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Brainless intelligence: the curious case of acellular slime mold *Physarum polycephalum*

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12th October, 2017

SwarmLab


Where to live?
or
Whom to mate?
or
What to eat?
or
Which path to adopt?
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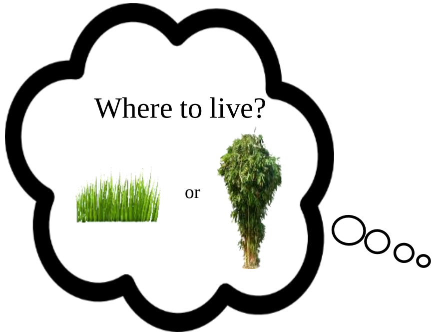
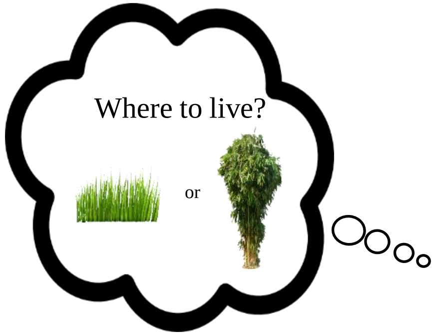
Complex decision-making



Requires simultaneous assessment of the options by an array of attributes:

1) Risk from the presence of a predator
2) Previous predation events
3) Food availability
4) Distance to the habitat

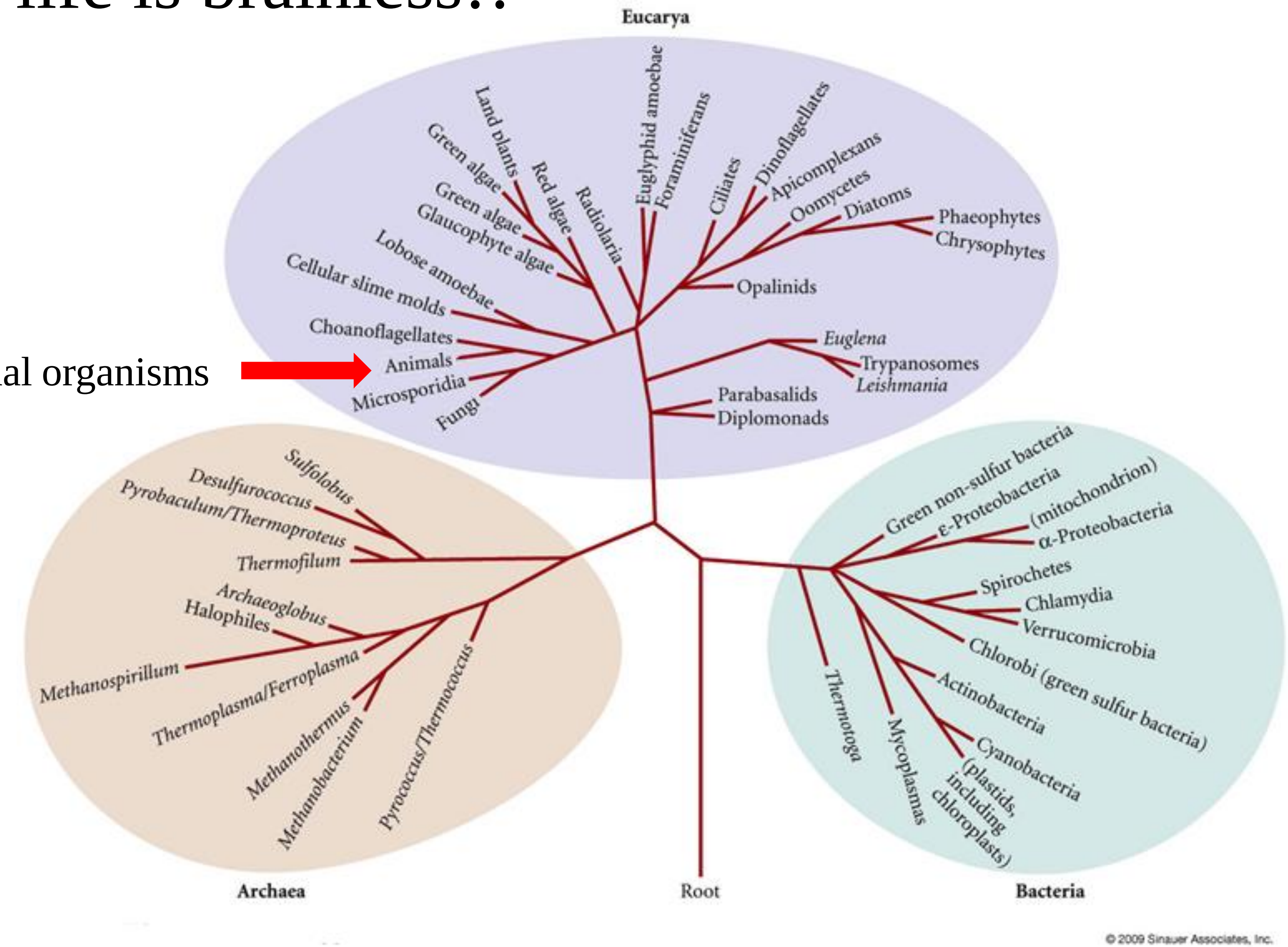
Complex decision-making



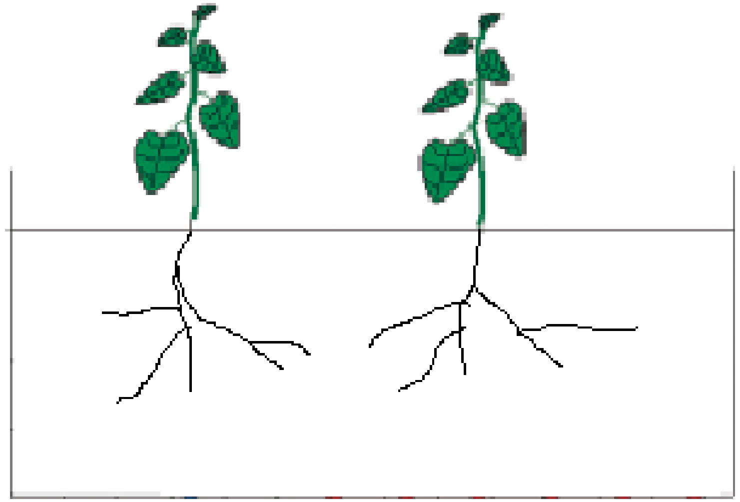
~ 7 billion neurons

Majority of life is brainless!!

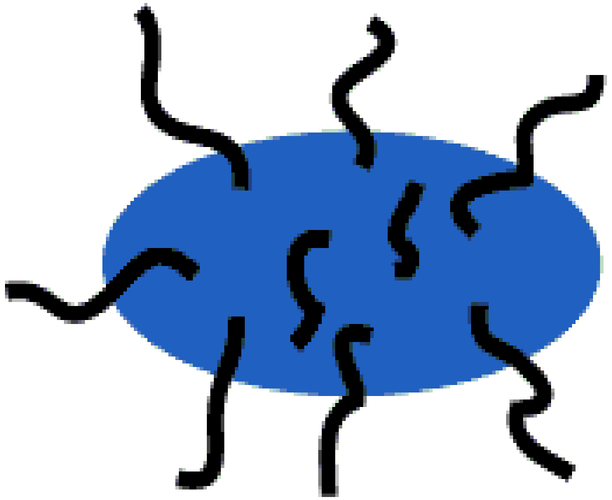
Neuronal organisms



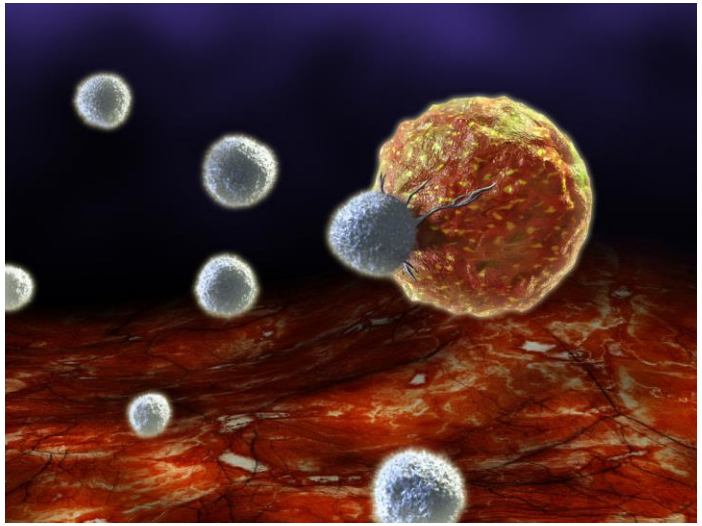
Non-neuronal organisms thrive in complex environments



