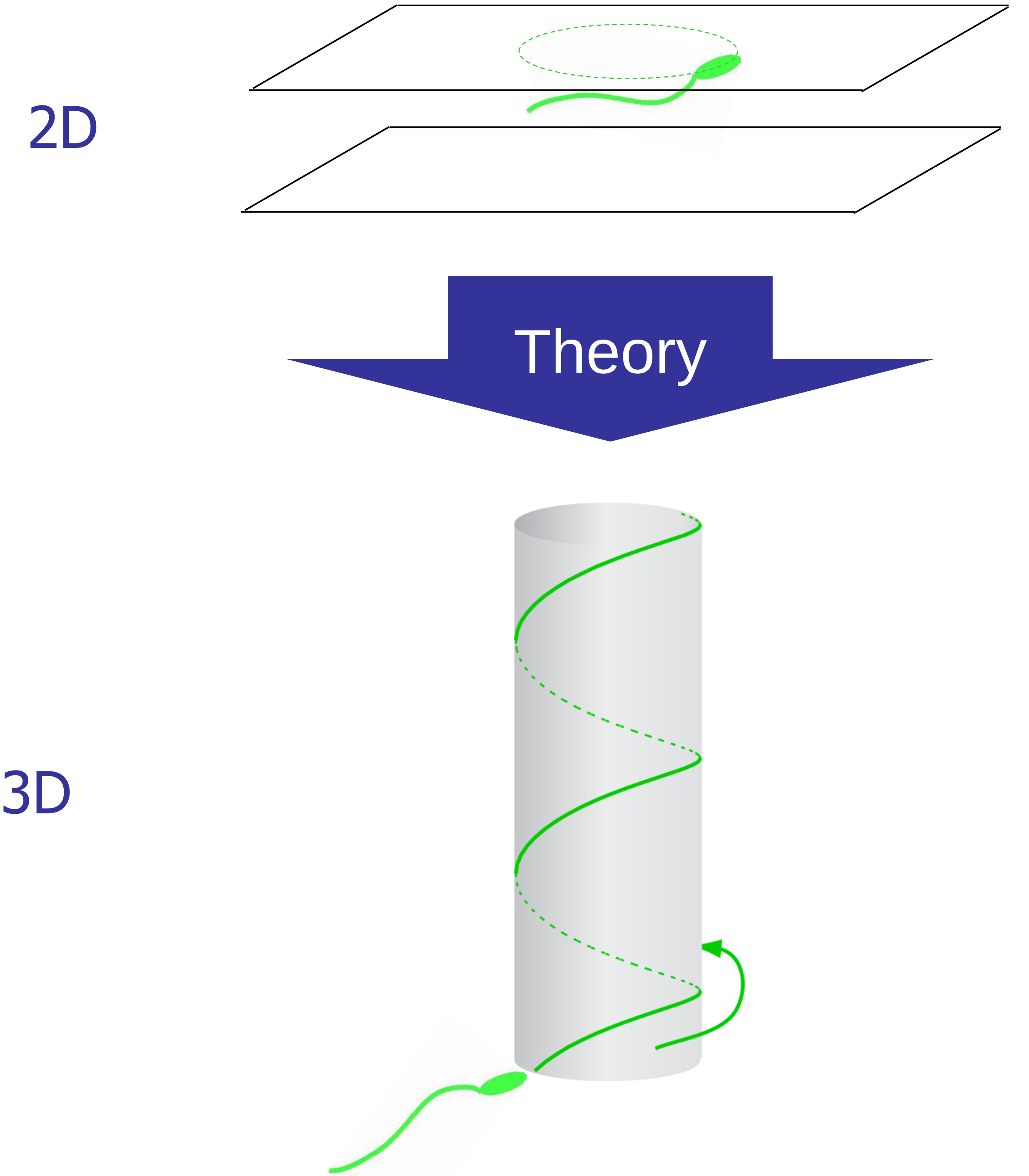


Theory and experiment match

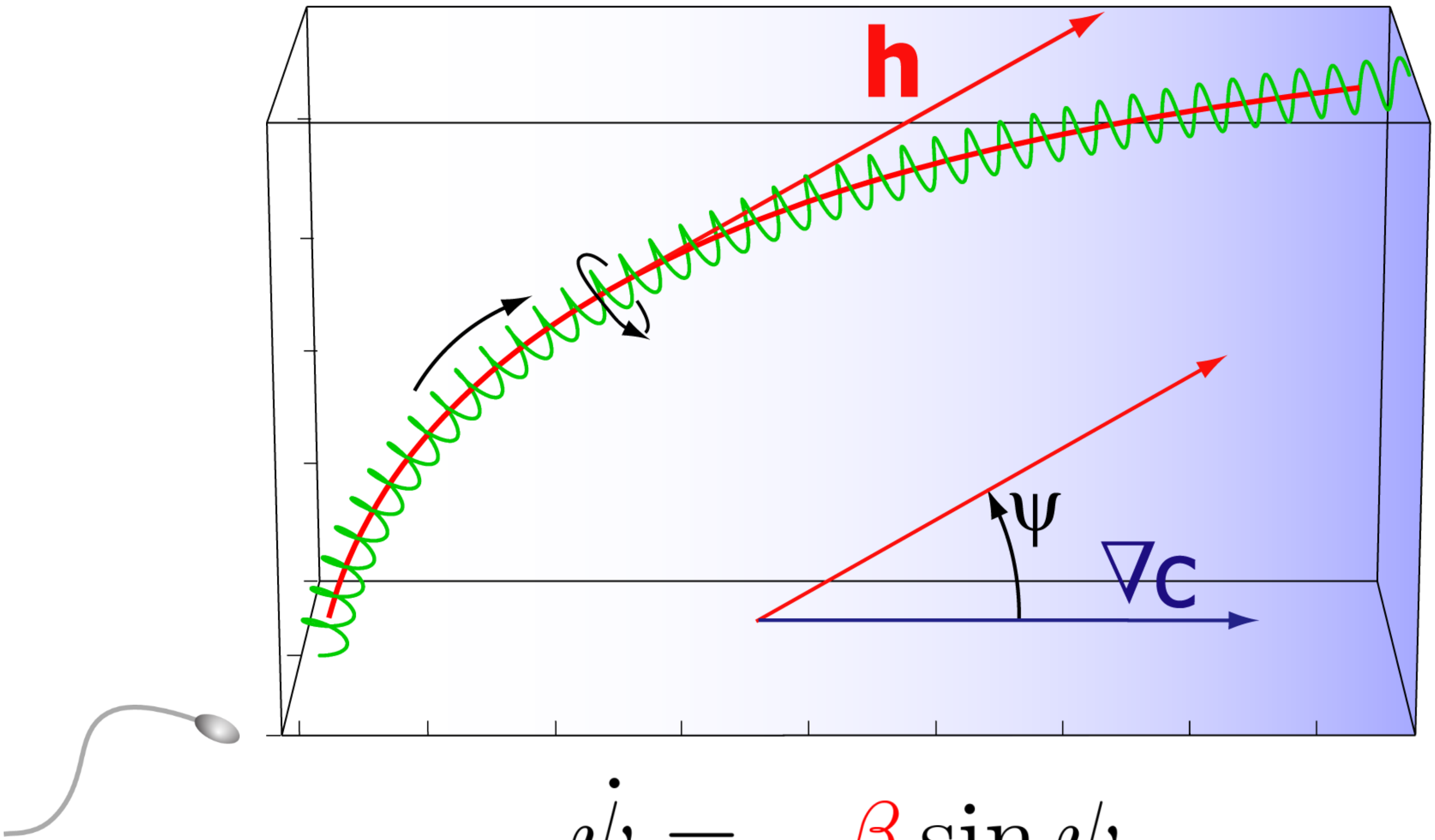


Experiments: Luis Alvarez, CAESAR

Sperm measure concentration
along circular paths and dynamically
adjust their beat
in a precisely timed manner


2D
Theory
3D

Steering feedback aligns helical paths with the gradient



$$\dot{\psi} = -\beta \sin \psi$$

$$\beta \sim \frac{\nabla c}{c}$$

Friedrich, Jülicher: PNAS (2007)

How to test the theory?

