SHAPE-SHIFTING SOFT MATTER ACROSS THE TREE OF LIFE

Anđela Šarić

Computational Soft & Living Matter

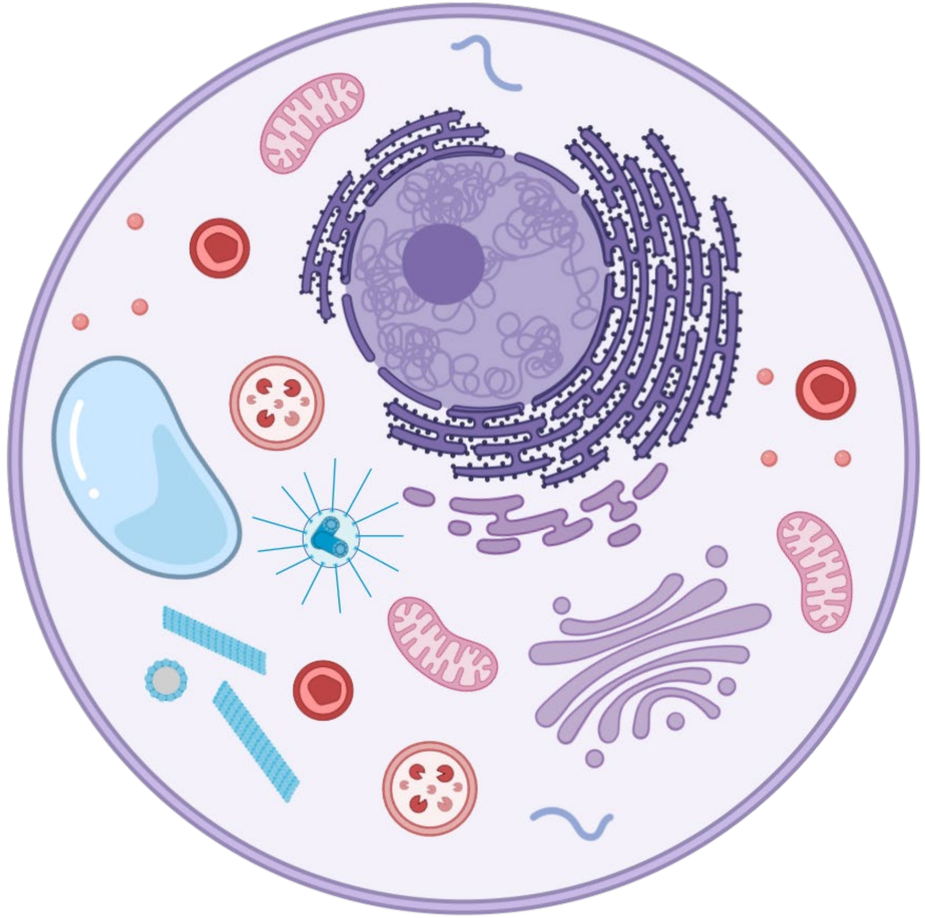
Institute of Science and Technology Austria