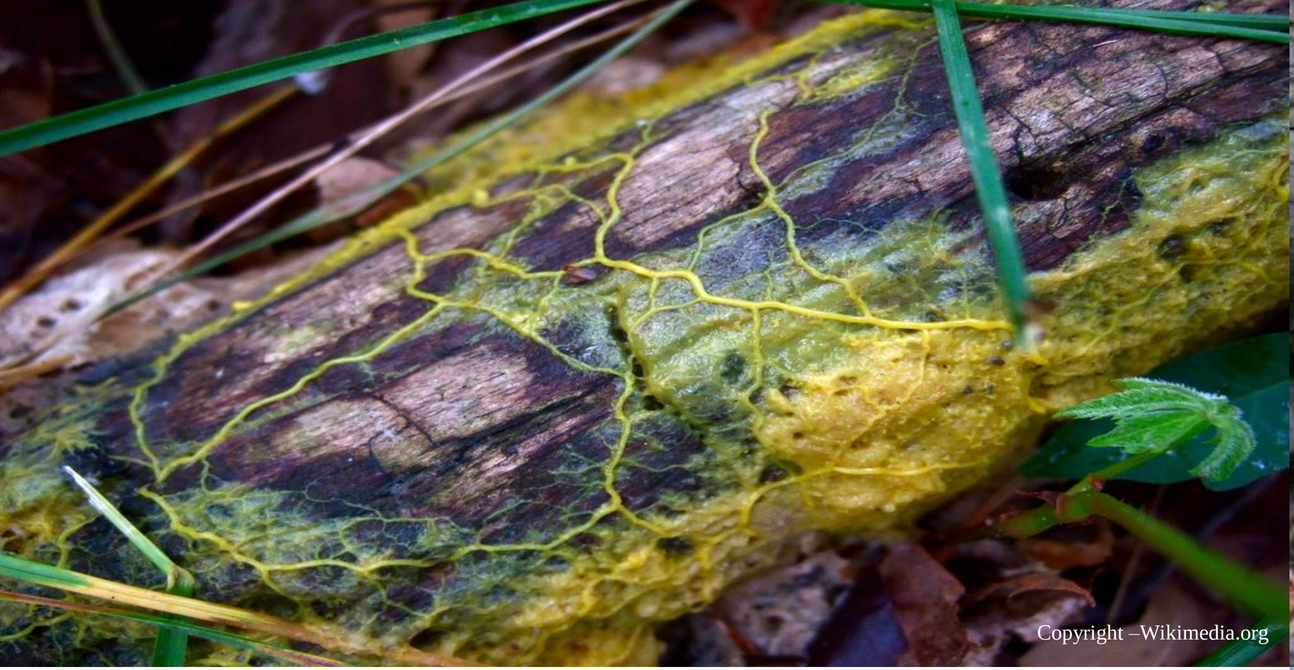
Plant roots



Bacterial cells

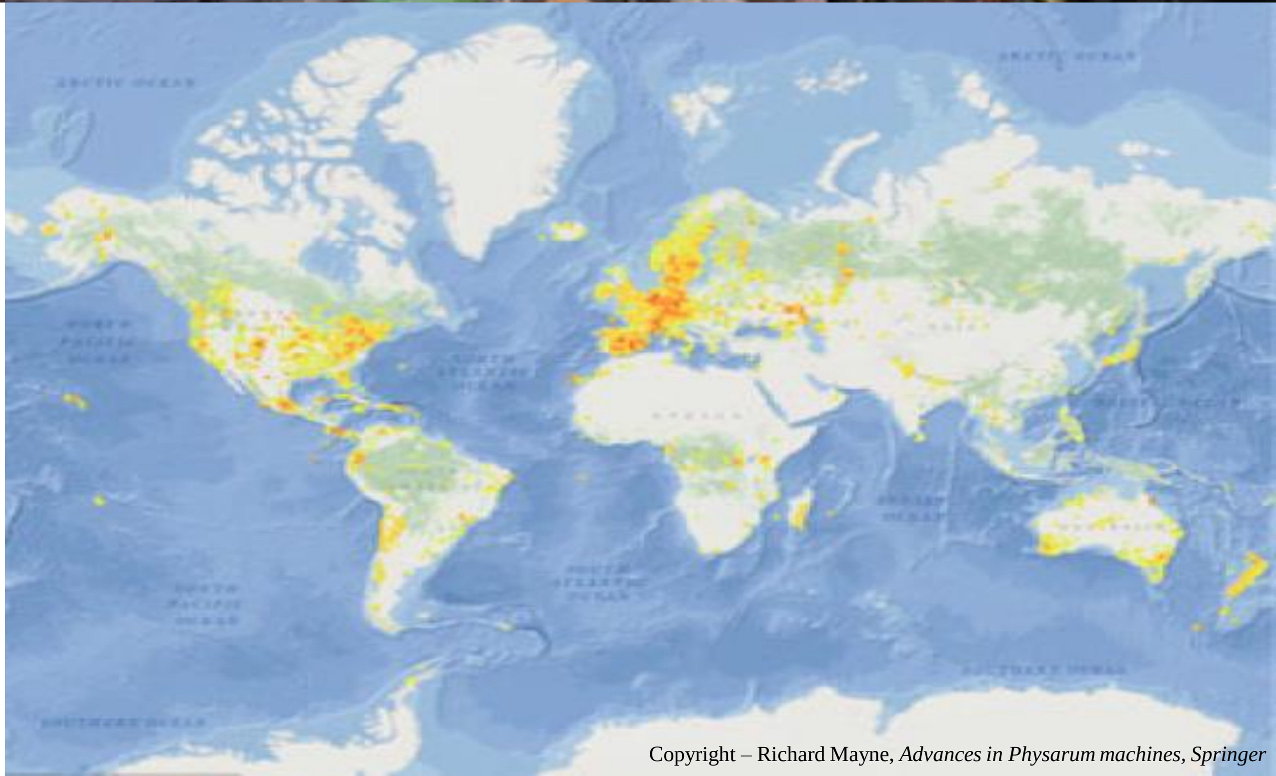


Immunoglobulins

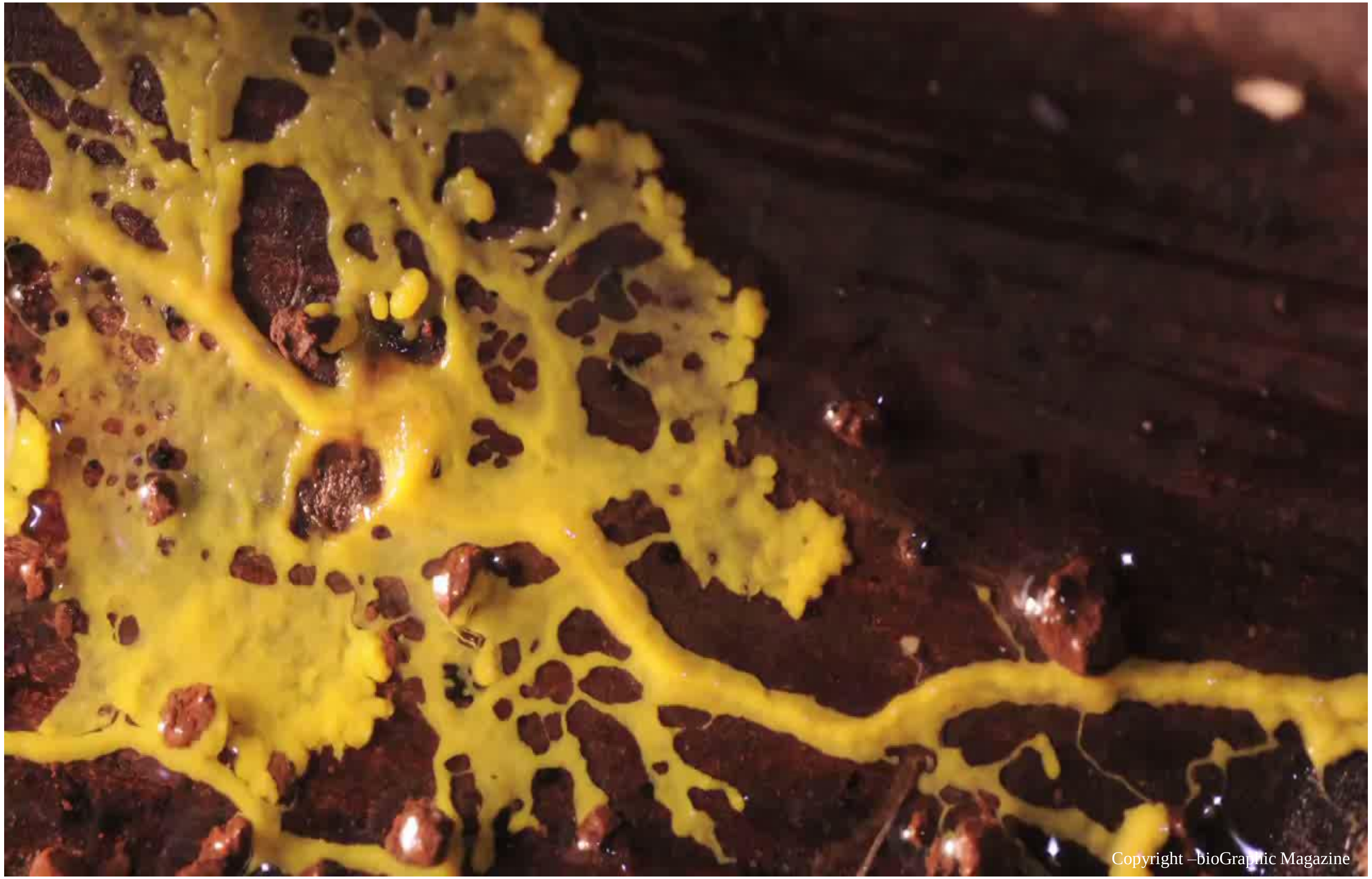


Acellular slime mold *Physarum polycephalum*

Phylum – Amoebozoa
Class - Myxogastria



Brainless but multi-headed



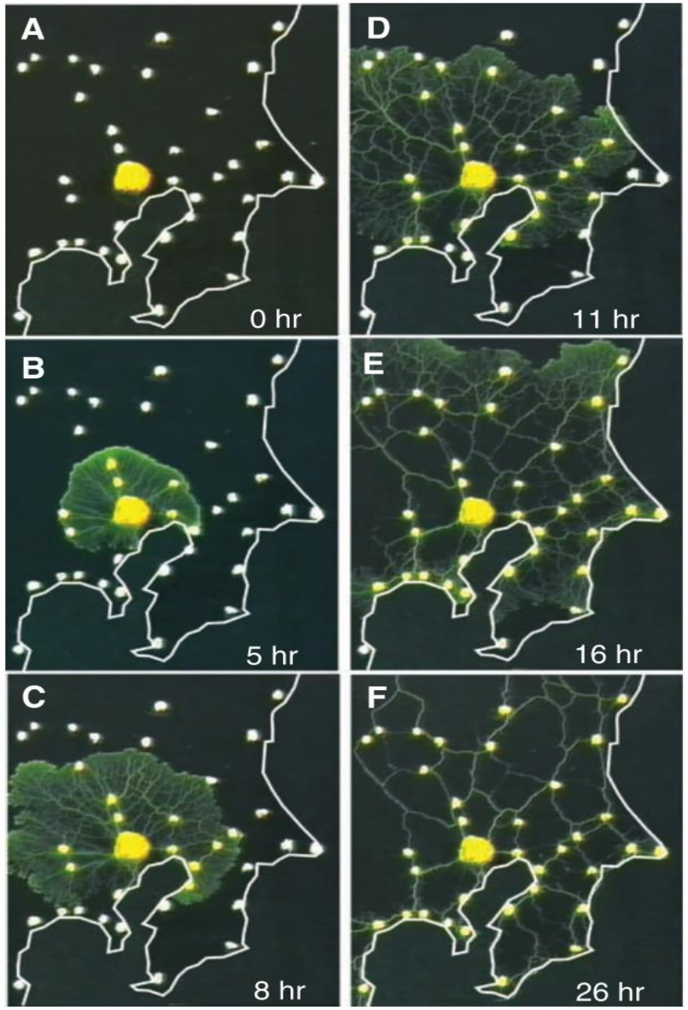
Solve labyrinth mazes

Nakagaki et al. (2000)

Construct Smart Networks

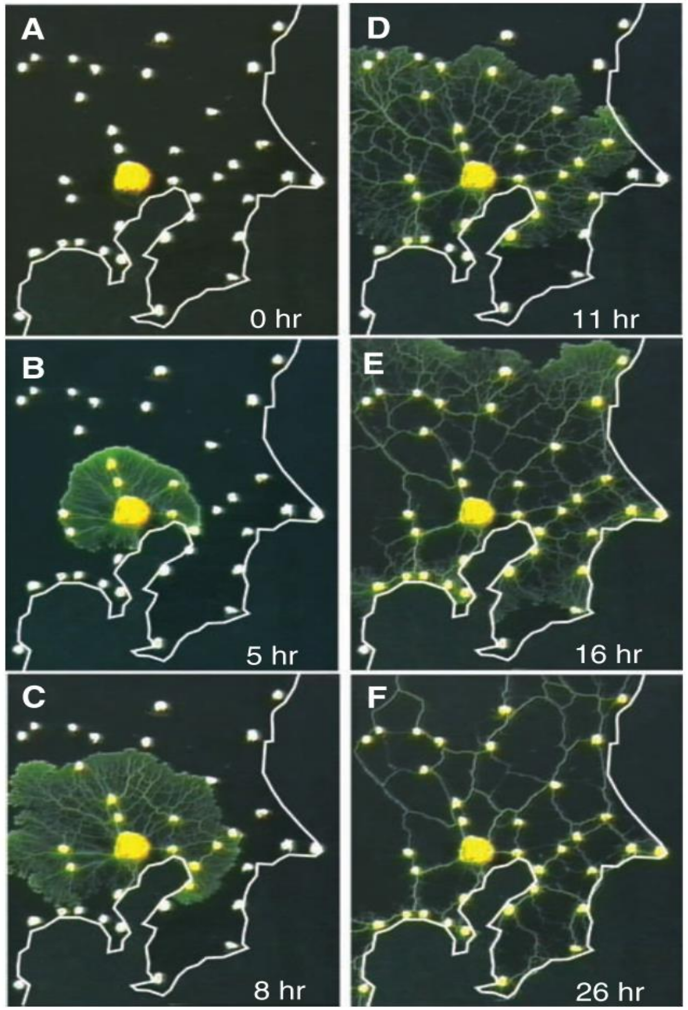
Tero et al. (2010)

Construct Smart Networks



Tero et al. (2010)

Construct Smart Networks



Rail road network in Tokyo metropolitan area

Total length (cost), average mean distance (transport efficiency) and fault tolerance (robustness) similar to real world man-made structures.

Tero et al. (2010)

Trade-off between exploration and exploitation

Exploitation

Exploration

Make the best decision given current information

Gather more information

Reid et al. (2016)

Trade-off between exploration and exploitation

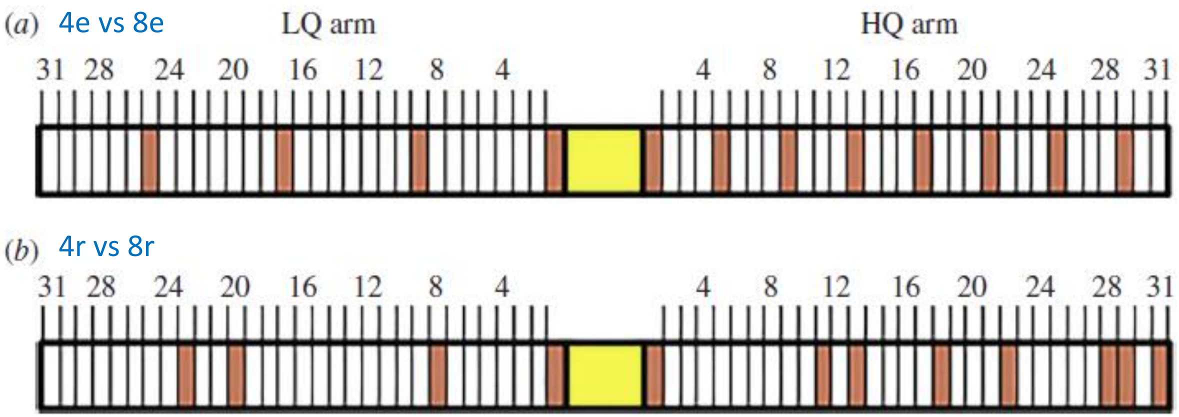
Casino slot machine

Reid et al. (2016)

Trade-off between exploration and exploitation

e – evenly distributed food sources
r – randomly distributed food sources
LQ – low-quality arm
HQ – high-quality arm

Casino slot machine

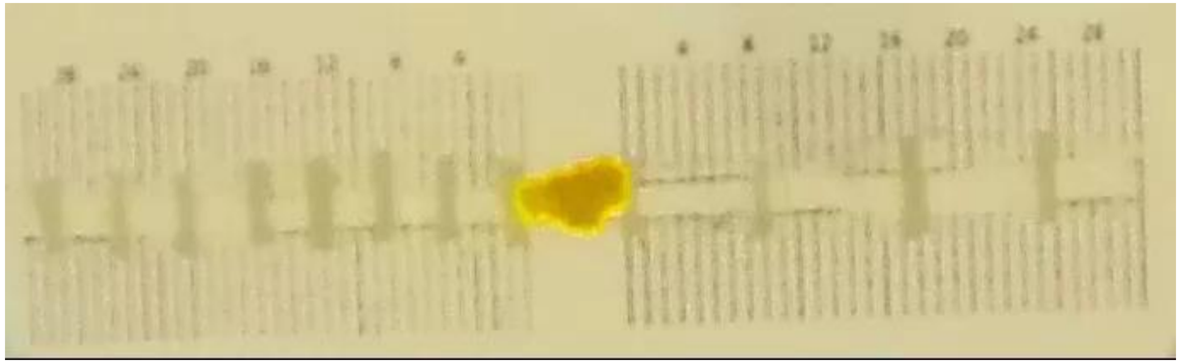


Slot machine for slime mold

Reid et al. (2016)

Trade-off between exploration and exploitation

Example 8e vs 4e

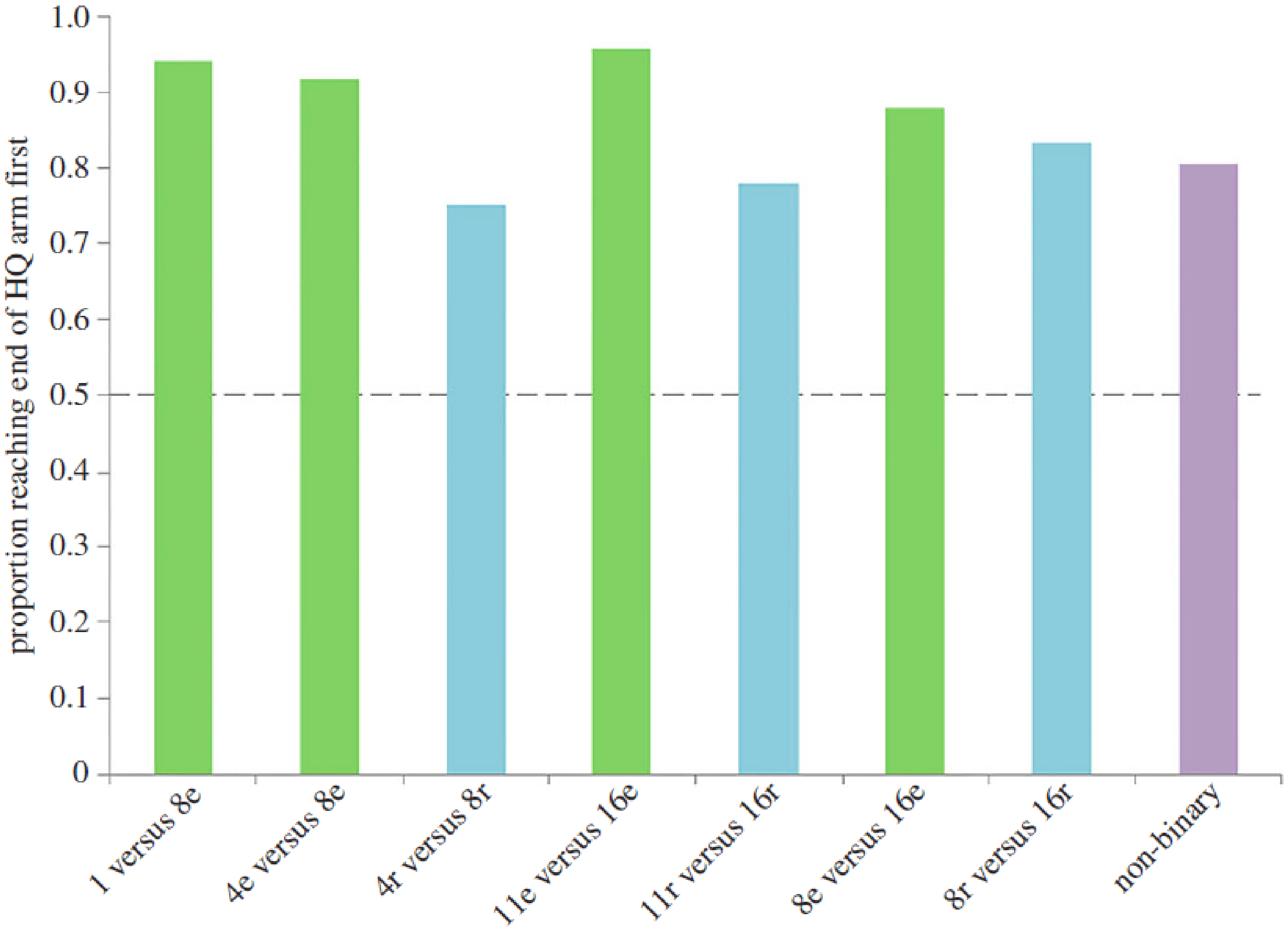


Casino slot machine

Slot machine for slime mold

Reid et al. (2016)