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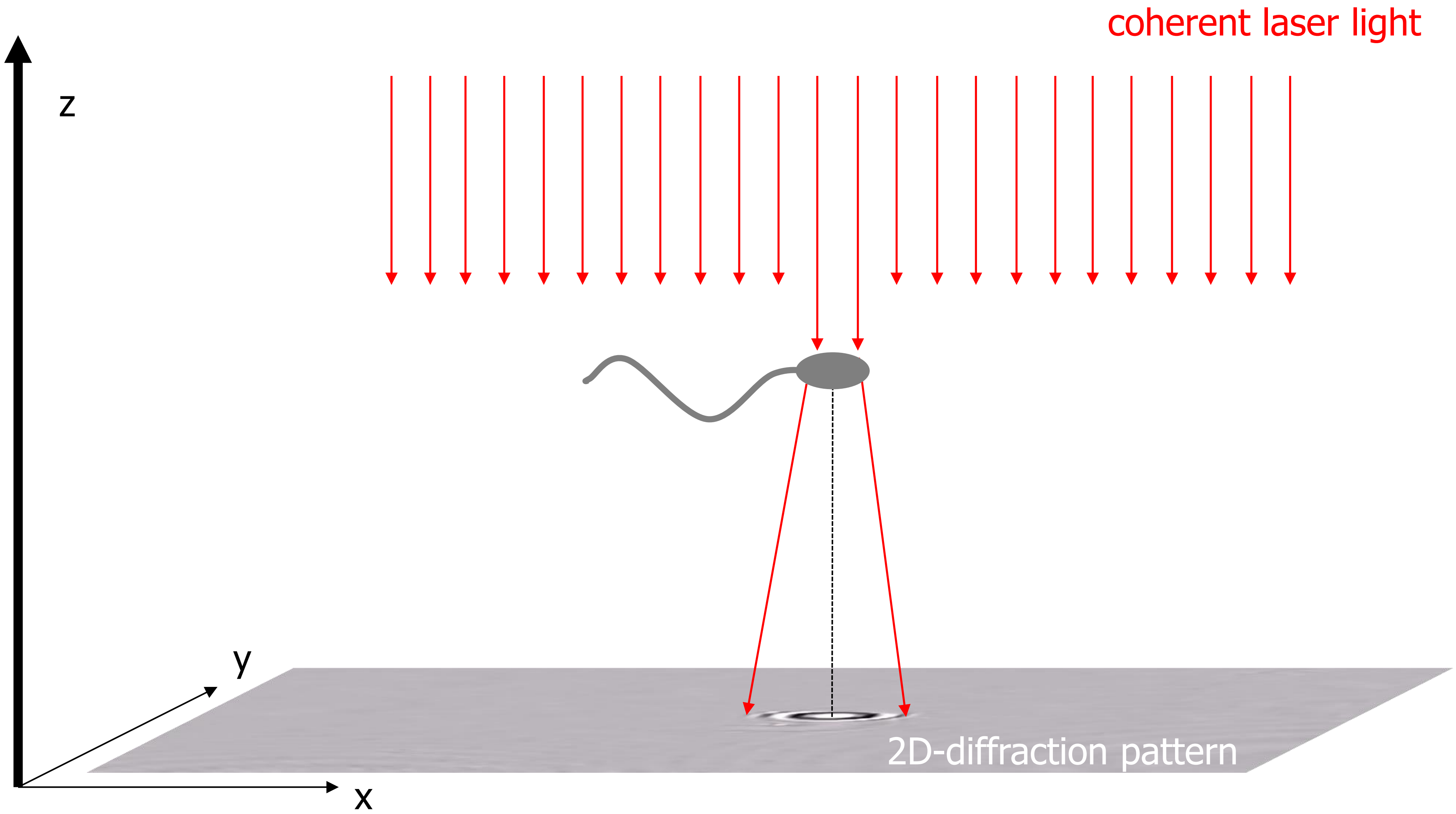
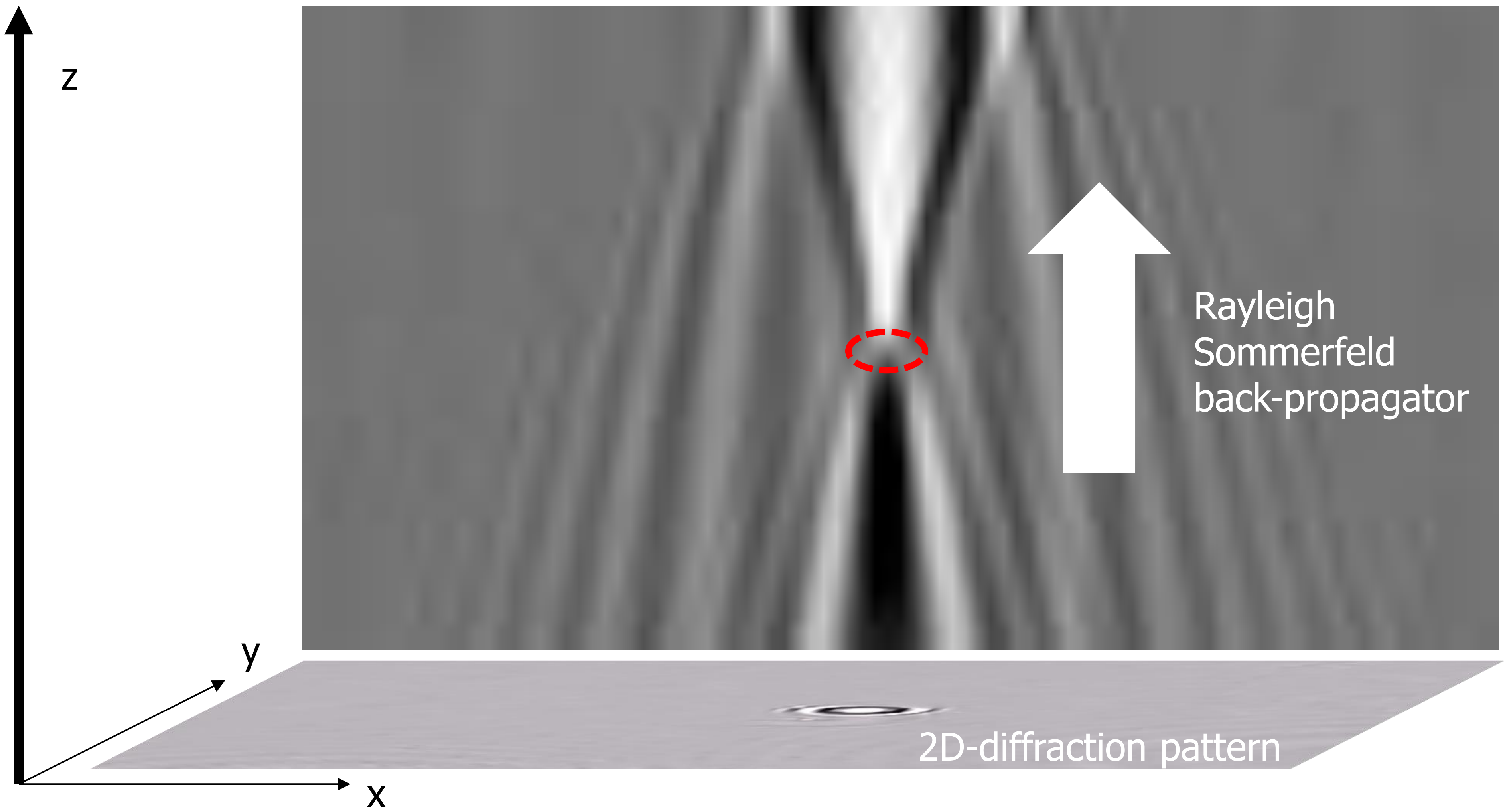
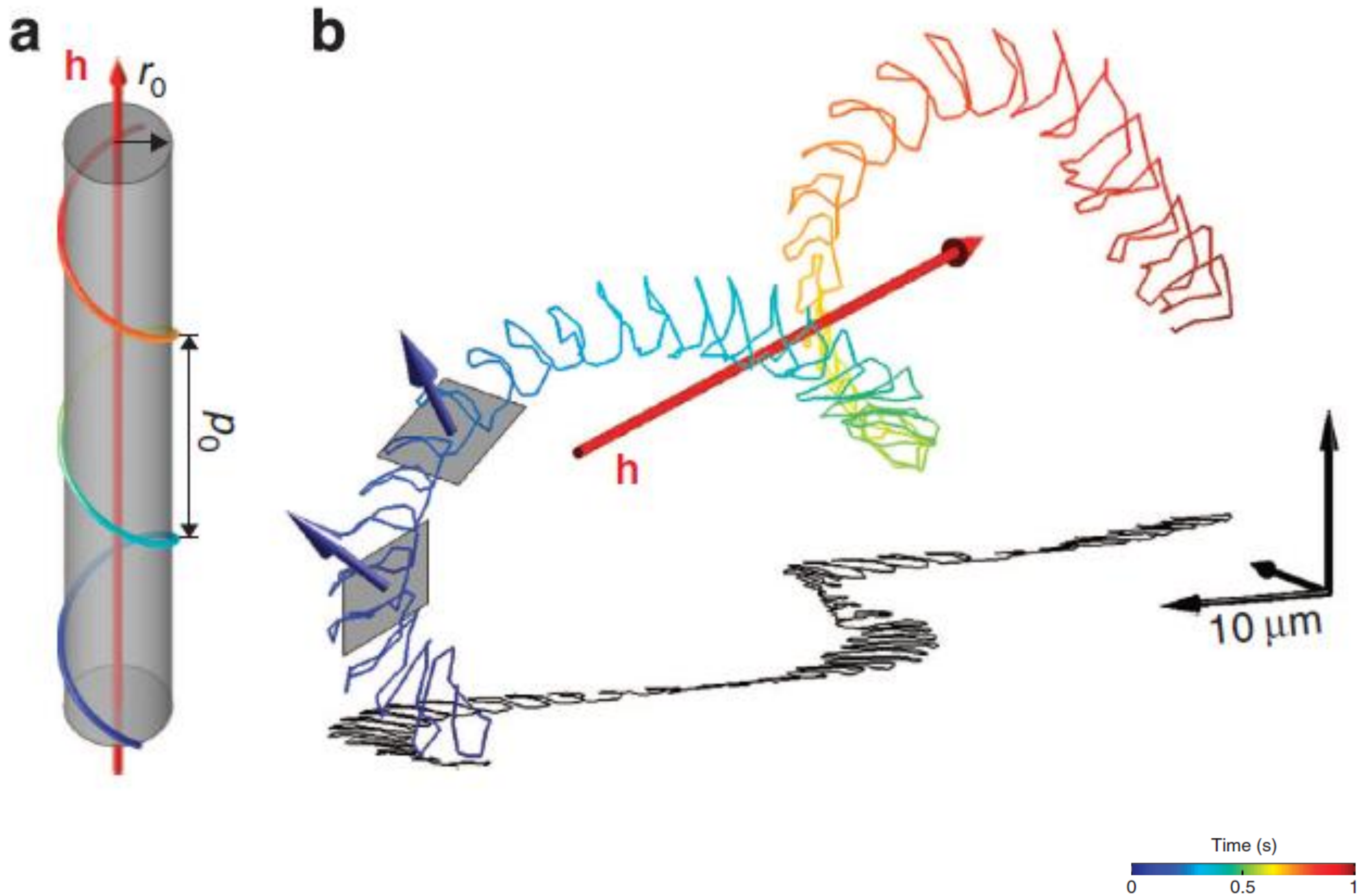
3D-tracking from 2D-holographic images