5 µm
LIFE

THE CELL

PROKARYOTIC

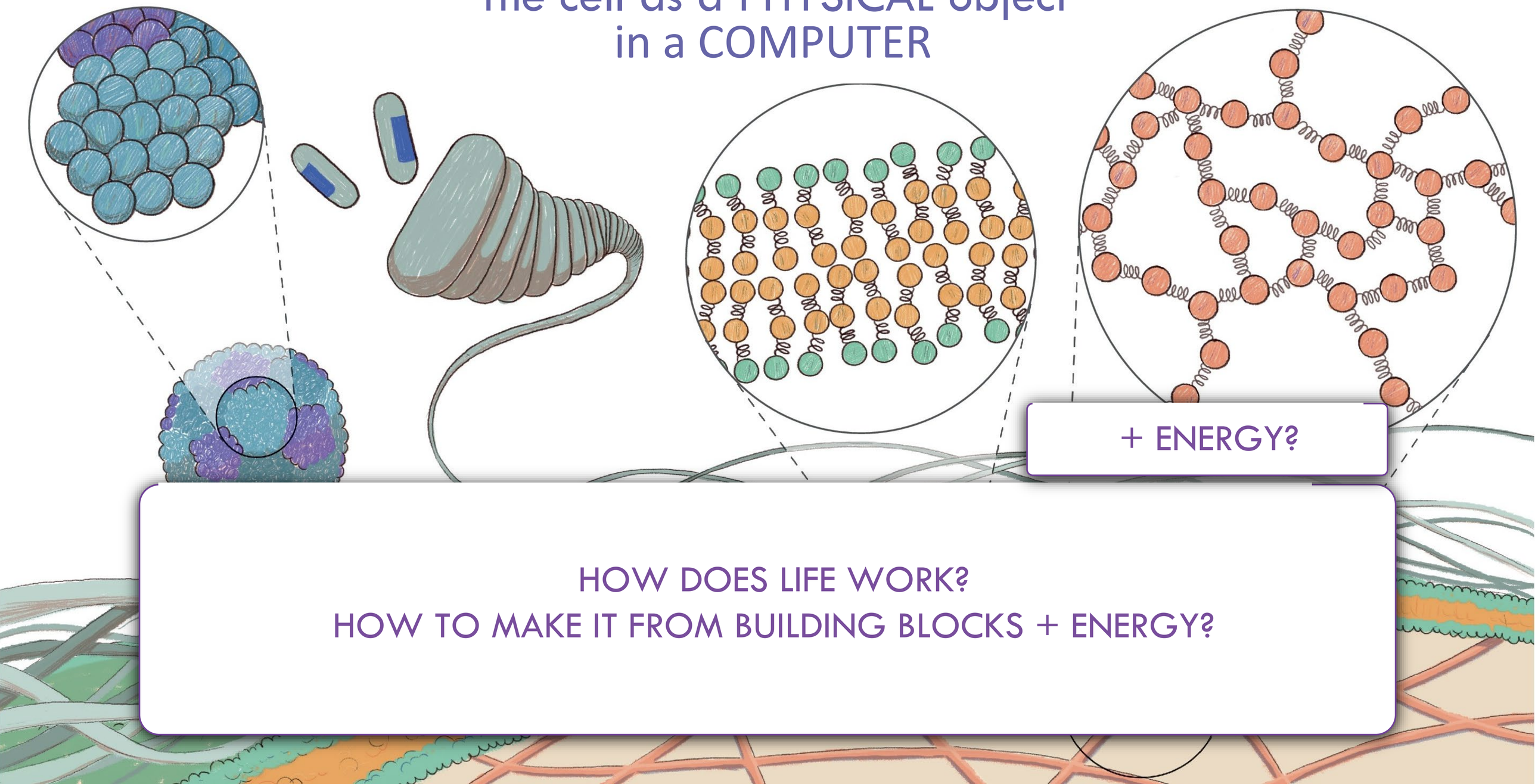
Bacteria & archaea



EUKARYOTIC

Us, plants, animals, fungi