Trade-off between exploration and exploitation

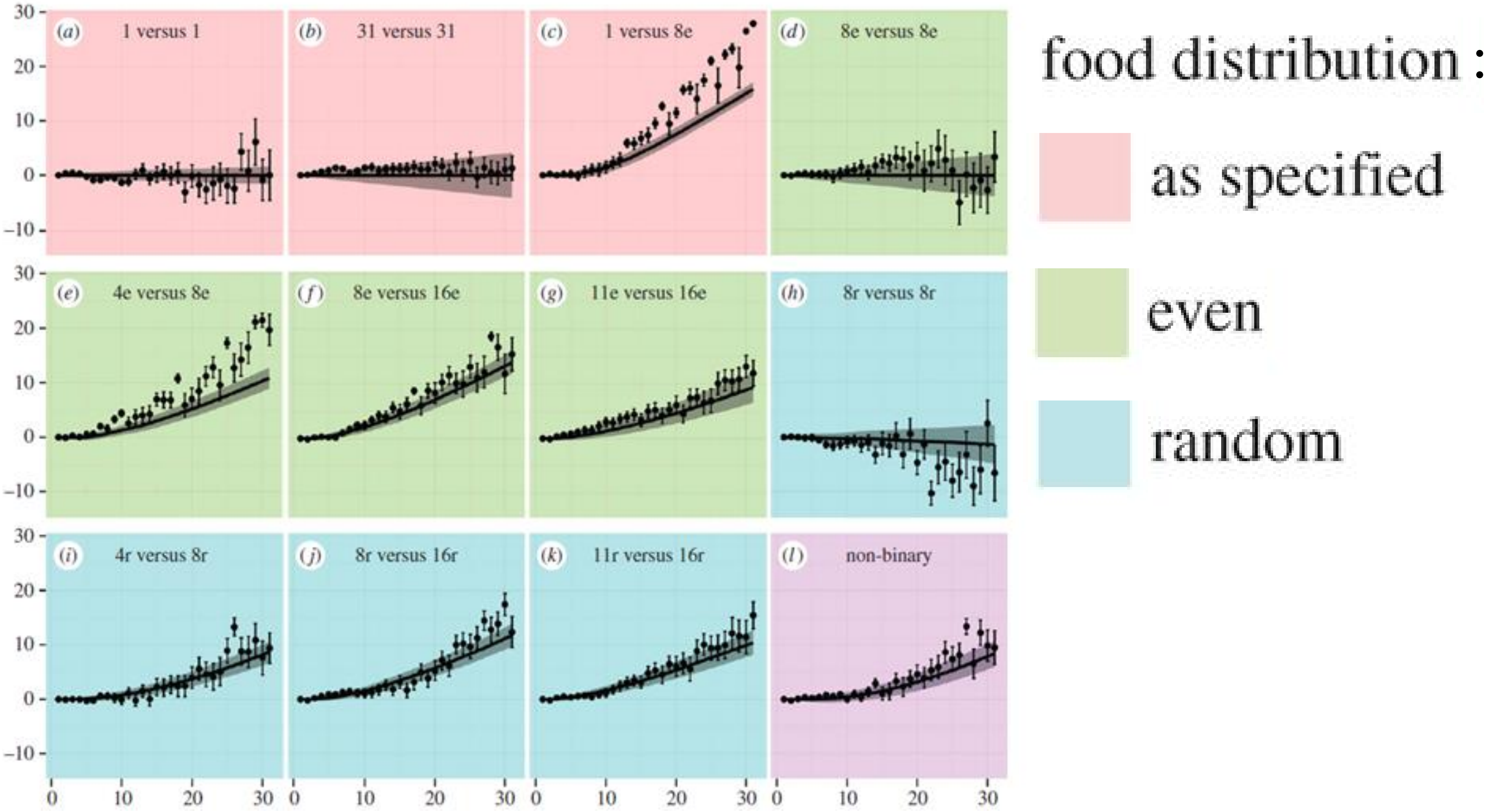


e – evenly distributed food source

r – randomly distributed food source

Reid et al. (2016)

Trade-off between exploration and exploitation

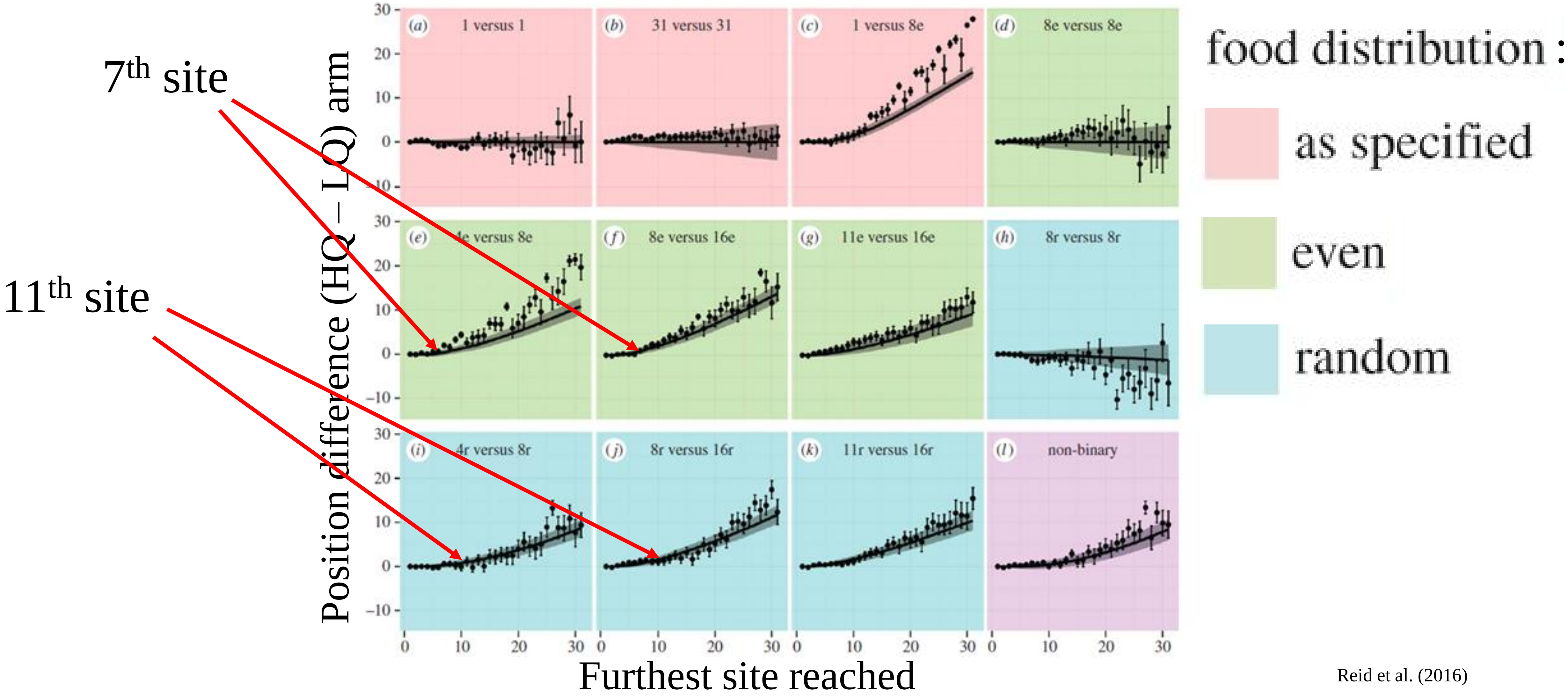


Position difference (HQ – LQ) arm

Furthest site reached

Reid et al. (2016)

Trade-off between exploration and exploitation



Reid et al. (2016)

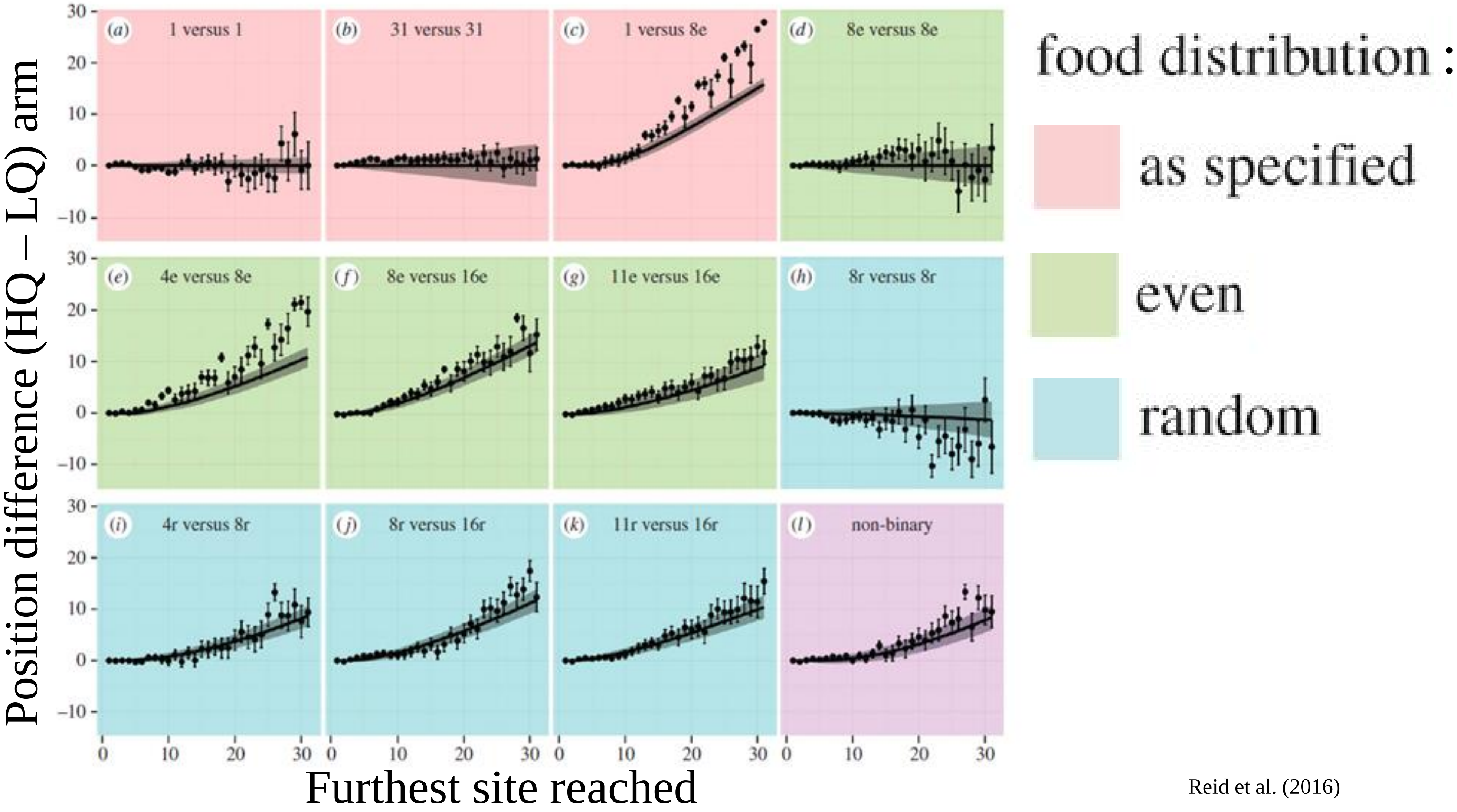
Trade-off between exploration and exploitation

$$P(m_t = \mathrm{R}) = \frac{A_R}{A_R + A_L}$$

m_t – probability of the cell moving right in the next move
A_L - No. of rewards sites encountered on the right arm
A_R - No. of rewards sites encountered on the left arm

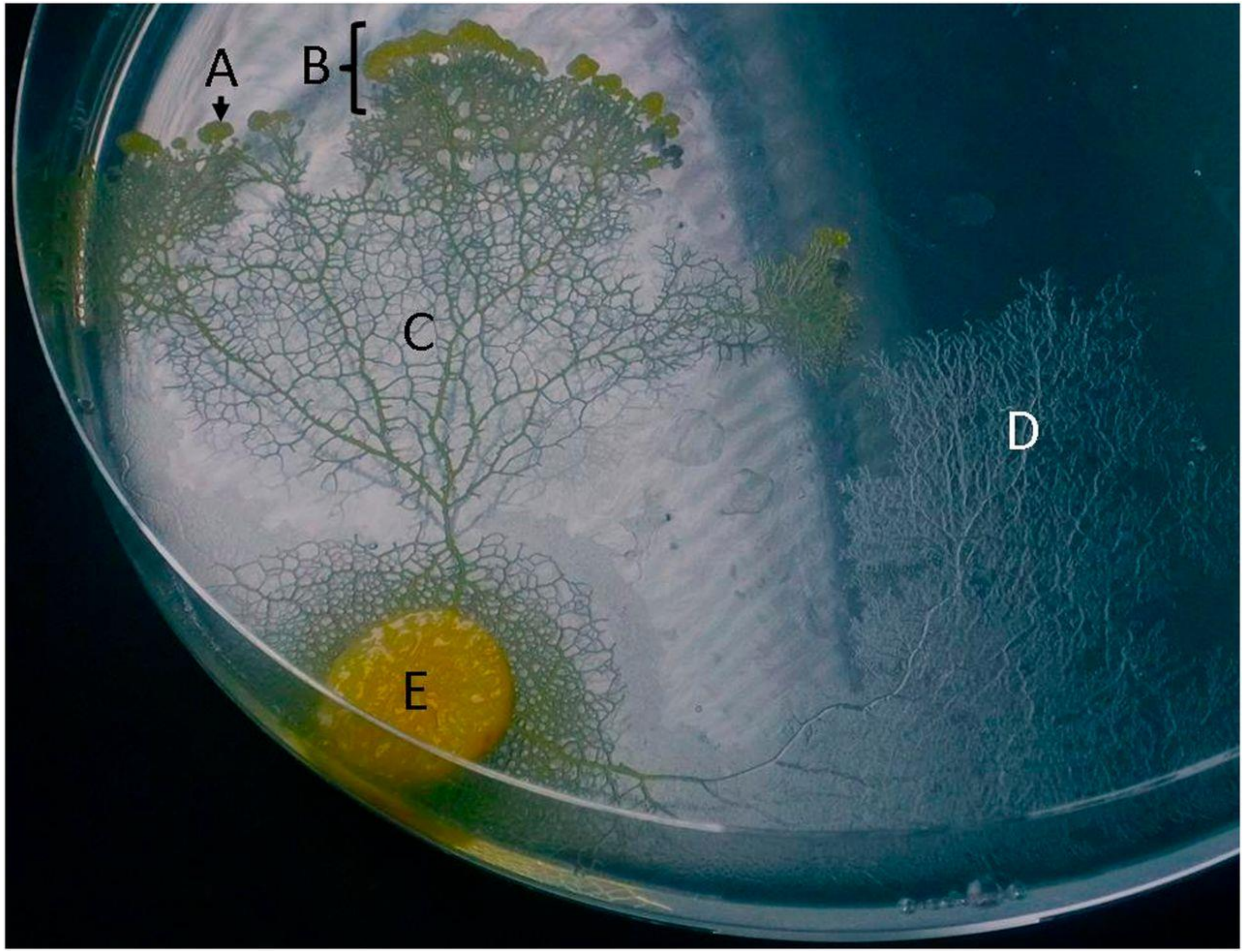
Reid et al. (2016)