Numerical reconstruction of 3D-light beam

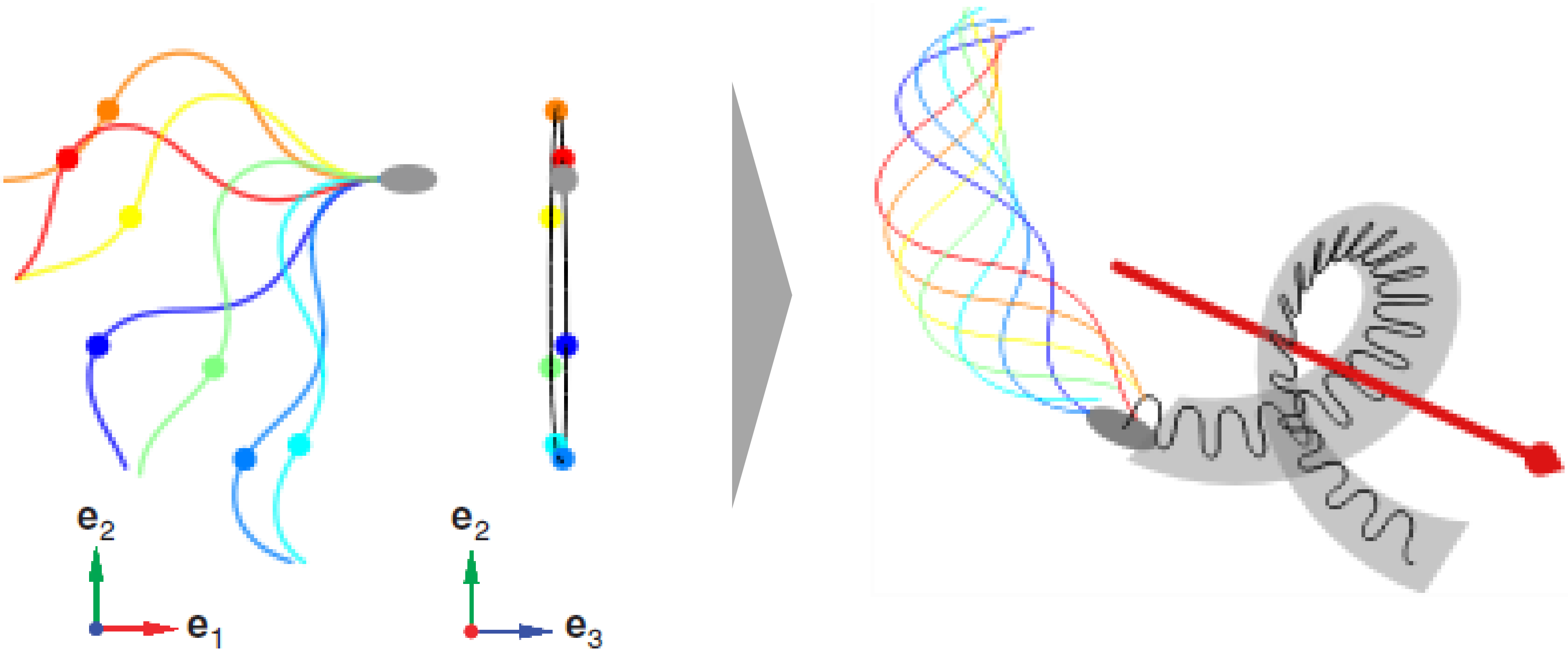


Sperm swim along helical paths



Jikeli*, Alvarez*, Friedrich*, …, Kaupp: Nature Comm (in press); *=equal contribution

A chiral beat pattern accounts for helical paths

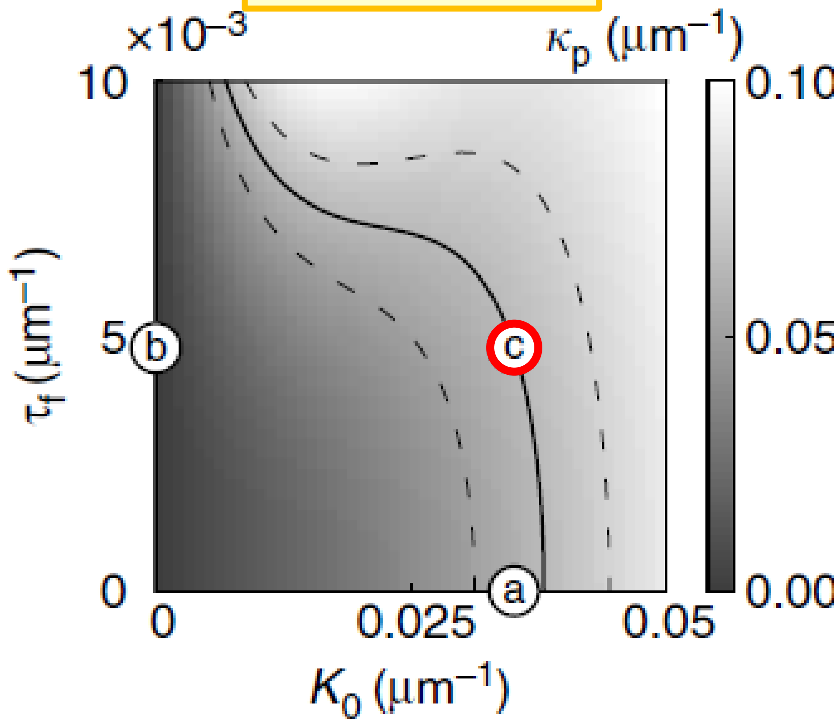


Jikeli*, Alvarez*, Friedrich*, …, Kaupp: Nature Comm (in press); *=equal contribution