The cell as a PHYSICAL object in a COMPUTER

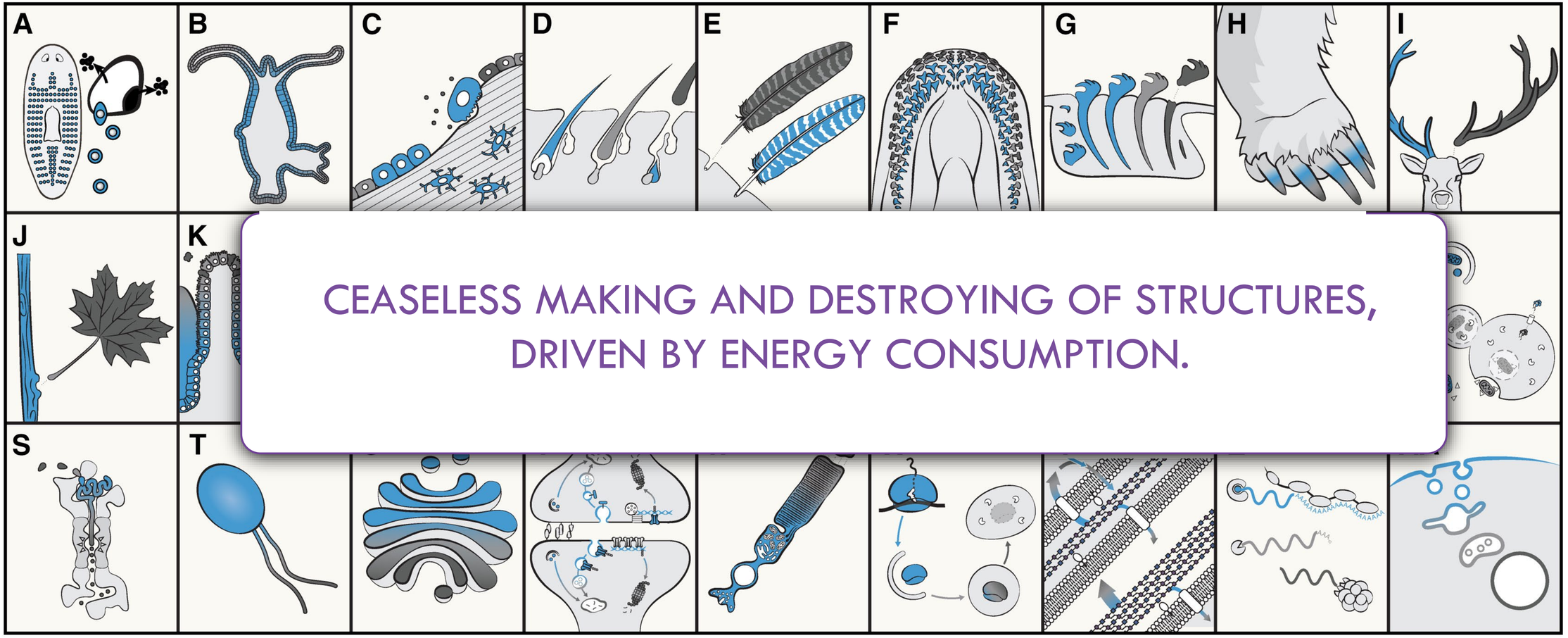


+ ENERGY?

HOW DOES LIFE WORK?

HOW TO MAKE IT FROM BUILDING BLOCKS + ENERGY?