Trade-off between exploration and exploitation



Reid et al. (2016)

External memory

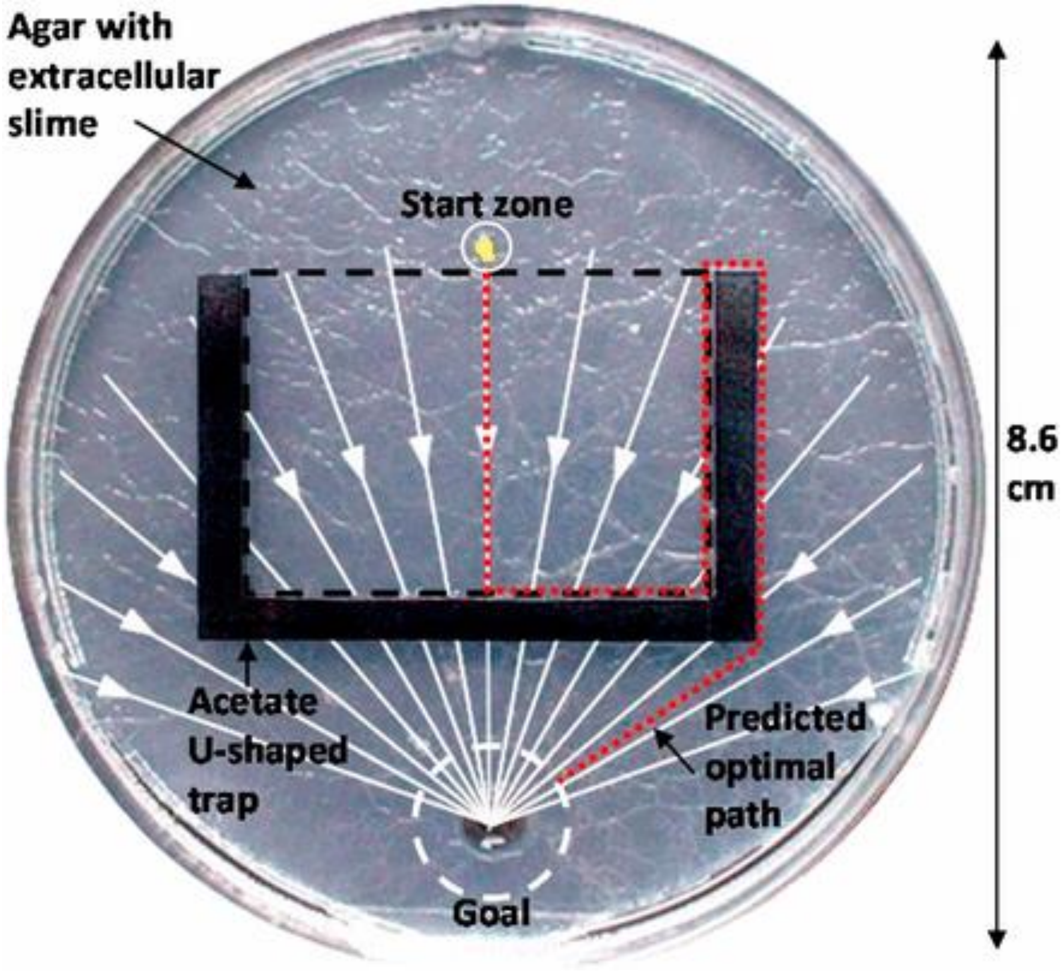


(A) extending pseudopod
(B) search front
(C) tubule network, and
(D) extracellular slime deposited where the cell has previously explored.

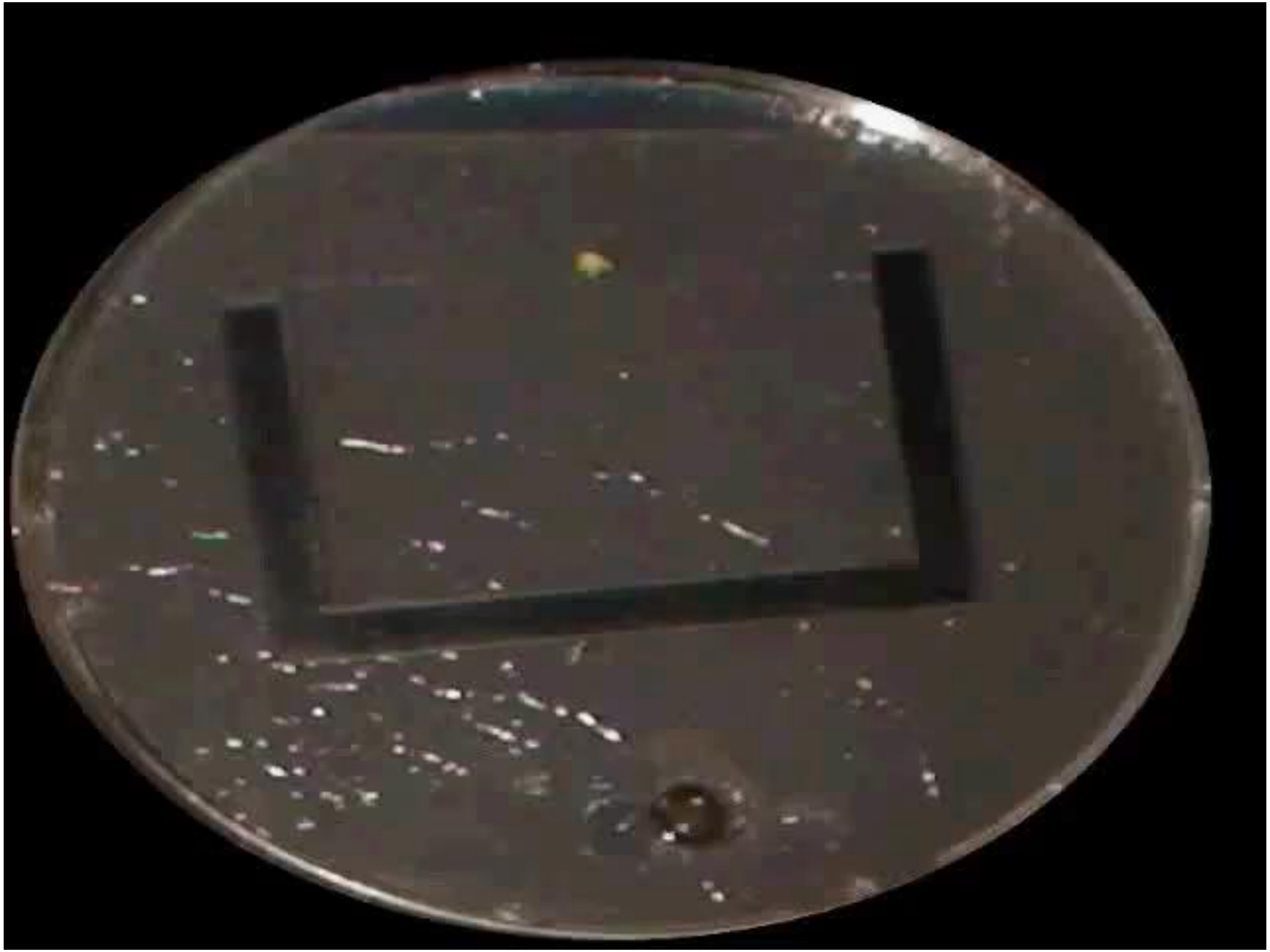
Reid et al. (2012)

External memory

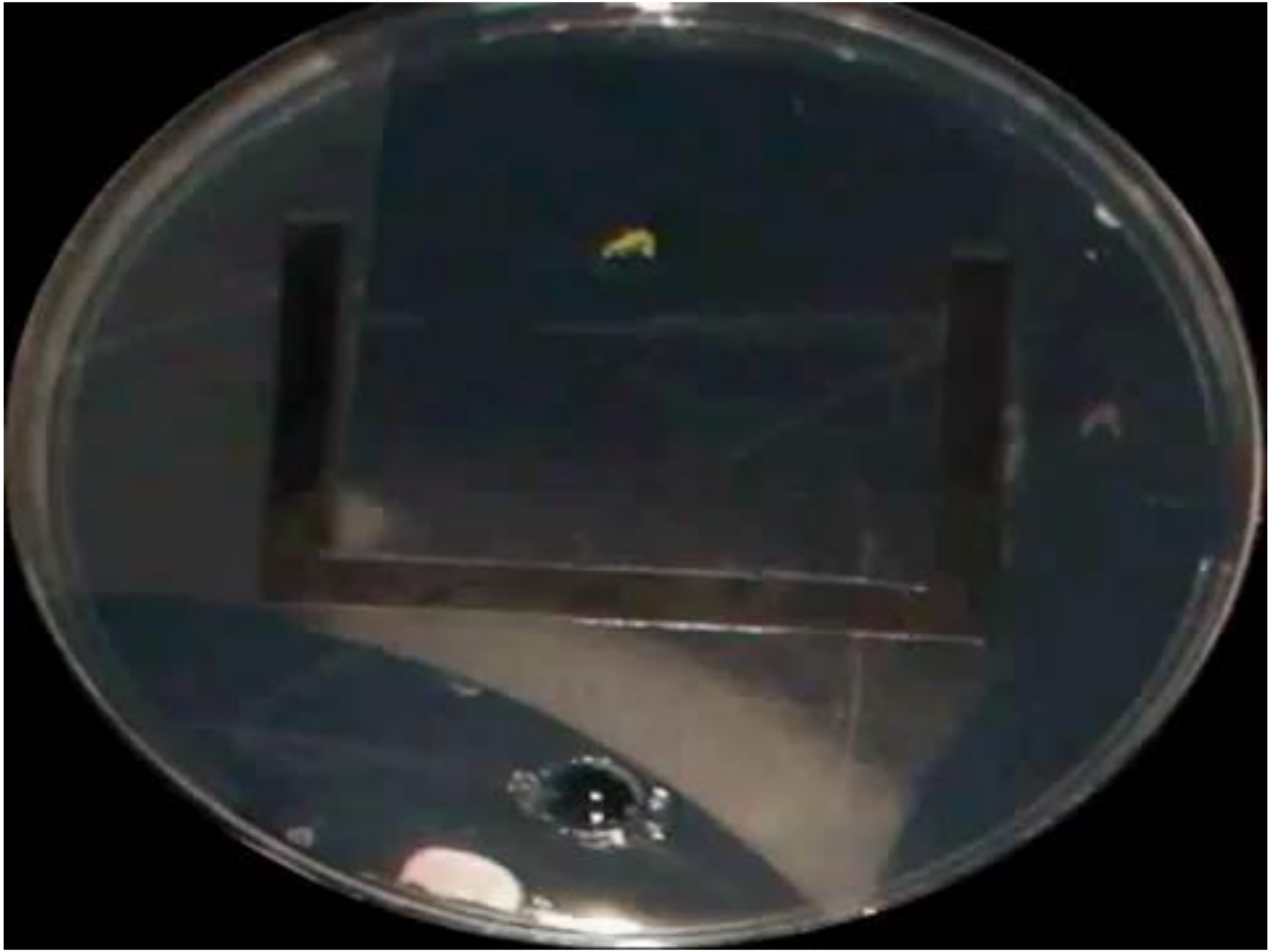
"U-shaped trap" problem



Reid et al. (2012)



Reid et al. (2012)



Reid et al. (2012)