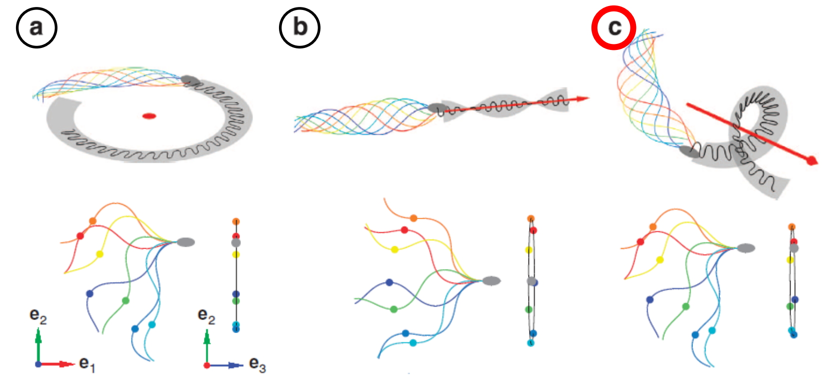
From the helical path, we can infer the beat pattern

helix curvature

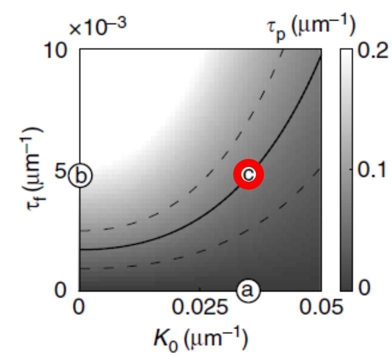
static flagellar twist



mean flagellar curvature



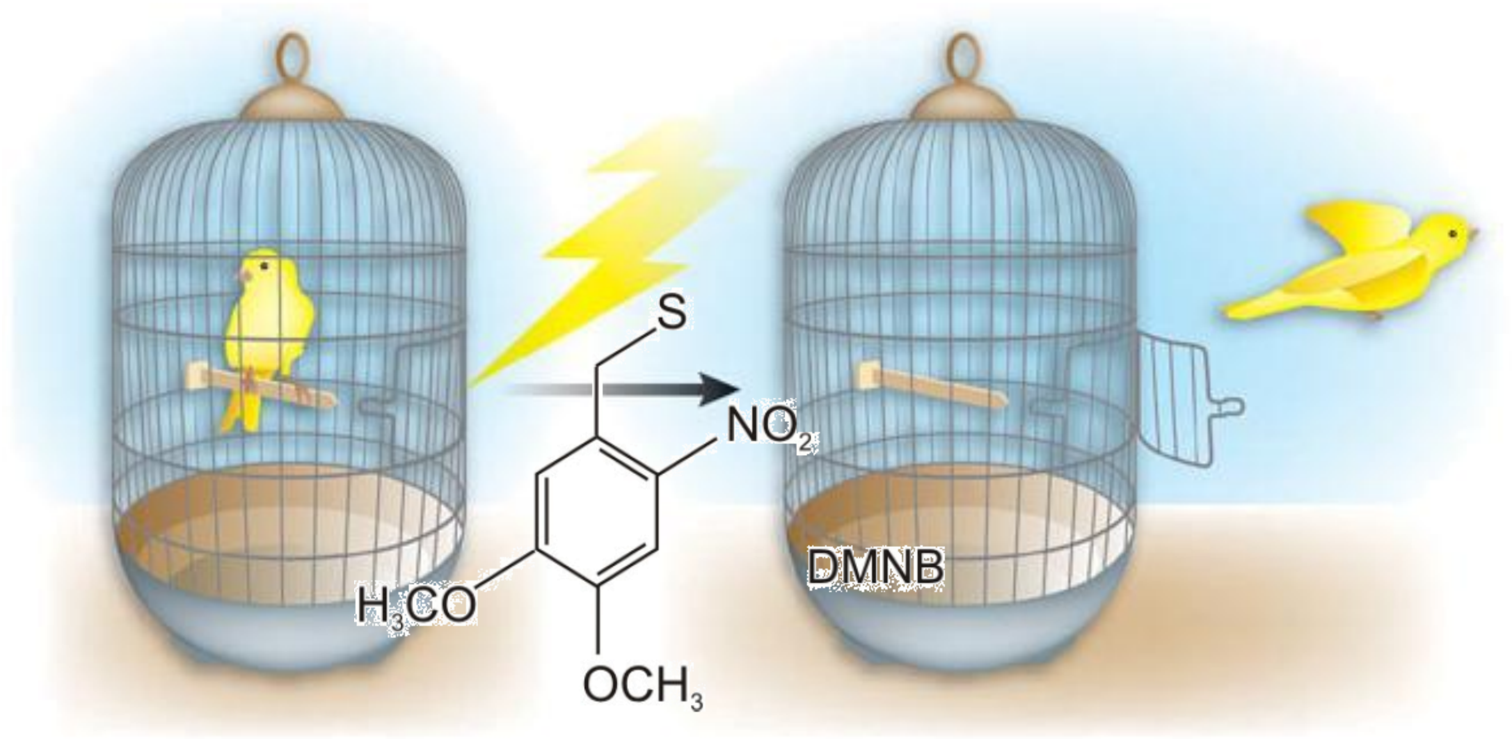
helix torsion



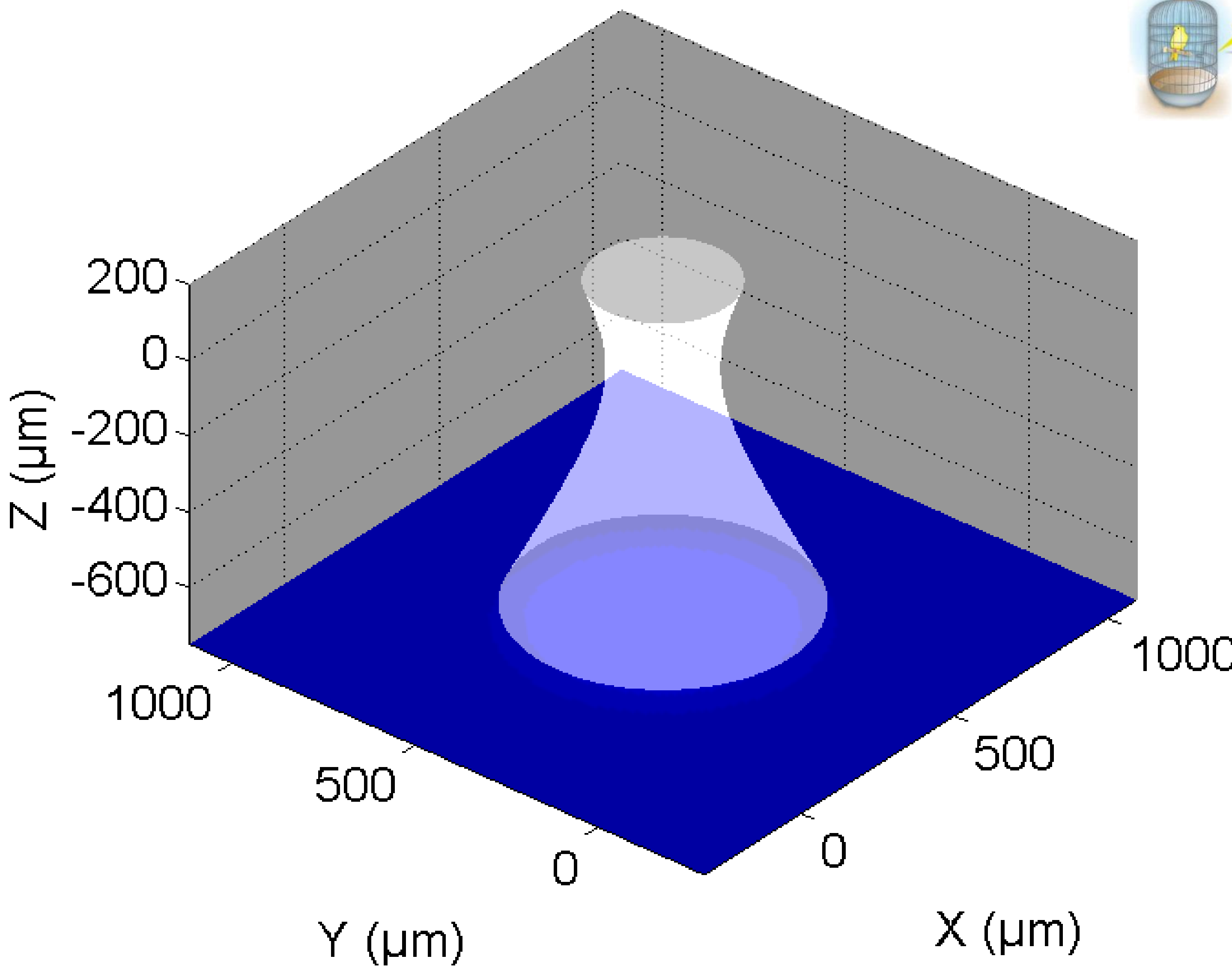
How do sperm steer along helical paths?