ONLY CHANGE IS CONSTANT
ACTIVE DISASSEMBLY IS NEEDED FOR LIFE

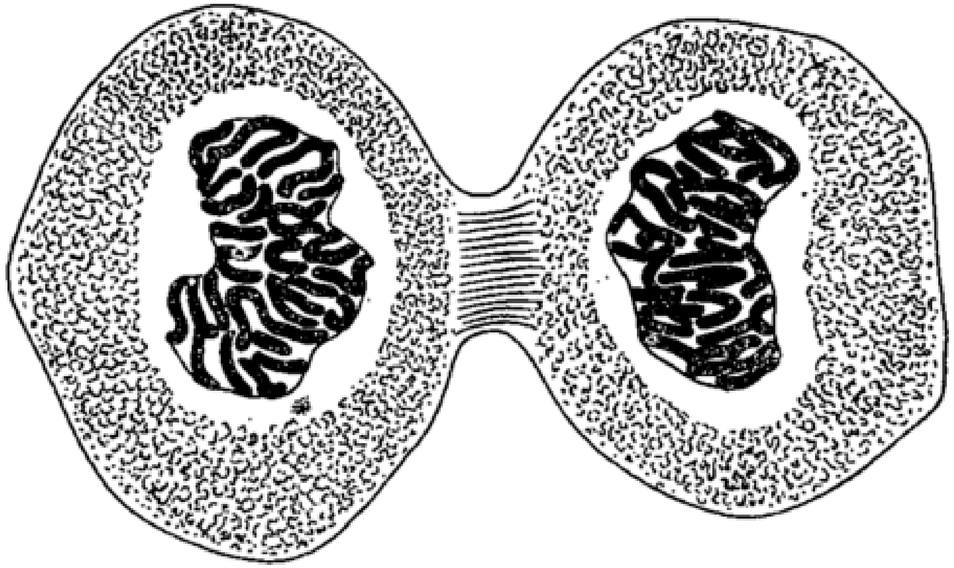


CEASELESS MAKING AND DESTROYING OF STRUCTURES,
DRIVEN BY ENERGY CONSUMPTION.

P. W. Reddien, Cell (2024).

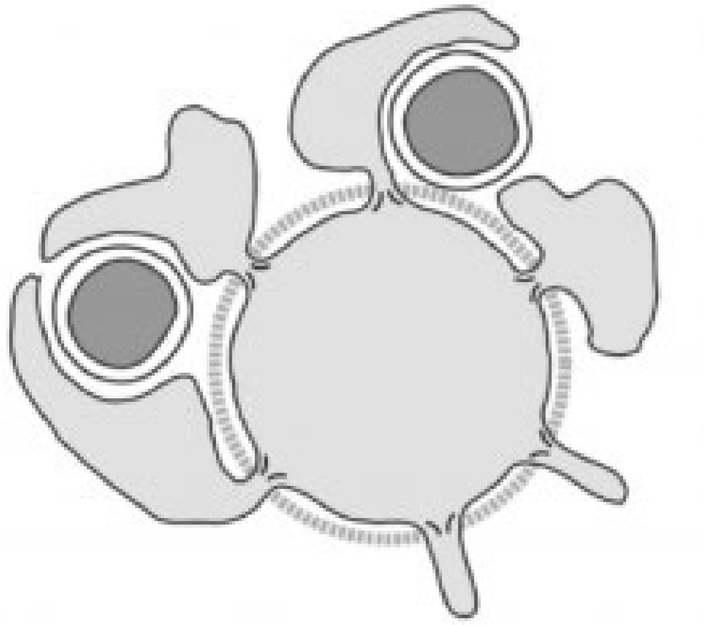
TODAY:
ONE BECOMES TWO & TWO BECOME ONE

CELL DIVISION



Walther Flemming; ~1879

CELL SYMBIOSIS

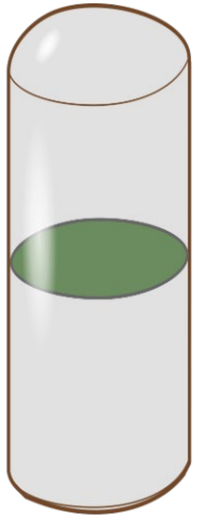


Baum & Baum, 2014

Physical processes of splitting & merging droplets.