BBC one
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BBC one


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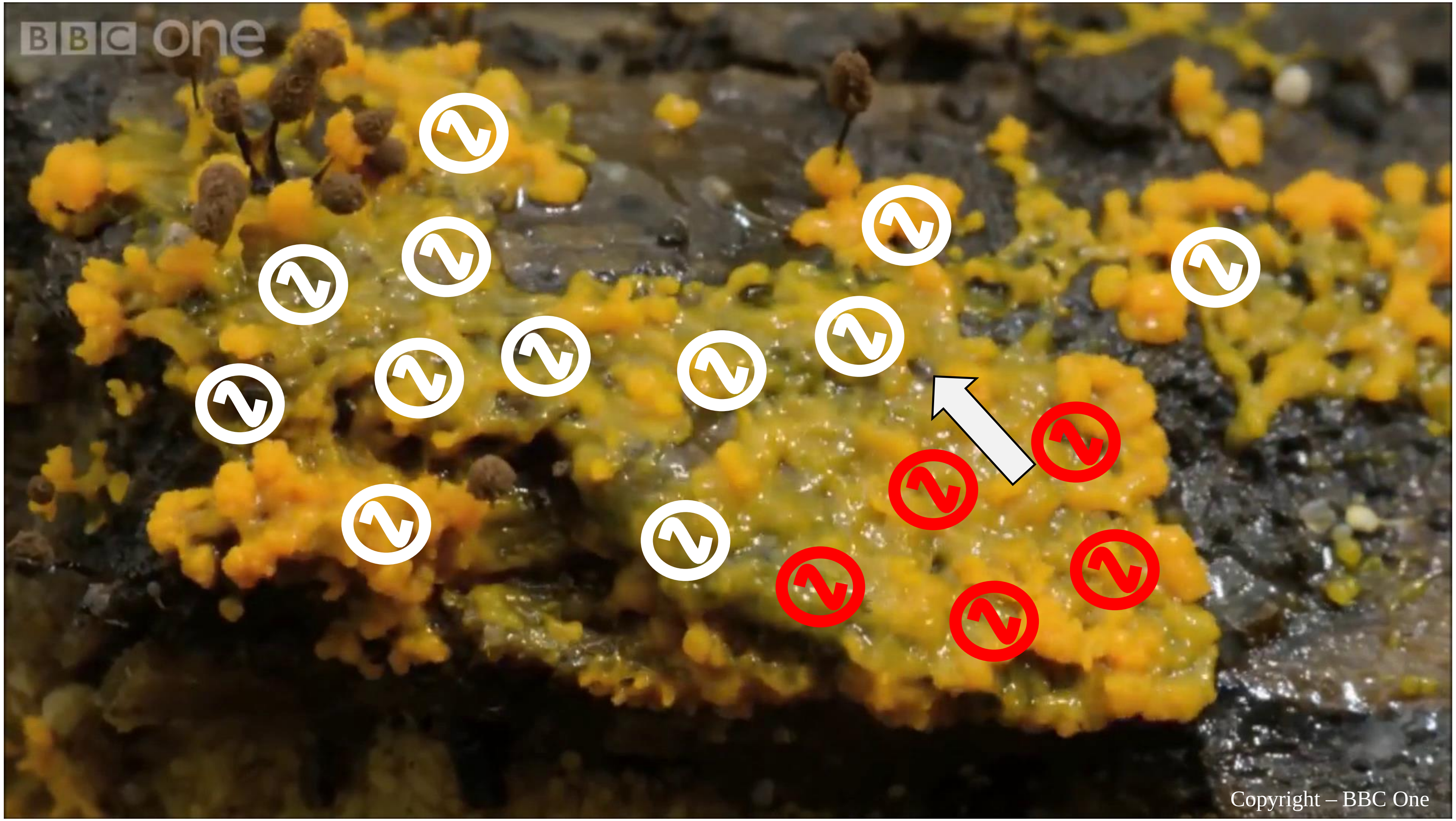
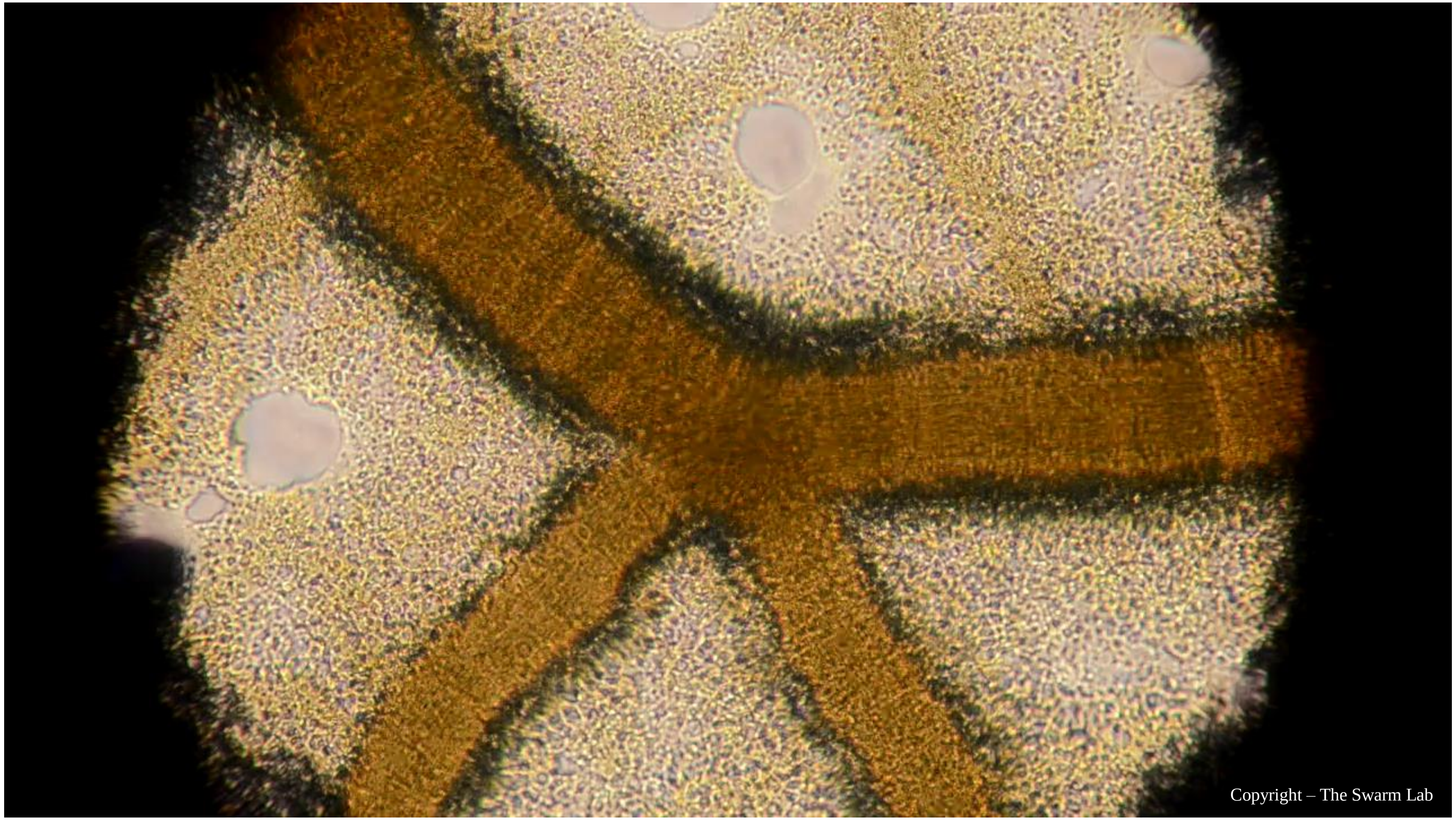
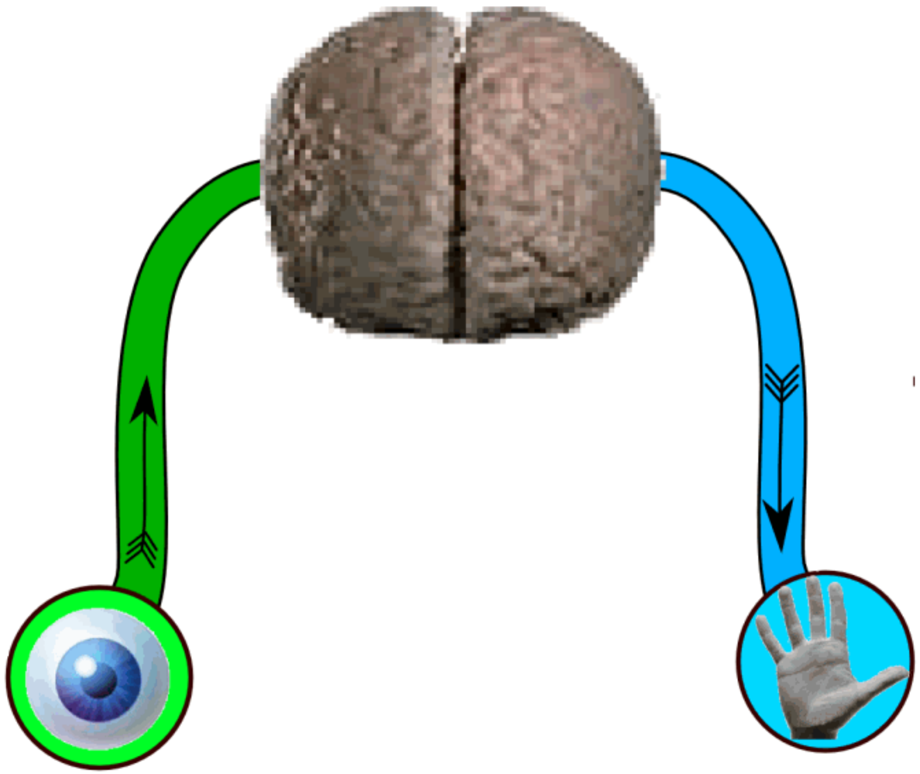

BBC one

Membrane contractions cause shuttle streaming



Alim et al. (2013)

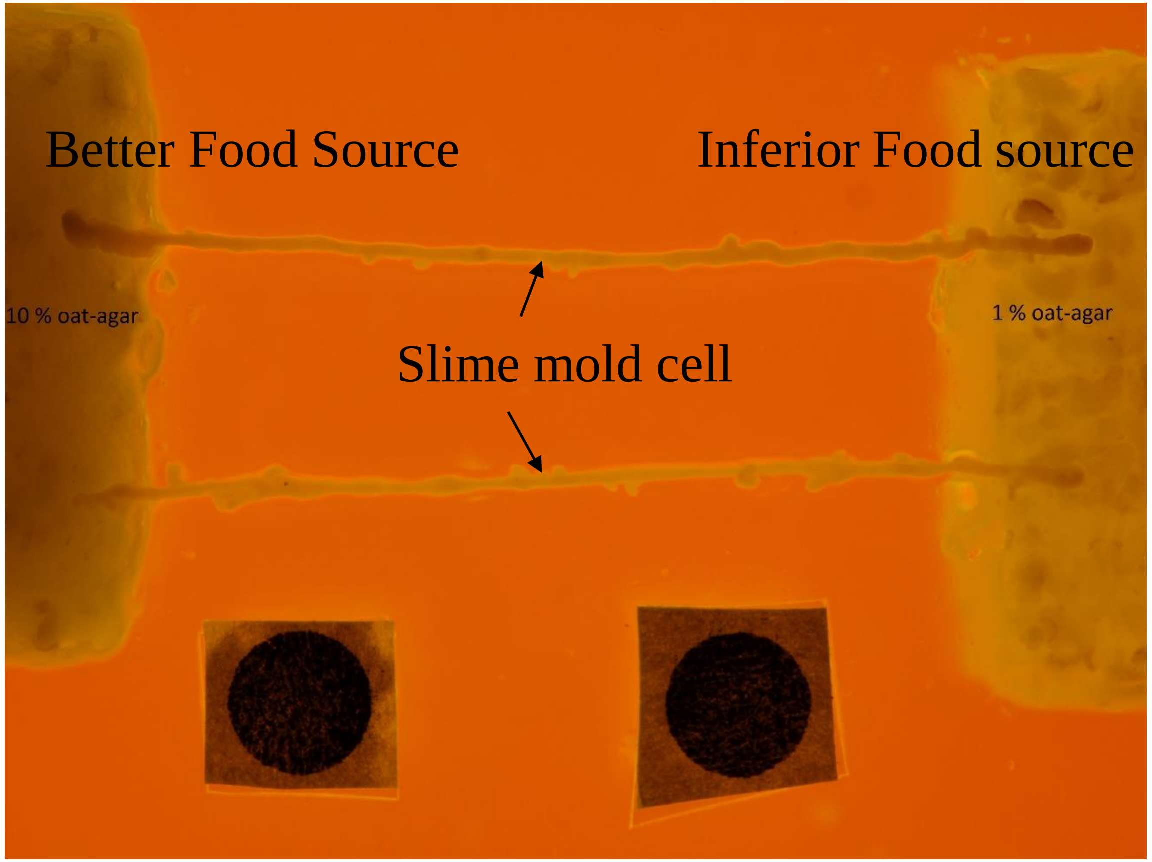
Slime mold cell membrane = the “brain” of slime mold?

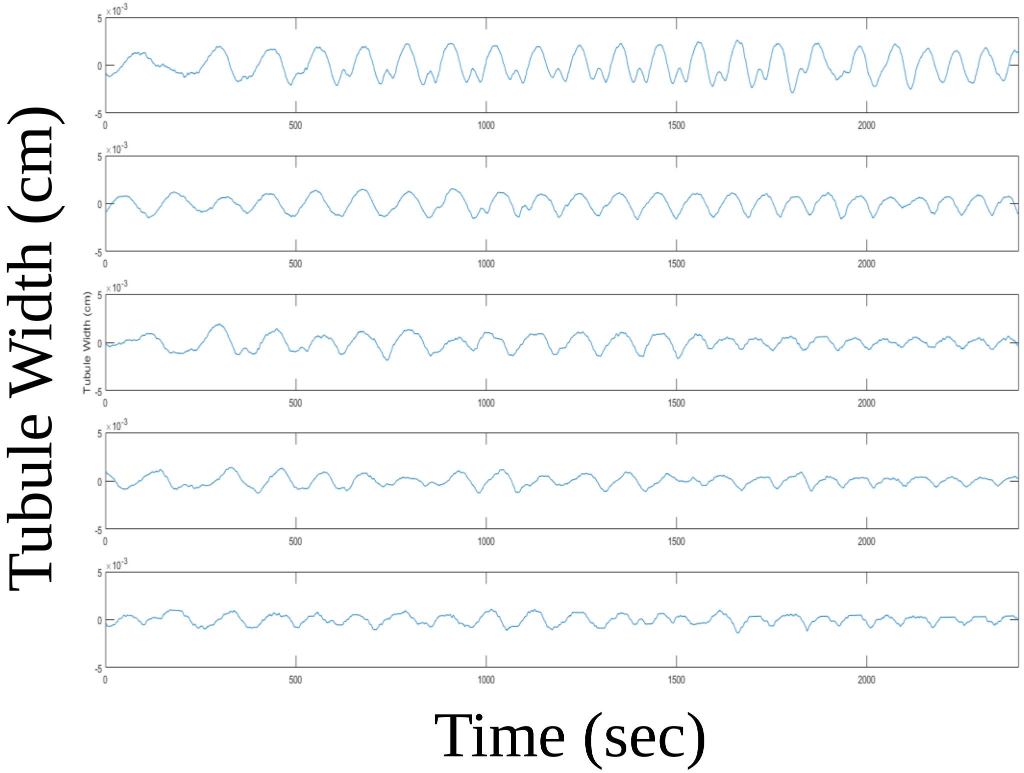


Stimulus sensed by the membrane

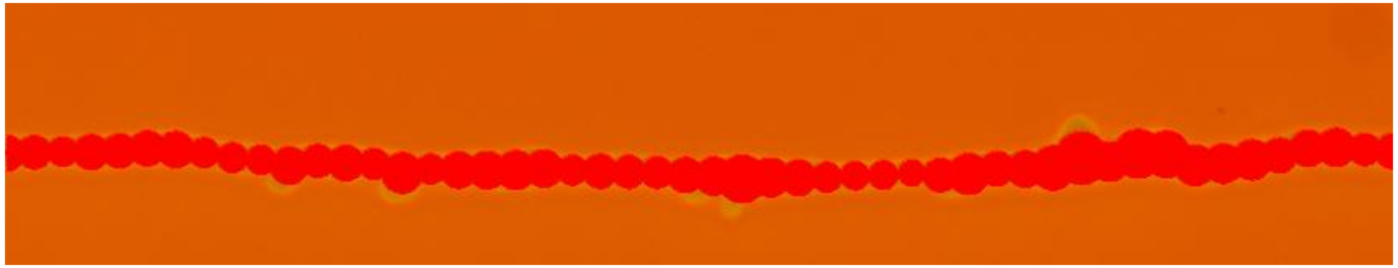
Membrane performs the action

Aim 1: Establish a relationship between membrane oscillations and decision-making