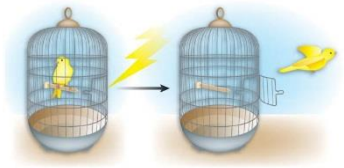
Using light to "print" 3D concentration gradients

- Chemoattractant with chemical cage
- UV light removes cage



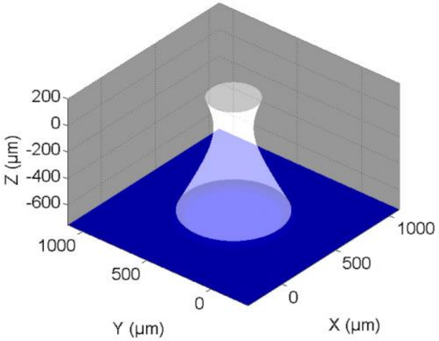
Using light to "print" 3D concentration profiles

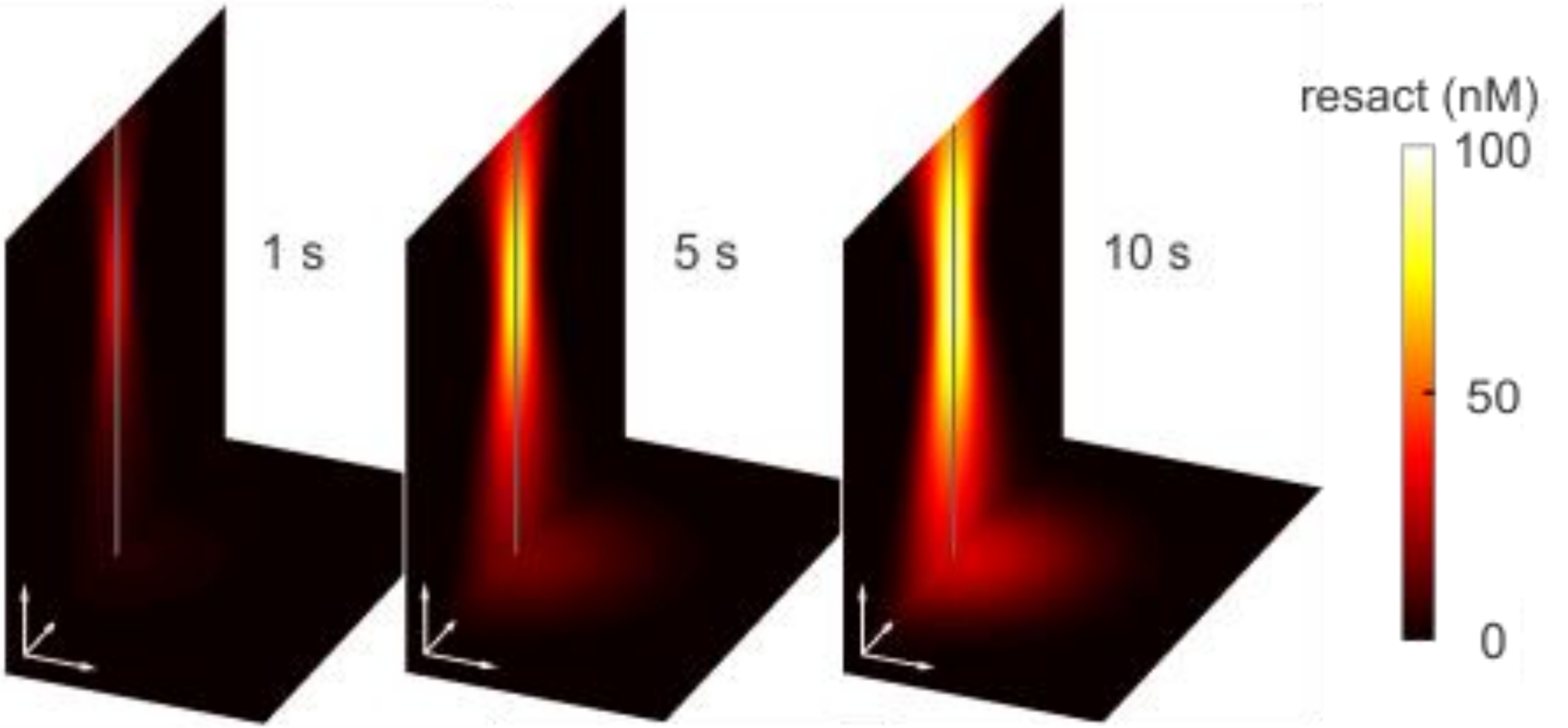




We compute how the concentration evolves in time

- calibrated light intensity
- quantum yield
- diffusion coefficient





Tracking a sperm cell in a 3D concentration profiles

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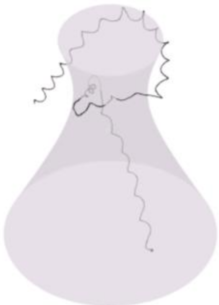
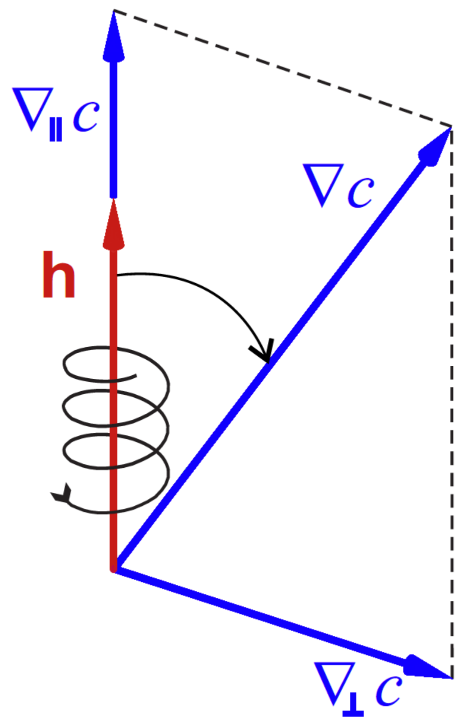
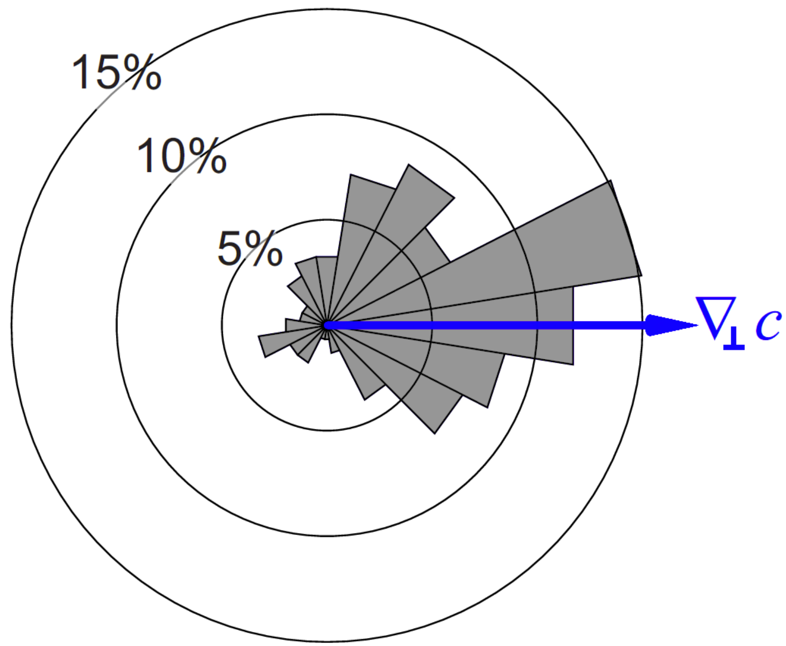
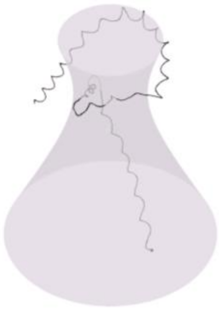
Helical paths bend in the direction of the local gradient