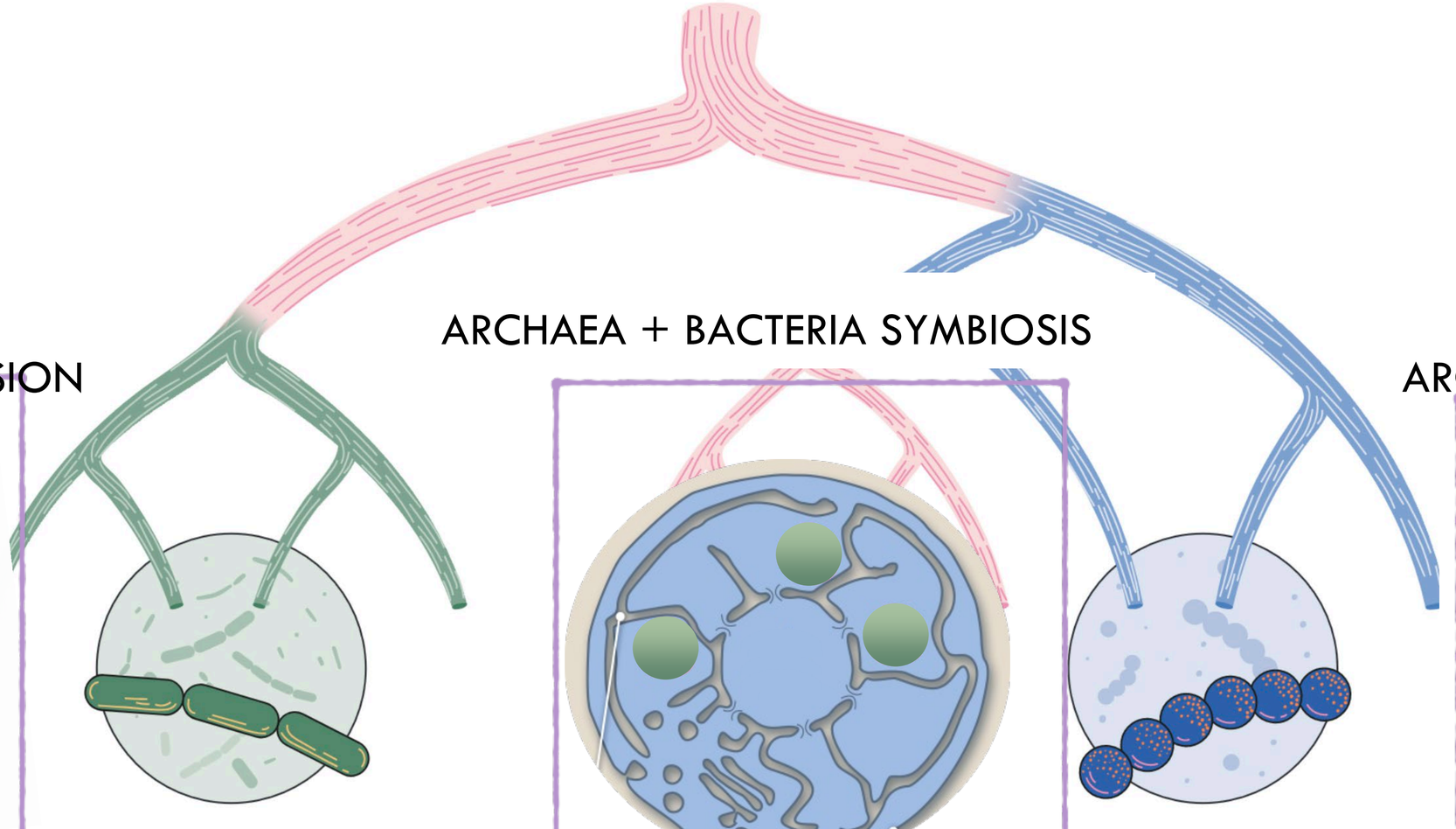
CELL DIVISION & MERGING ACROSS THE TREE OF LIFE