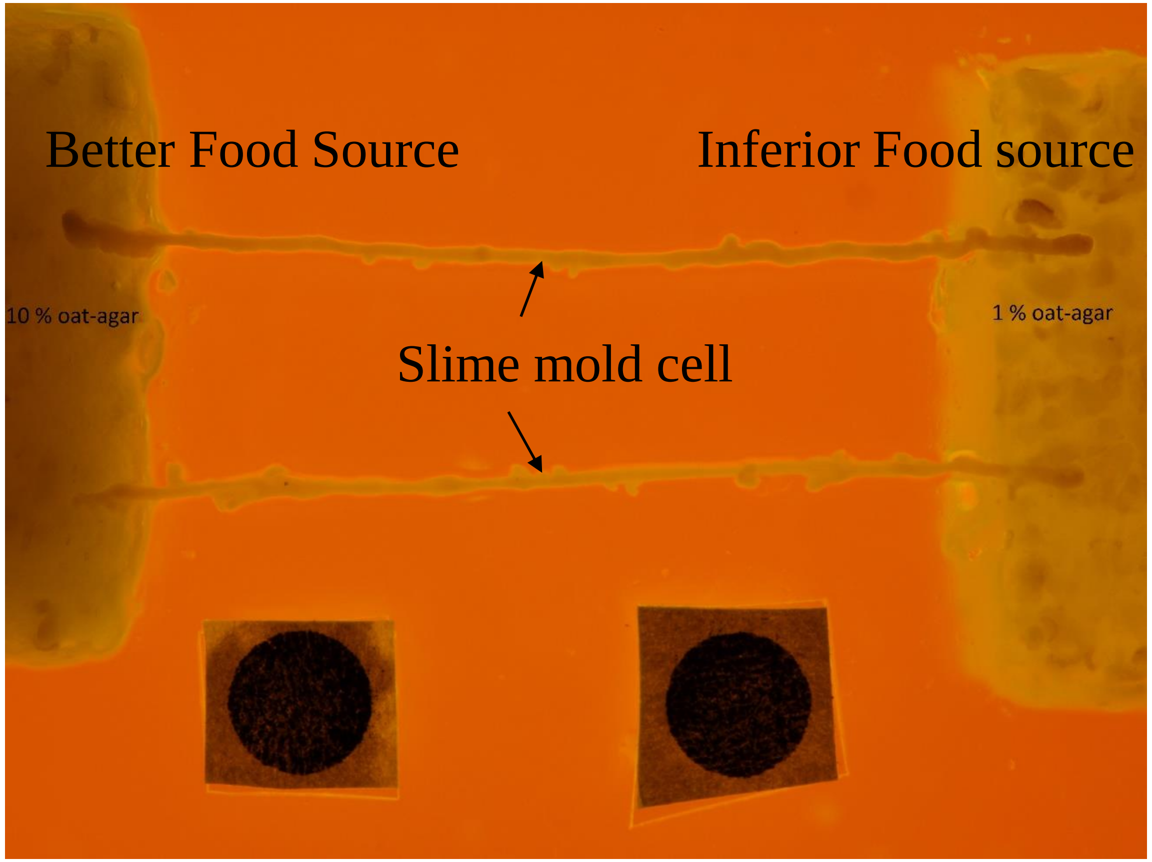




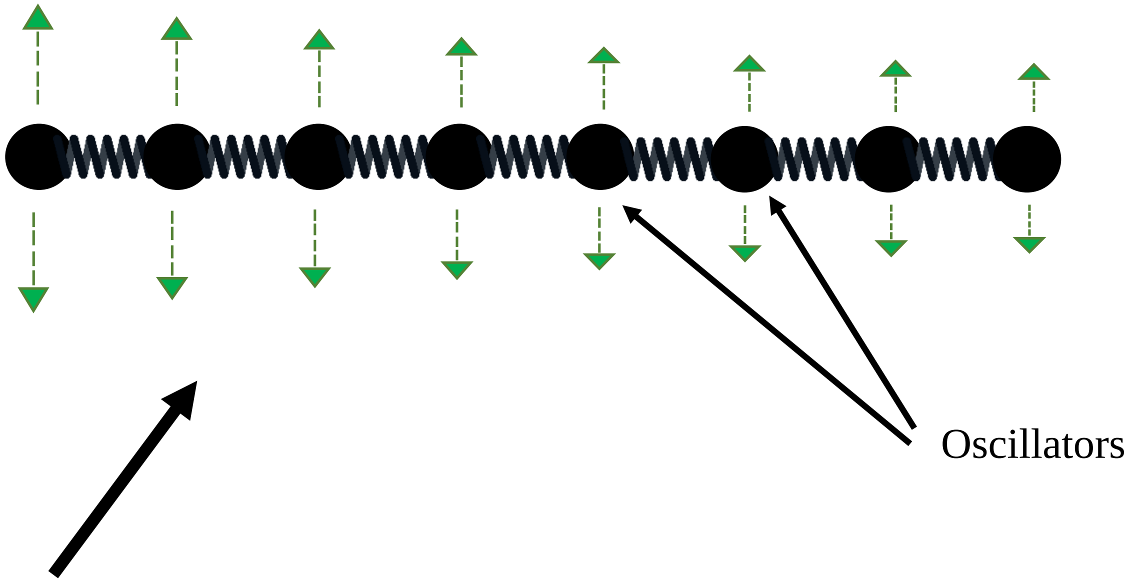
Sampled segments



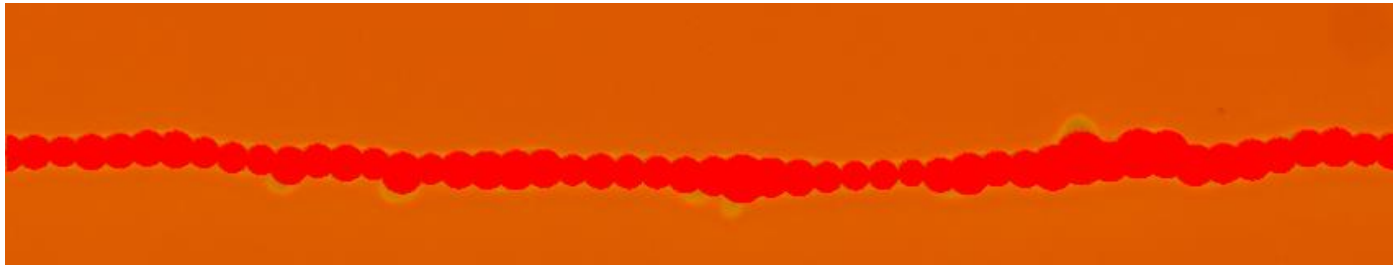
Aim 1: Establish a relationship between membrane oscillations and decision-making



Model using **chains** of **coupled oscillators**



Sampled segments



Aim 1: Establish a relationship between membrane oscillations and decision-making

Coupled Oscillator Model

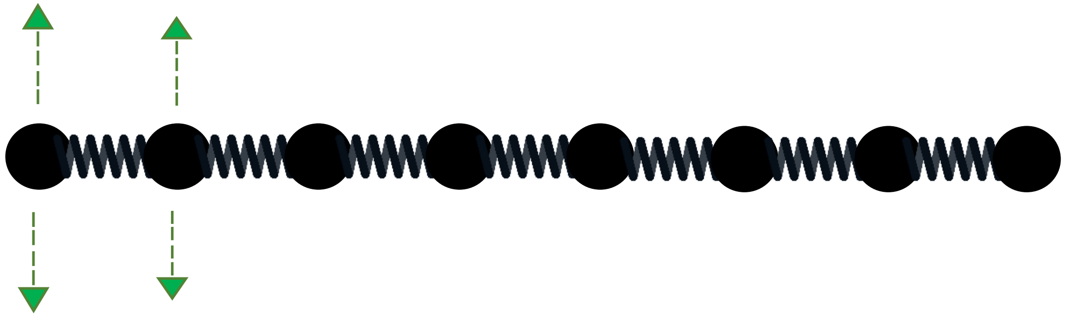
Kuramoto Model:

$$\frac{d\theta_k}{dt} = \omega_k + \frac{K}{N}\sum_{j=1}^{N}\sin(\theta_j - \theta_k)$$

θ_k = rate of change of phase
ω_k = natural frequency of the oscillator
K = coupling strength
N = number of oscillator influencing frequency
θ_j = phase of the j^{th} oscillator

Aim 2: Oscillation patterns in response to direct mechanical stimulation

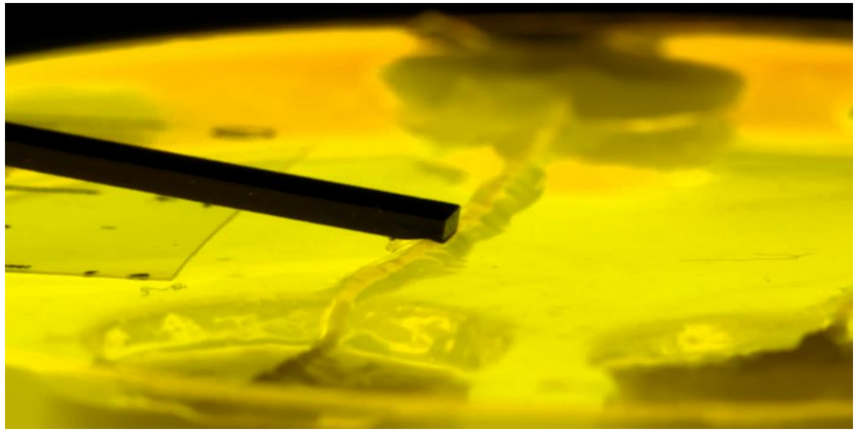
"Poking" cell membrane to induce oscillations



Predictions

Slime mold cell (straight tubule shape)

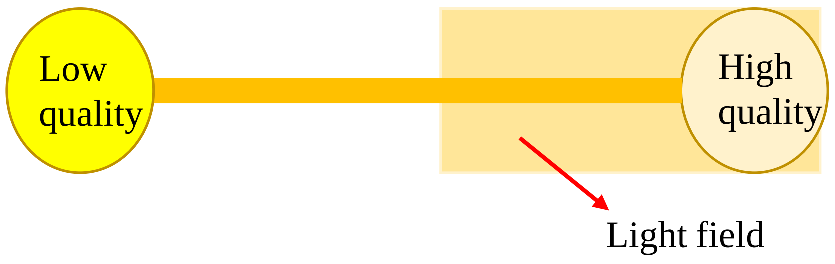
Few oscillators on an oscillation regime



Investigate the **causal link** between **mechanical oscillations** and **decision-making**

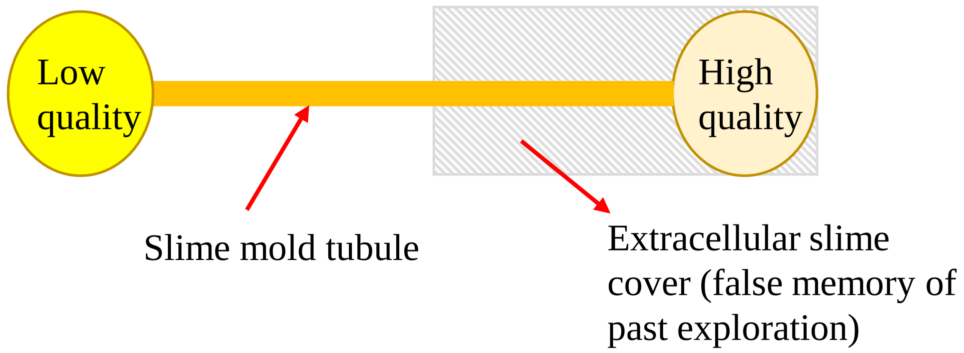
Next ….

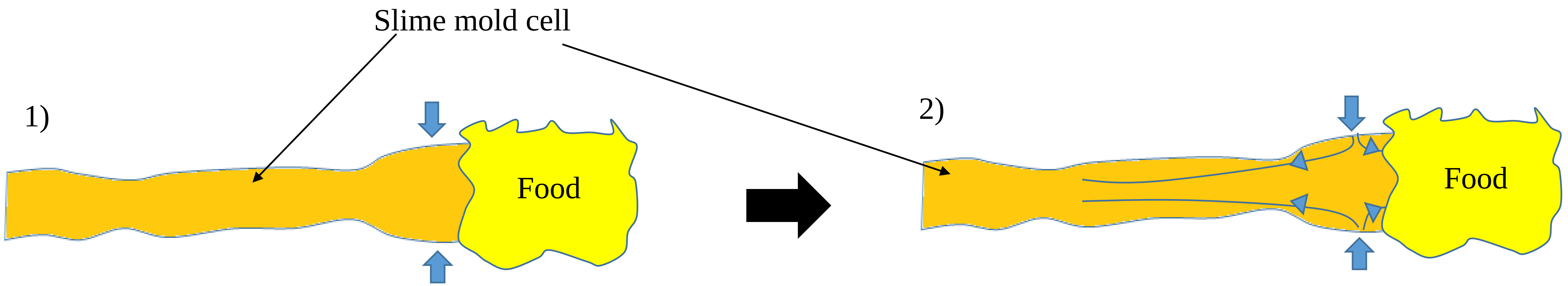
1) Oscillatory patterns while making trade-offs (i.e. when making trade-offs)



Contradictory information: High-quality food source – **reward** Light field – **risk (danger)**

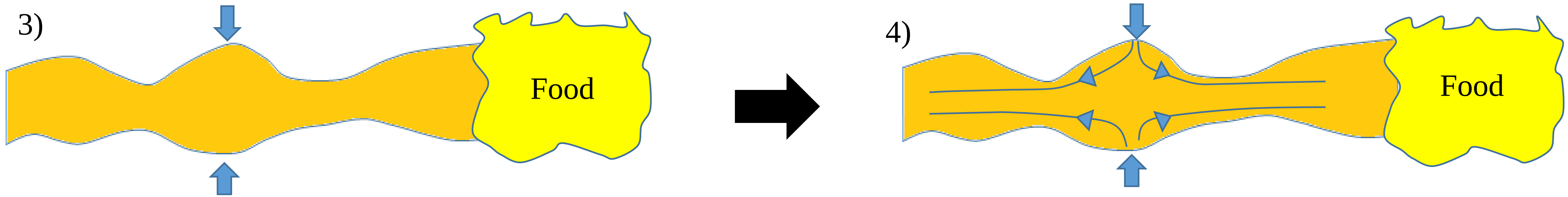
2) Oscillatory patterns in the presence of extra-cellular slime