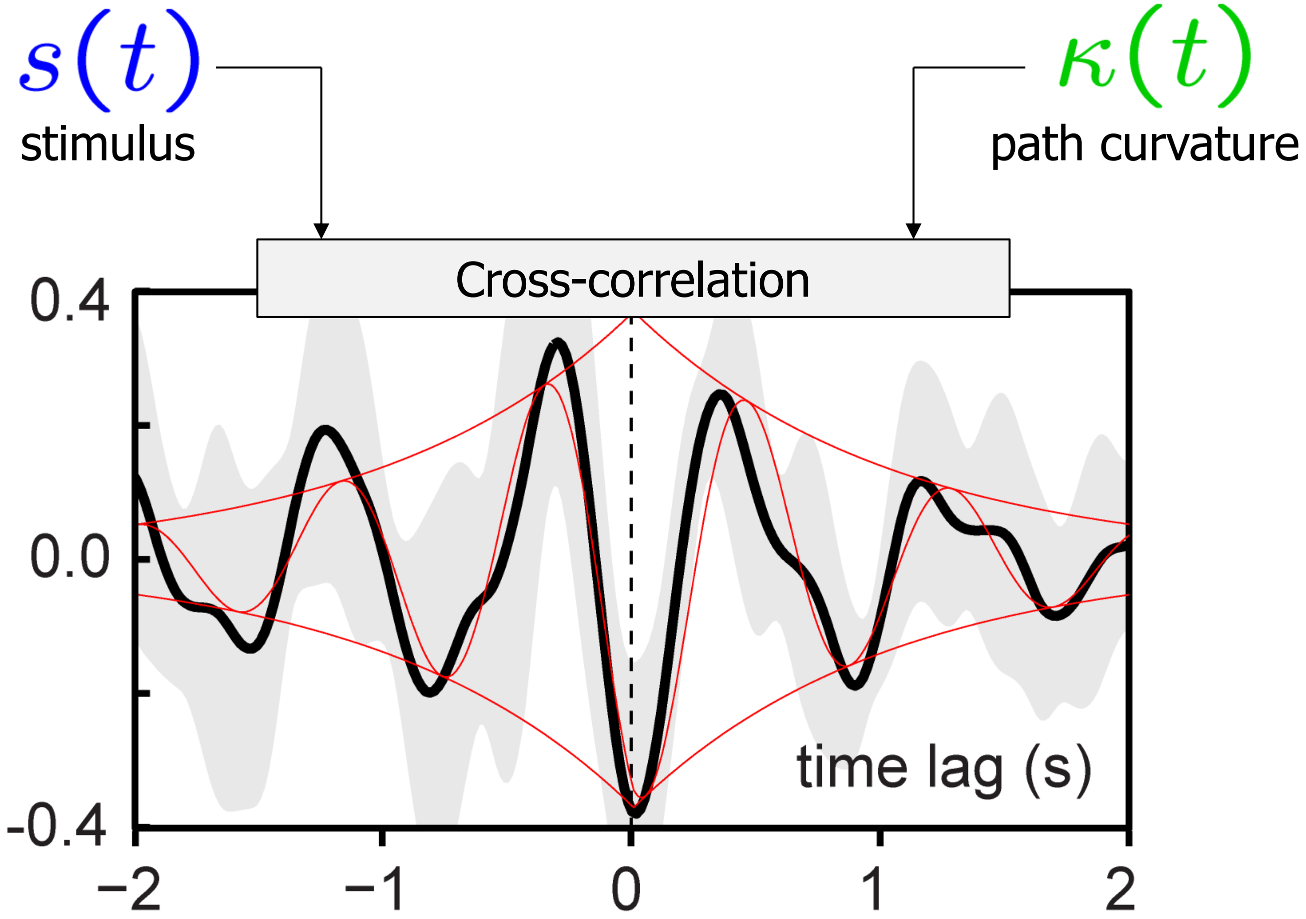






We can extract the sensory-motor transfer function

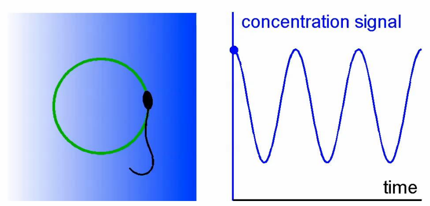


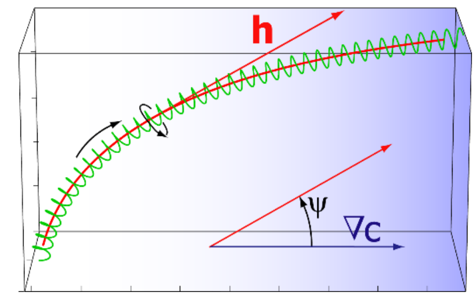


Phase-locked oscillations with phase-lag of 167°±35°, close to the optimum value 180°

Theory and experiment of helical steering

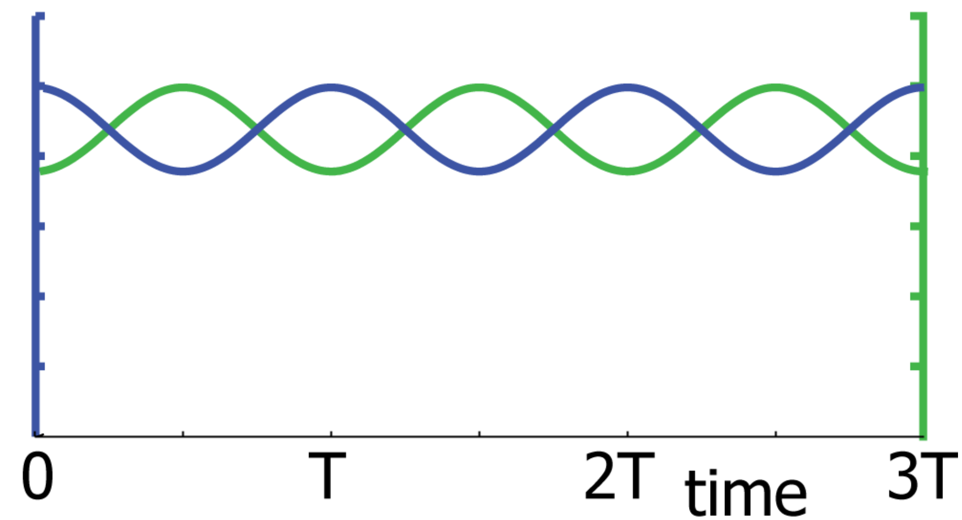
swimming path $\mathbf{r}(t)$





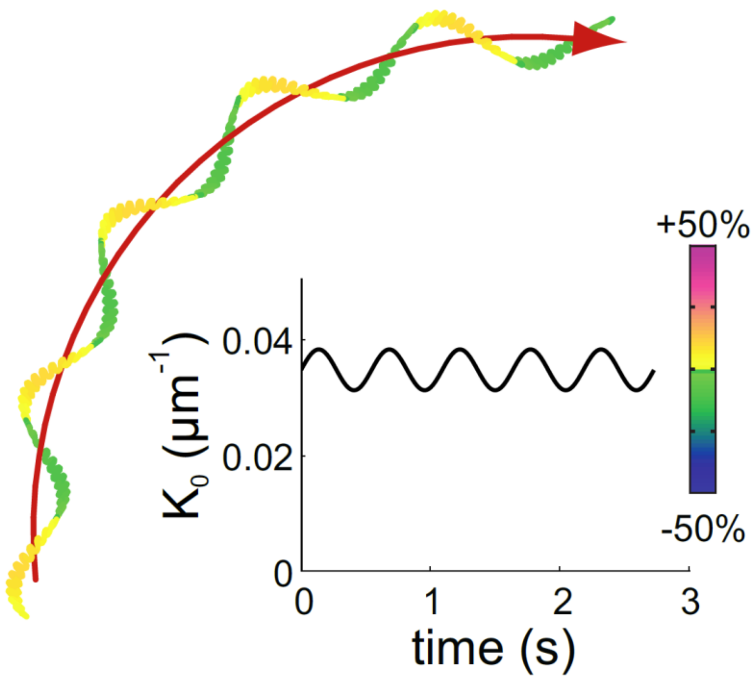
concentration stimulus $s(t)$

path curvature $\kappa(t)$



Experiments prompt an extension of the theory

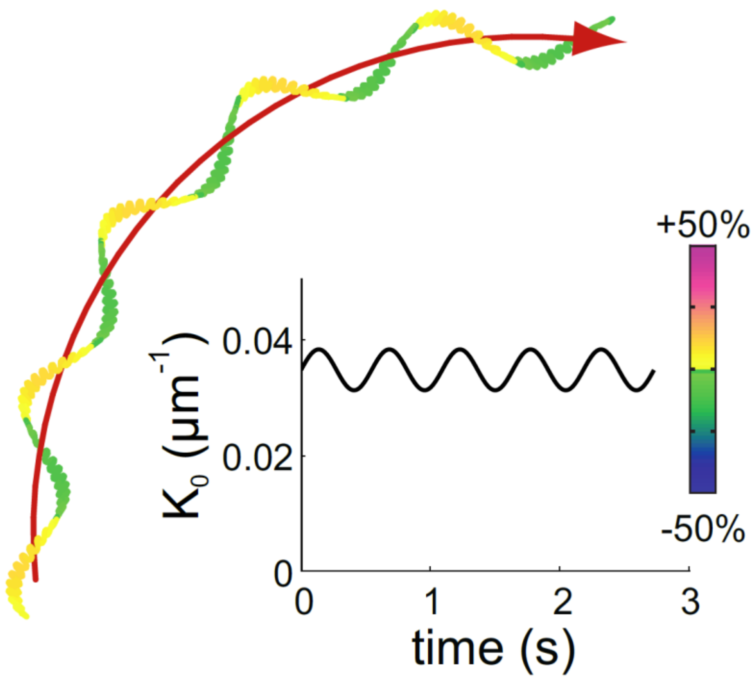
Small-amplitude oscillations of flagellar asymmetry
↓
gradual helix alignment