BACTERIAL DIVISION



ARCHAEA + BACTERIA SYMBIOSIS

ARCHAEAL DIVISION



BACTERIA

EUKARYOTES

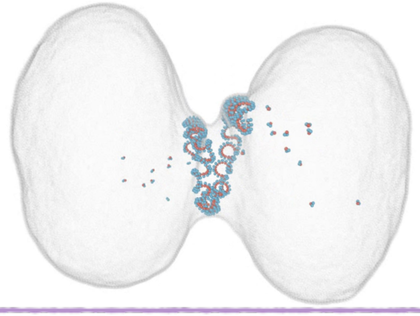
ARCHAEA

TODAY

CELL SHAPE-SHIFTING ACROSS EVOLUTION

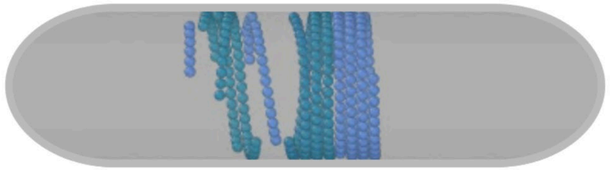
- DIVISION OF ARCHAEA

(CHEMICALLY ACTIVE FILAMENTS)



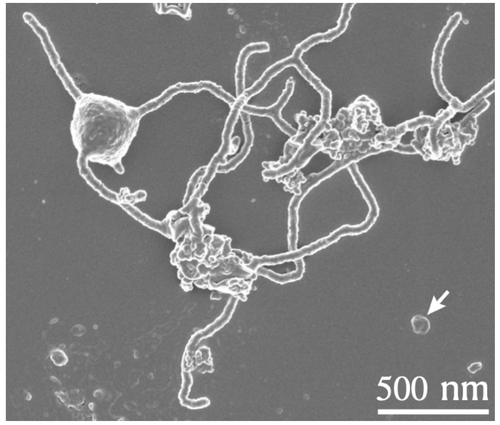
- DIVISION OF BACTERIA

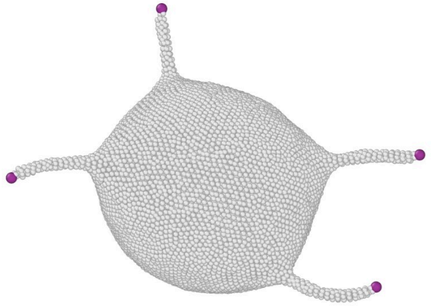
(CHEMICALLY ACTIVE FILAMENTS)



- SYMBIOSIS OF ARCHAEA AND BACTERIA

(CHEMICALLY ACTIVE MEMBRANES)