Oscillation amplitude **increases** in the local cell region

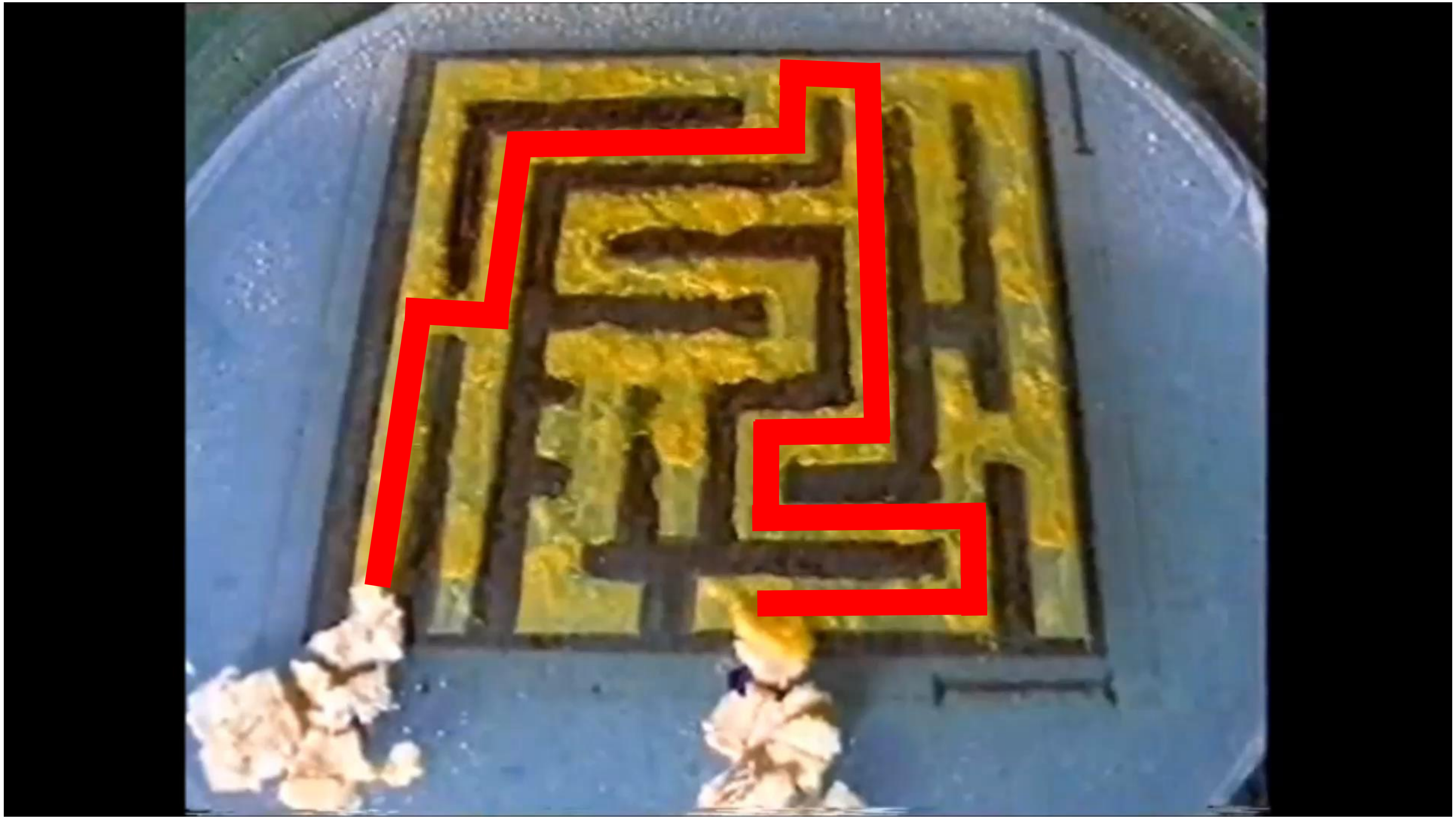
Causes **increase** in density of local fluid flow

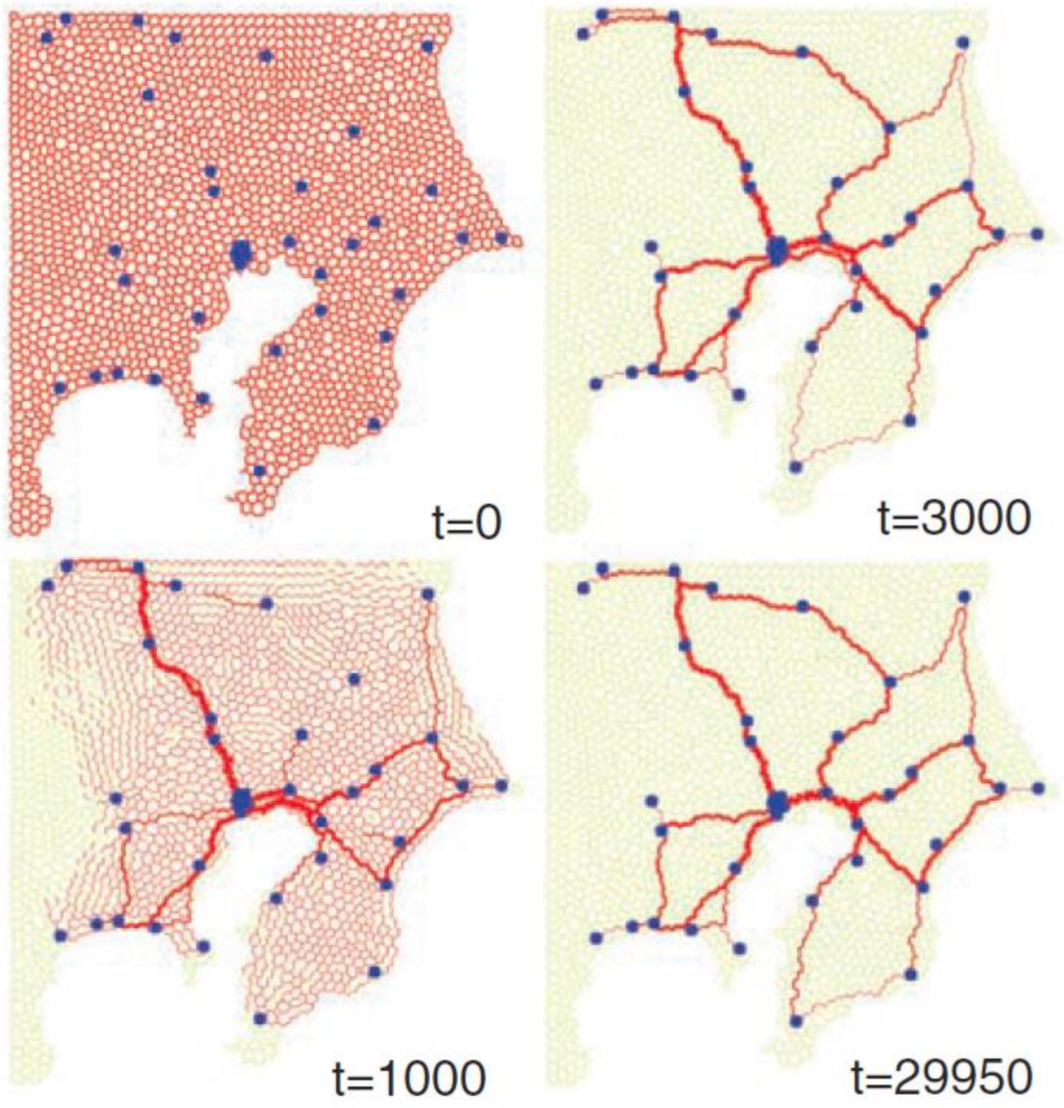


Greater fluid flow **increases** dispersion of contraction signaling molecule

Triggering an **increase** in contraction amplitude in the downstream of the network

Alim et al. (2017)





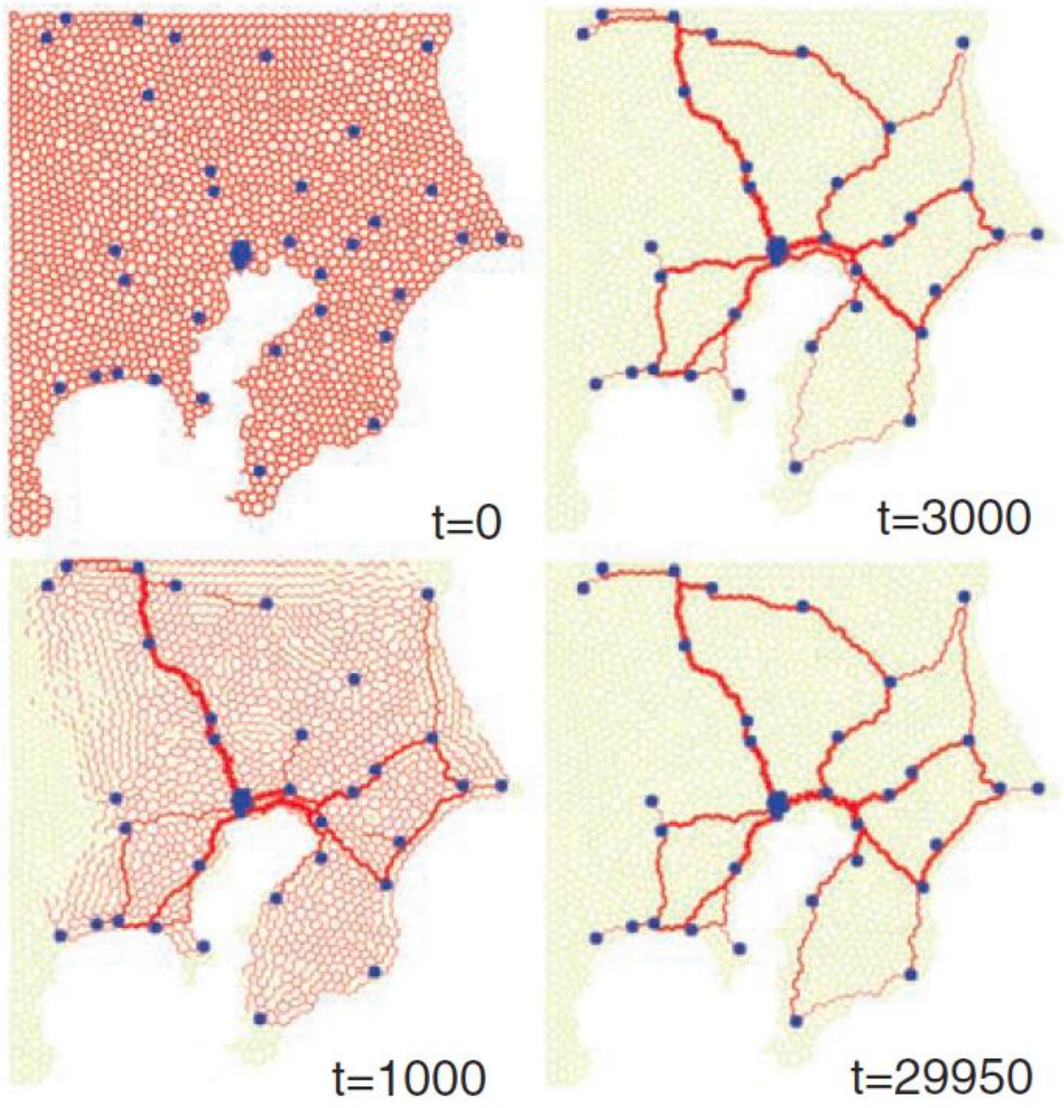
Hagen Poisseuille equation:

$$Q_{ij} = \frac{\pi r^4 (p_i - p_j)}{8\eta L_{ij}} = \frac{D_{ij}(p_i - p_j)}{L_{ij}}$$

p_i, p_j - pressure at node i and j
L_{ij}, r_{ij} - length and radius of the tubes

$D_{ij} = \frac{\pi r^4}{8\eta}$ - measure of conductivity of the tube

Tero et al. (2010)



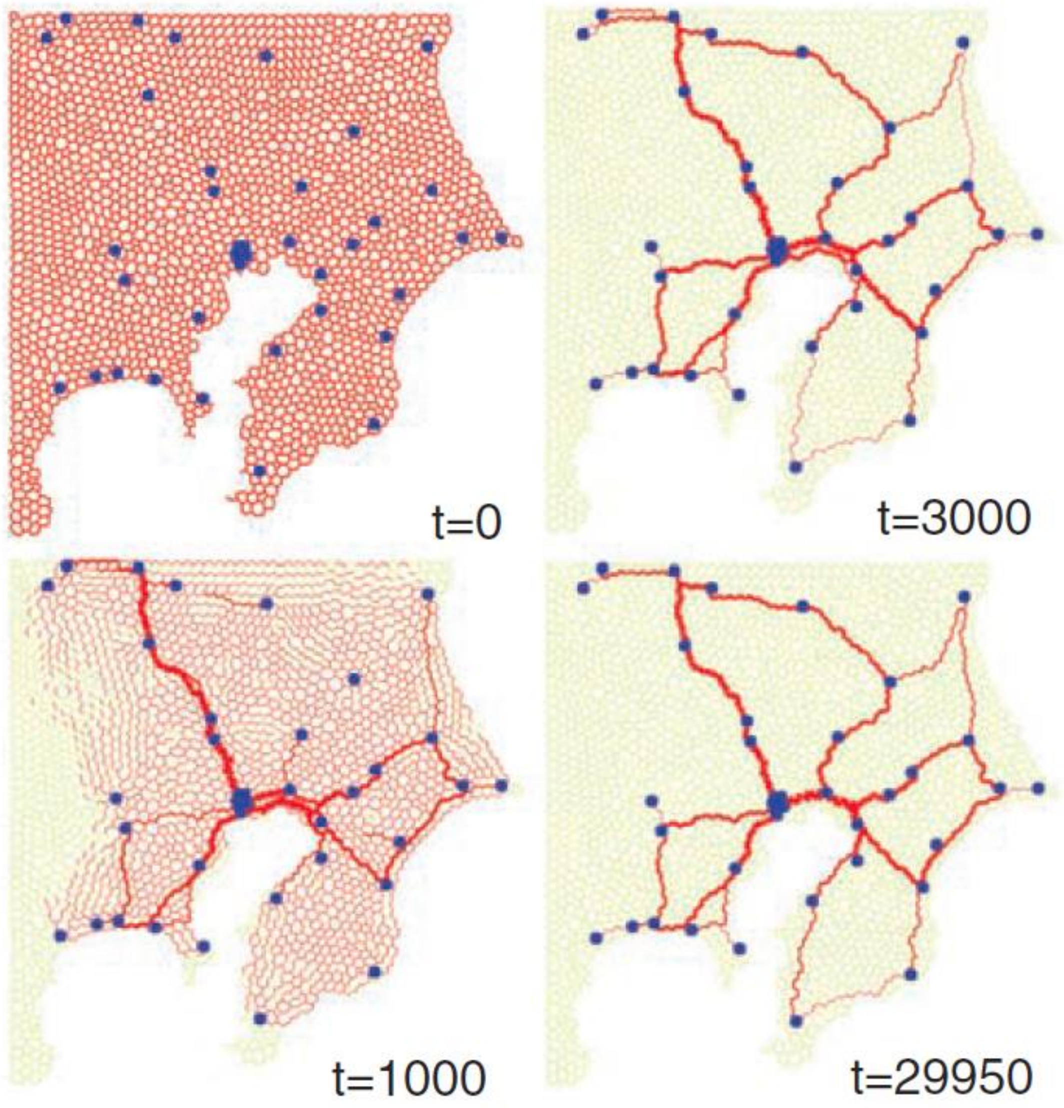
Two nodes were chosen at random, with flux terms:

$$\sum_j Q_{1j} = I_0$$
$$\sum_j Q_{2j} = -I_0$$

As the amount of fluid must conserved, i (i $\neq$ 1,2)

$$\sum_j Q_{ij} = 0$$

Tero et al. (2010)