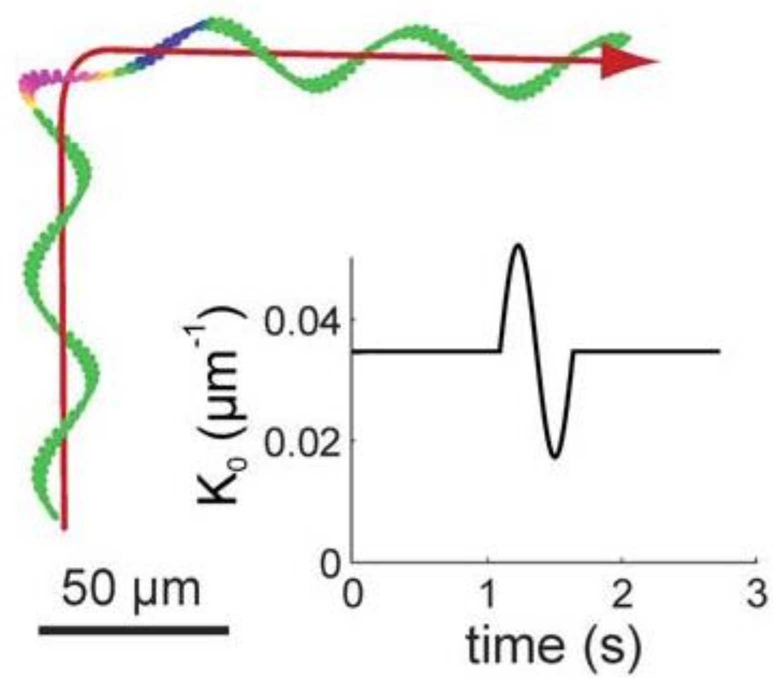


Experiments prompt an extension of the theory

Small-amplitude oscillations of flagellar asymmetry
↓
gradual helix alignment

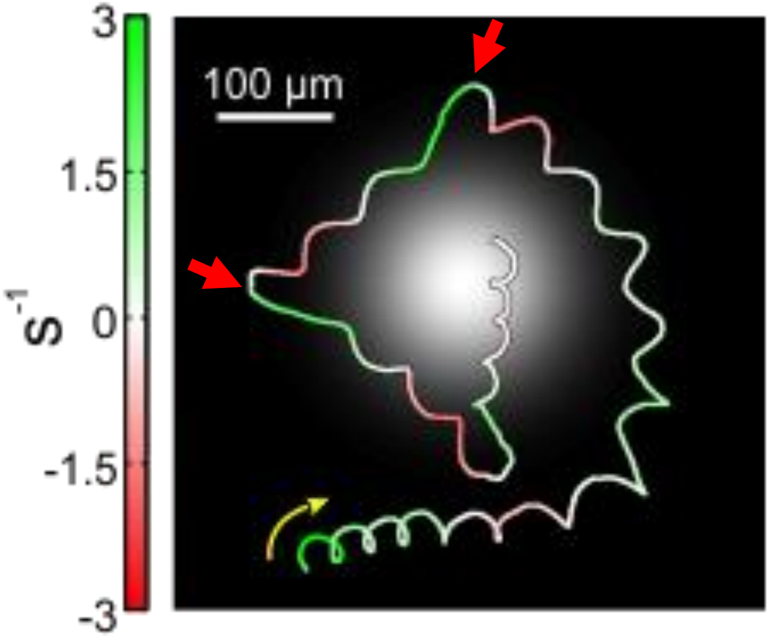
Large amplitude modulations of flagellar asymmetry
↓
sharp turns

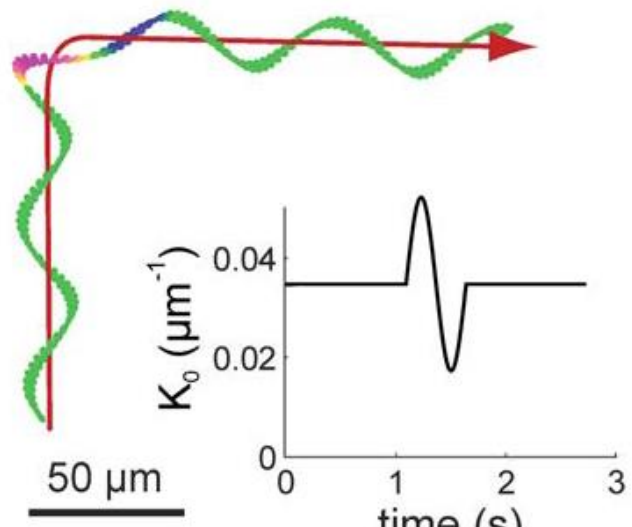




Sharp turns are used in emergencies

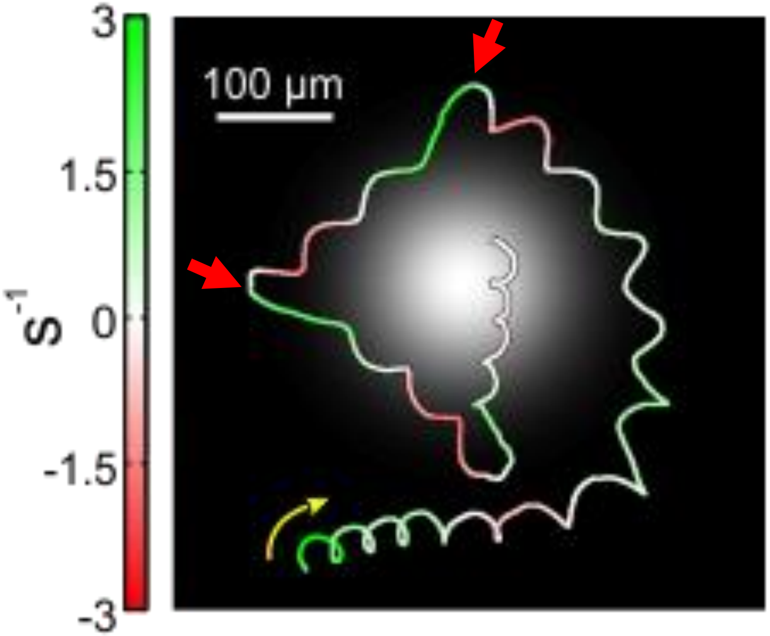
Experiment



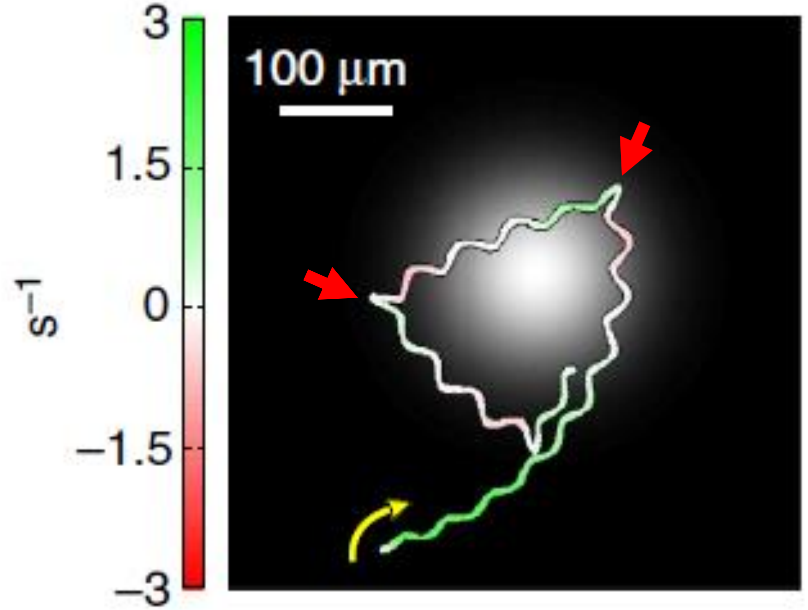


Experiment and theory of adaptive feedback

Experiment



Theory



“If life gets worse, respond strongly.”

Thank you for your attention !