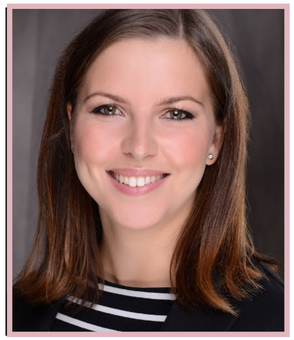




HEROES

THEORY

Anne Hafner



Lena Harker-Kirschneck

Xiuyun Sharon Jiang

Chris Vanhille Campos

Juraj Majek

Ferdinand Horthath

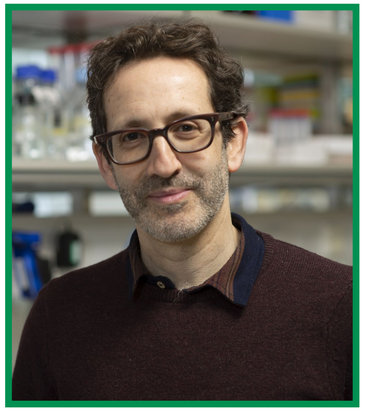
Maitane Muñoz Basagoiti

ARCHAEA

BACTERIA

SYMBIOSIS

EXPERIMENT



Buzz Baum
MRC LMB Cambridge

Seamus Holden
Warwick University

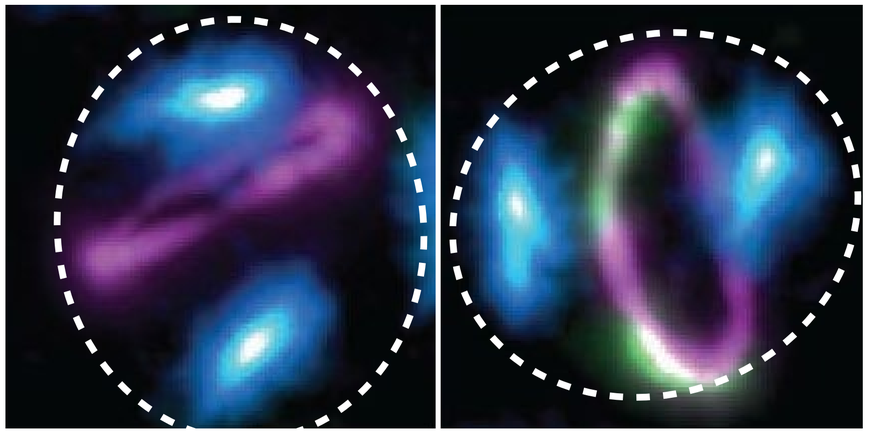
Martin Loose
ISTA

Kerstin Göpfrich
Heidelberg University

CELL DIVISION IN ARCHAEA

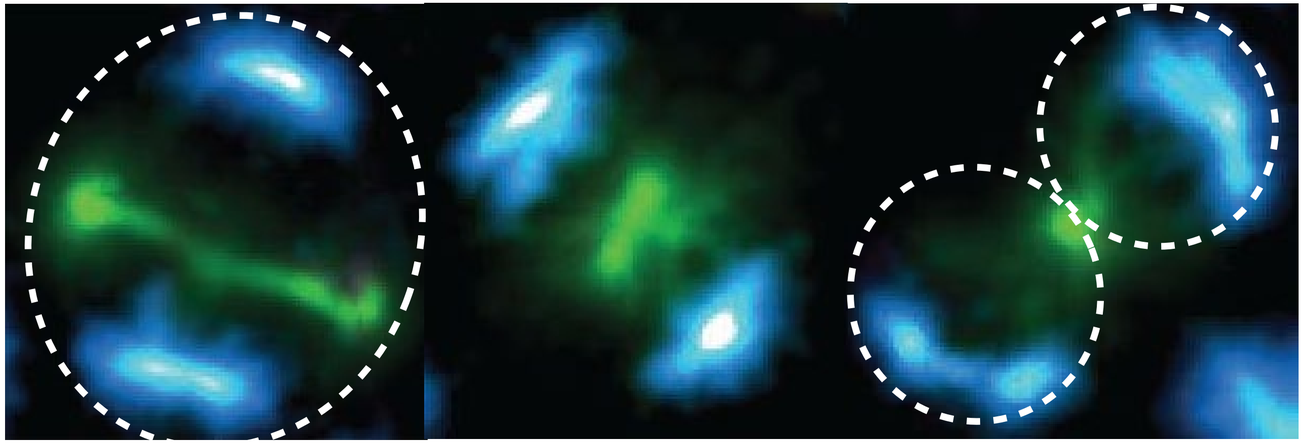
by chemically active filaments (ESCRT-III)