To accommodate adaptive behavior, conductivity evolves by:

$$dD_{ij}/dt = f(|Q_{ij}|) - D_{ij}$$

Expansion of tube in response to flux

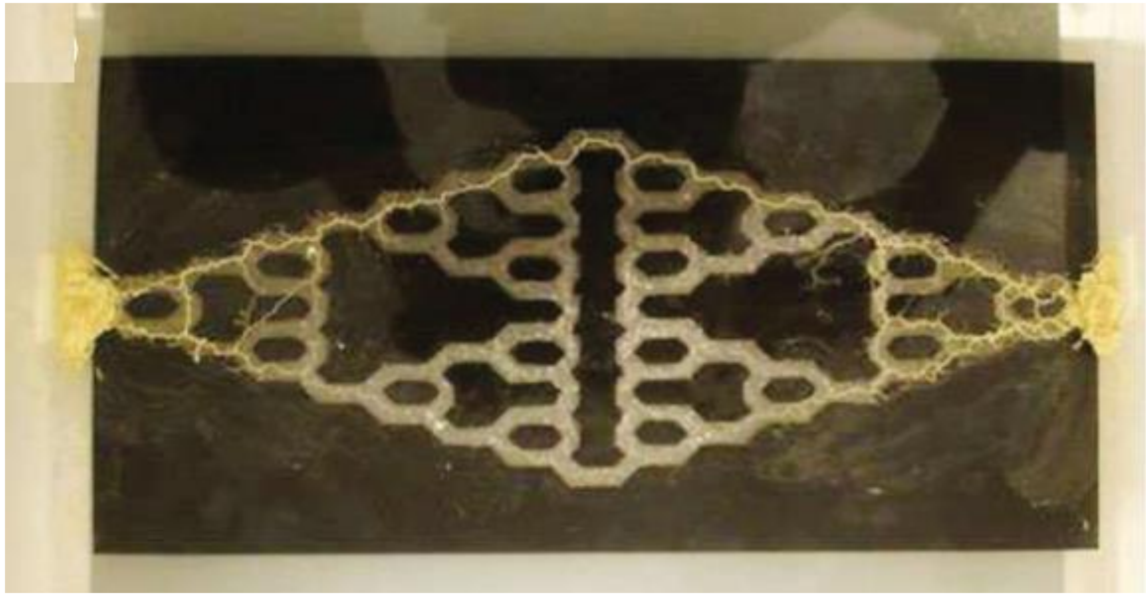
Rate of tube constriction

Where,

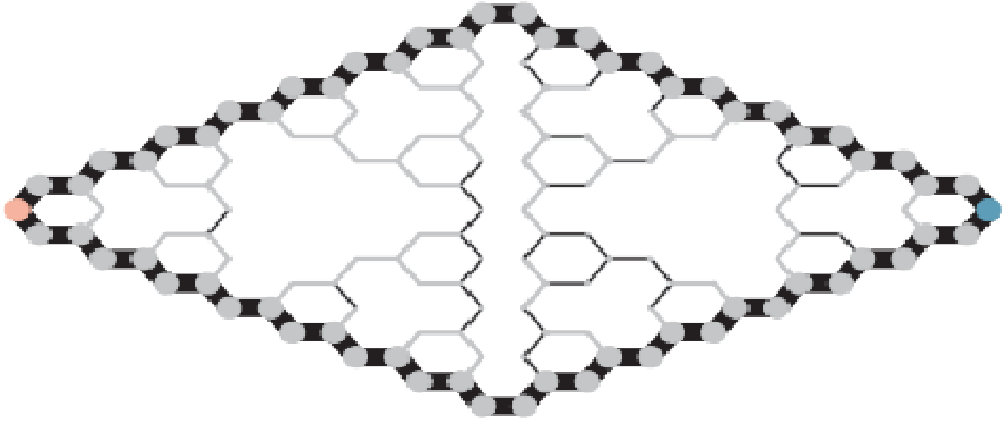
$$f(|Q|) = \frac{|Q|^{\gamma}}{1 + |Q|^{\gamma}}$$

$I_0 = 0.20$ and $\gamma = 1.15$

Tero et al. (2010)

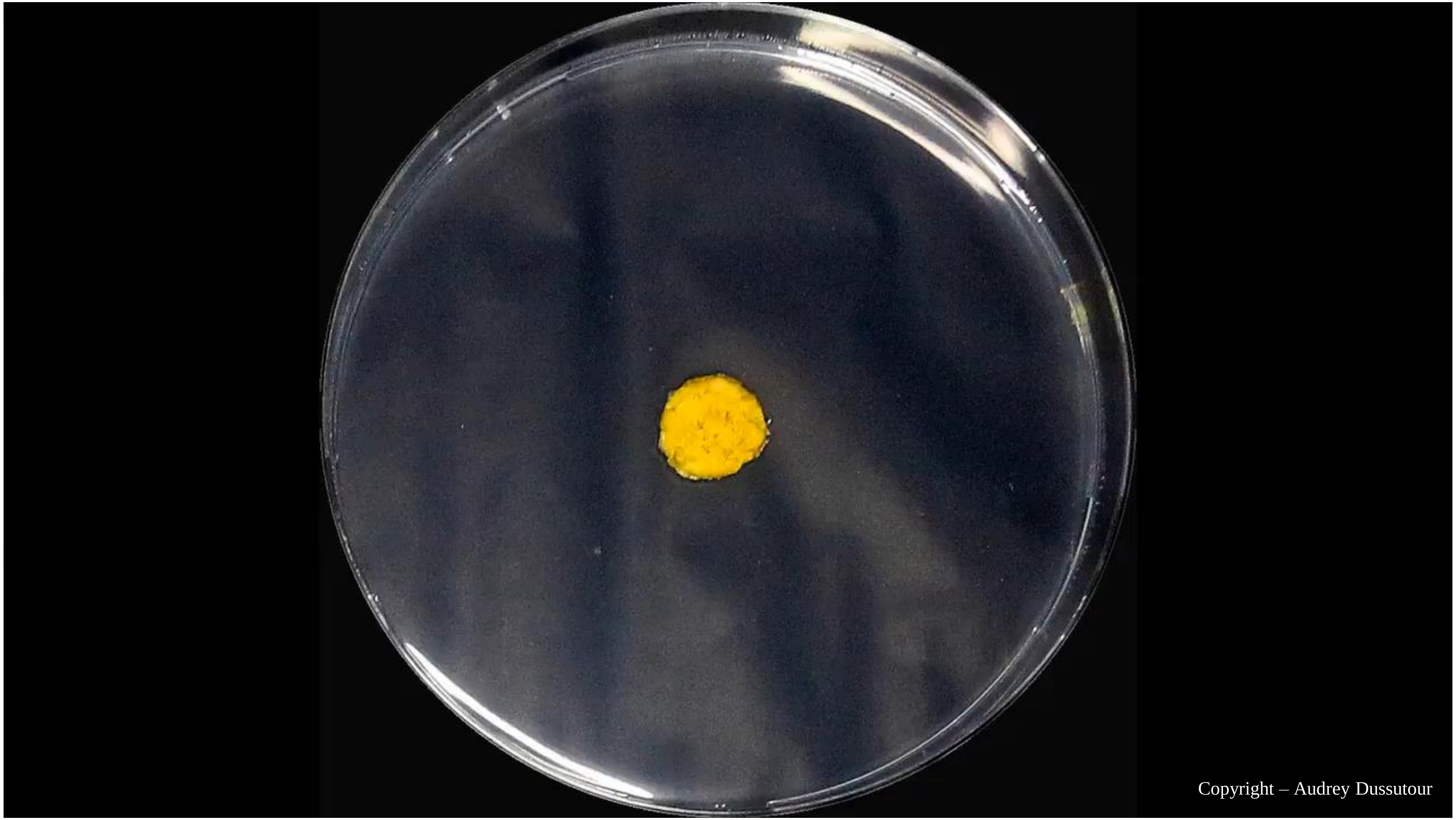


Experiment



Model

Ma et al. (2013)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Many Thanks to:

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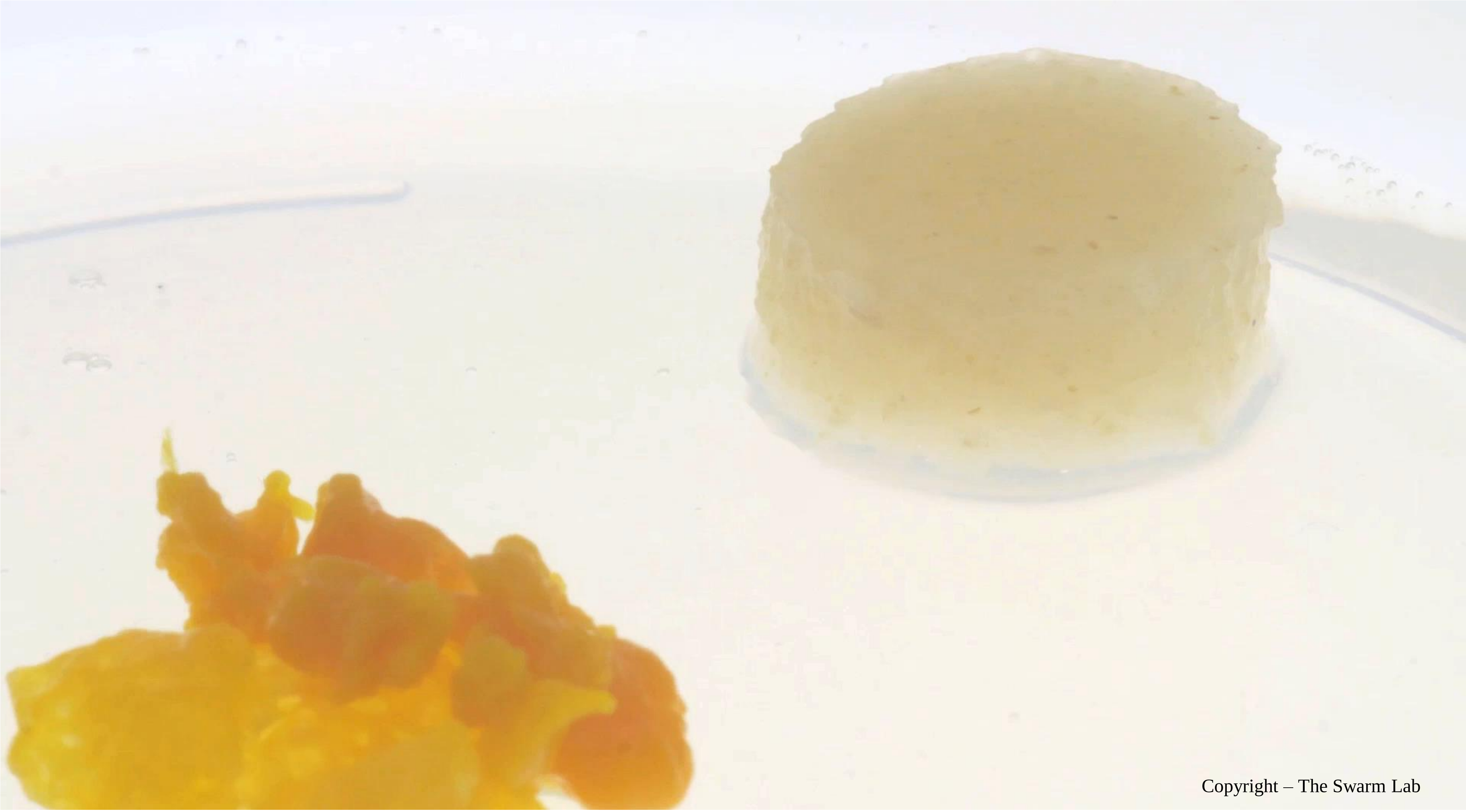
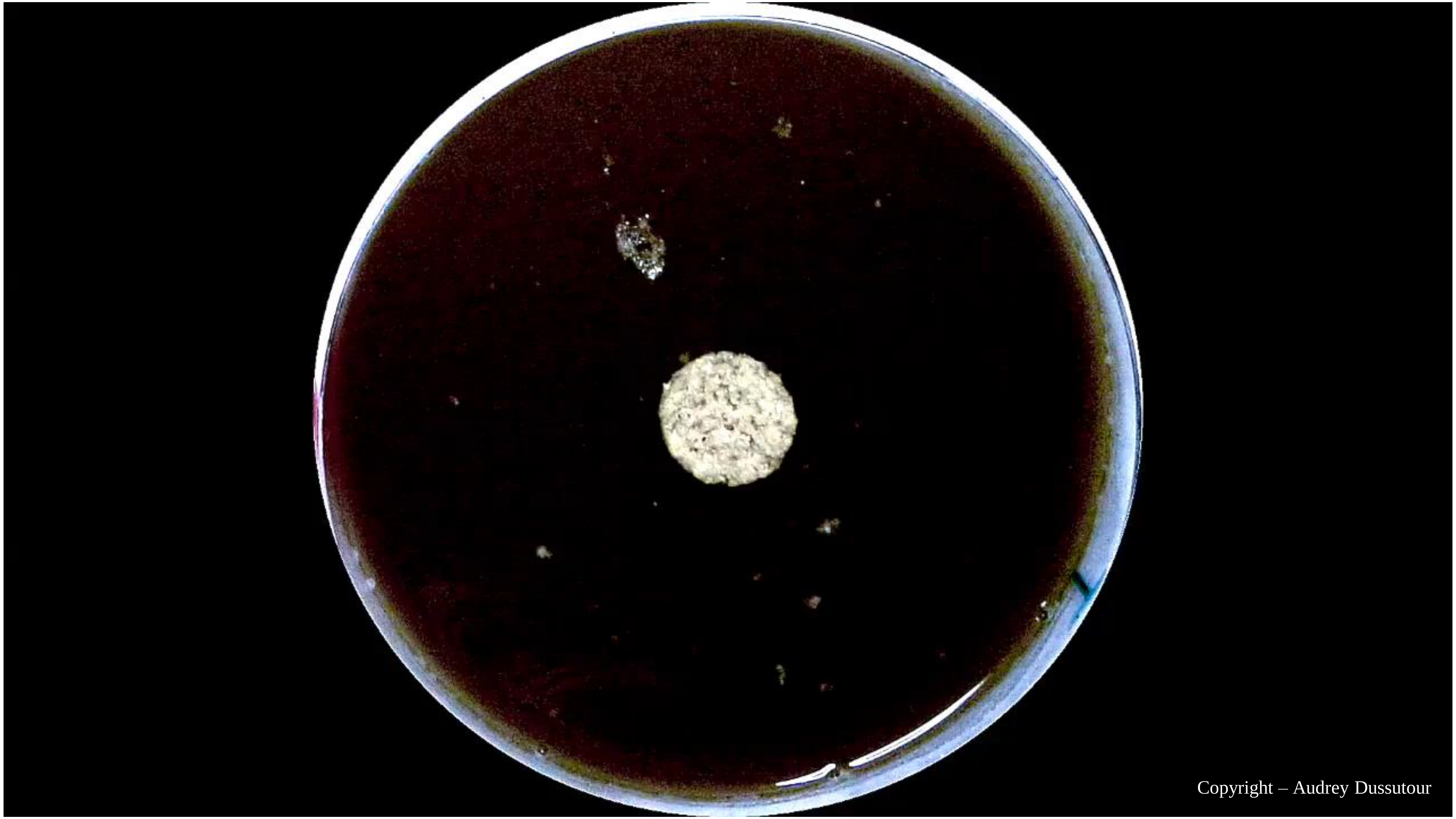
Purva Shah (Undergraduate research assistant)
Amisha Naik (Undergraduate research assistant)

Collaborators:
Gabriele Valentini (Post-doc) – **at Beyond Center, Arizona State University, AZ**

Thank you!

Questions and suggestions!!

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