- The experimental team
  - Jan Jikely
  - Luis Alvarez
  - Laurence Wilson



  - René Pascal
  - Rèmy Colin
  - Magdalena Pichlo
  - Andreas Rennhack
  - Christopher Brenker





  - U Benjamin Kaupp

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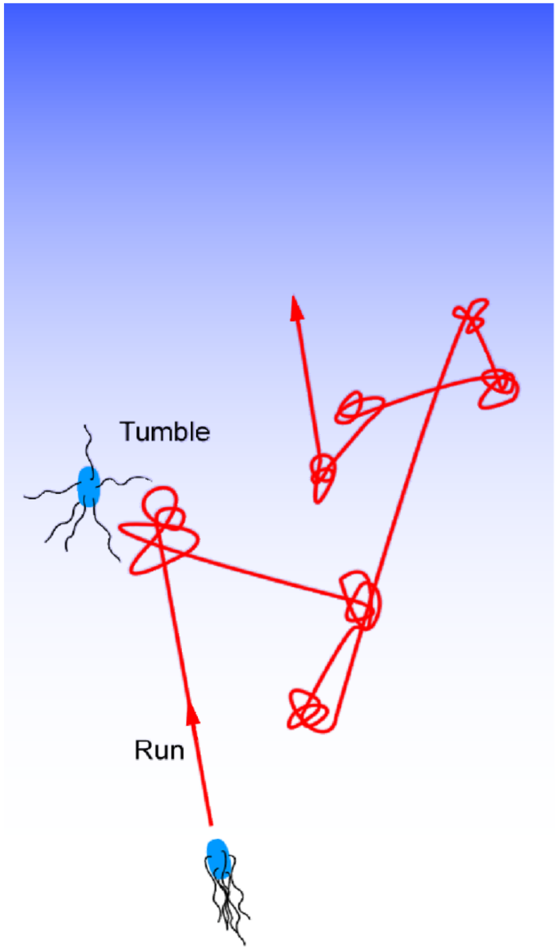
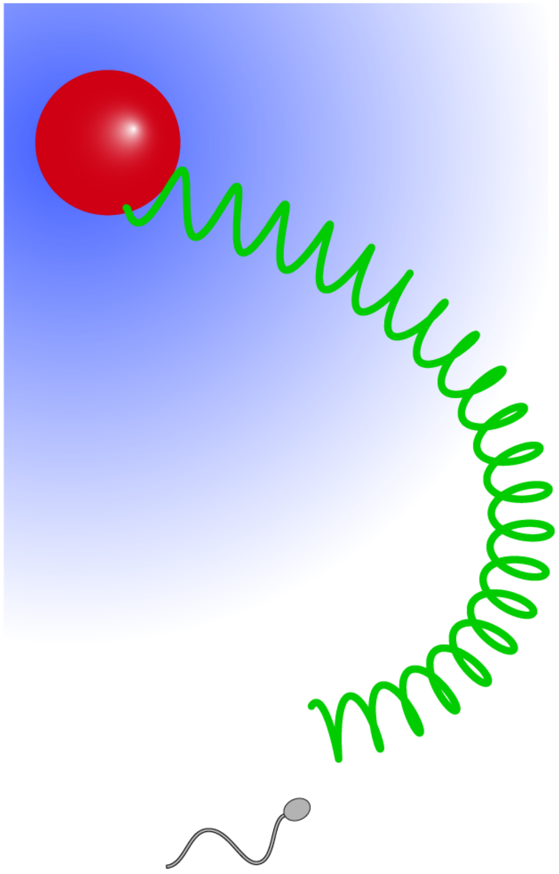
MICRO-
SWIMMERS

MAX-PLANCK-GESELLSCHAFT

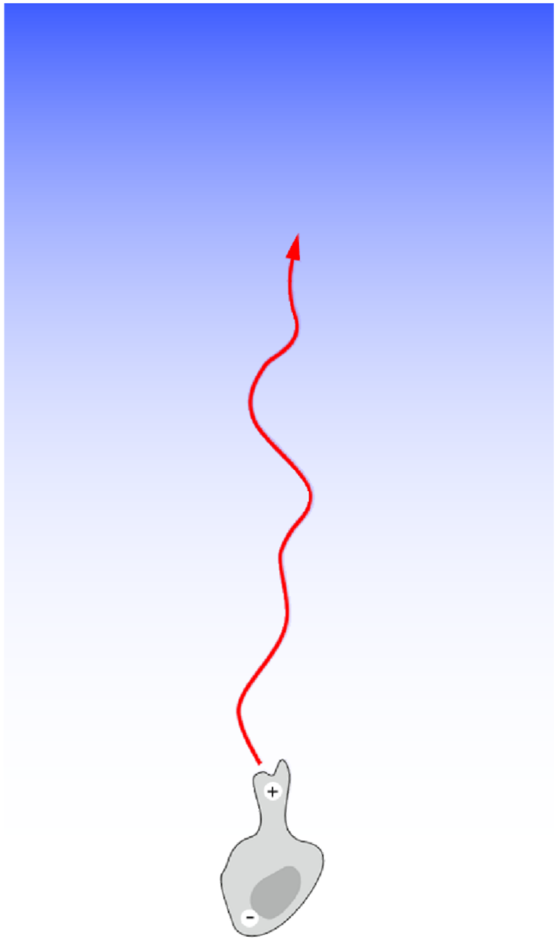
Navigation strategies of cells are adapted to their size



Bacterium *E. coli*



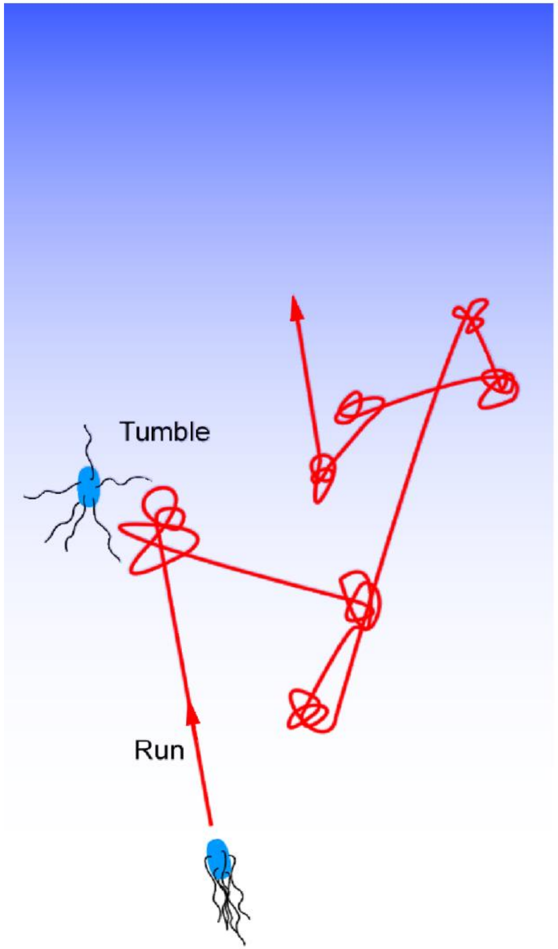
Sea urchin sperm



Slime mold *Dictyostelium*

Berg, Purcell: BPJ (1977)
Alvarez, Friedrich, Gompper, Kaupp: Trends Cell Biol. (2014)

Tiny bacteria can keep their direction only for a few seconds

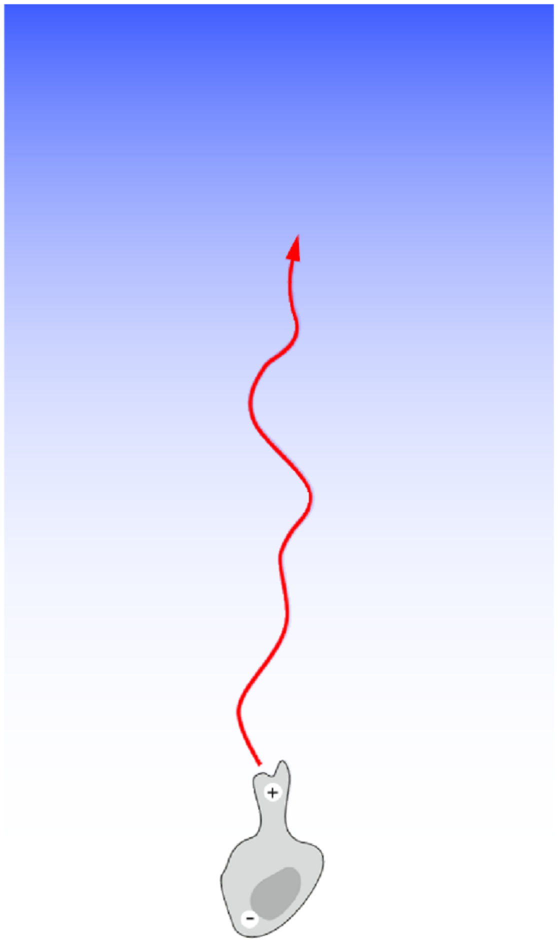


Bacterium *E. coli*

$$D_{\mathrm{rot}} \sim \frac{1}{L^3}$$

$L \sim 3\,\mu\mathrm{m},\ v \sim 10\,\mu\mathrm{m/s}$

Slow slime molds have sufficient time for spatial comparison



Slime mold *Dictyostelium*

- signal-to-noise ratio

$$\sim \sqrt{Dc} \cdot \frac{\nabla c}{c} \cdot \frac{L^2}{\sqrt{v}}$$

$L \sim 100\,\mu\text{m},\ v \sim 1\,\mu\text{m}/\text{min}$

Berg, Purcell: BPJ (1977)