DNA



ATP consumption

1st filament disassembles



2nd filament divides the cell

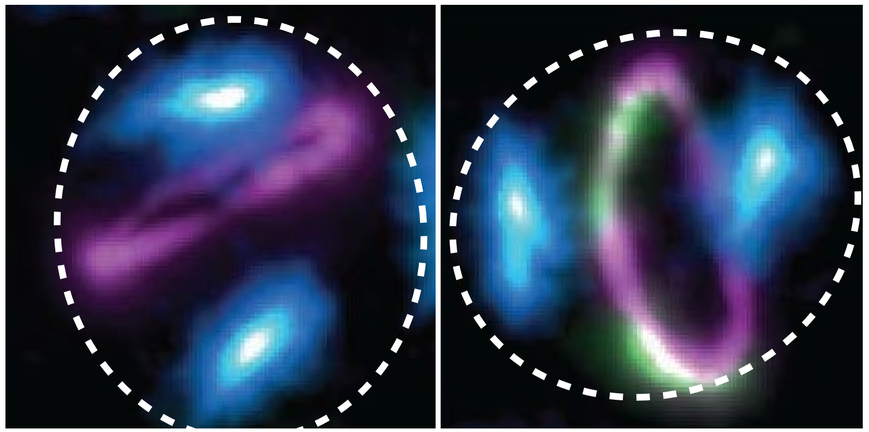
Sulfolobus acidocaldarius

by Buzz Baum, MRC LMB Cambridge

CELL DIVISION IN ARCHAEA

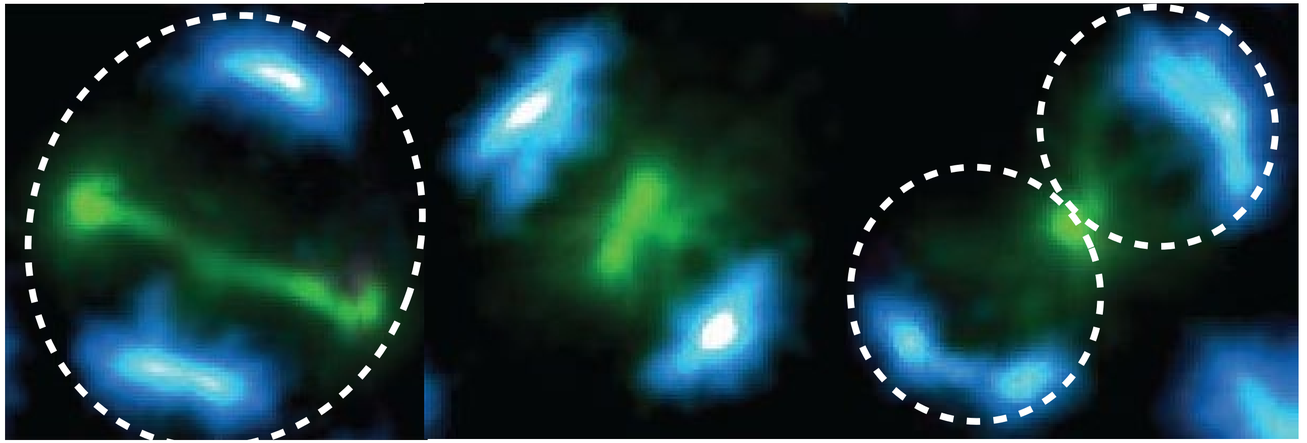
by chemically active filaments (ESCRT-III)

DNA

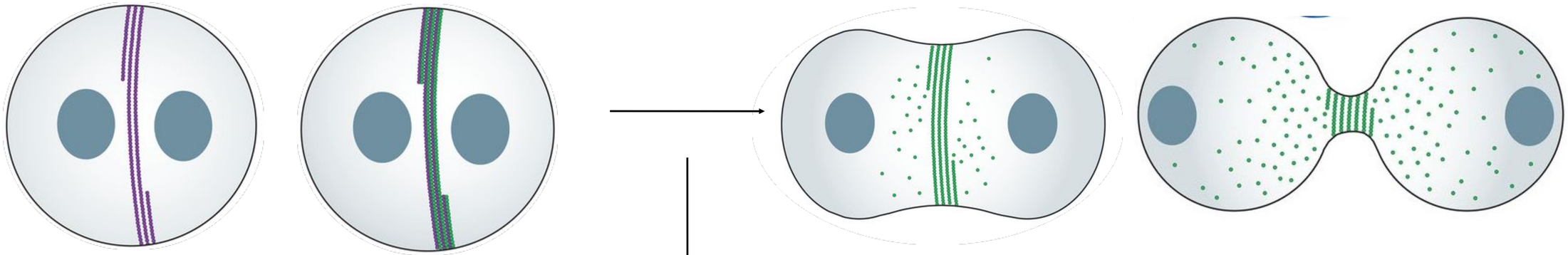


ATP

1st filament disassembles



2nd filament divides the cell



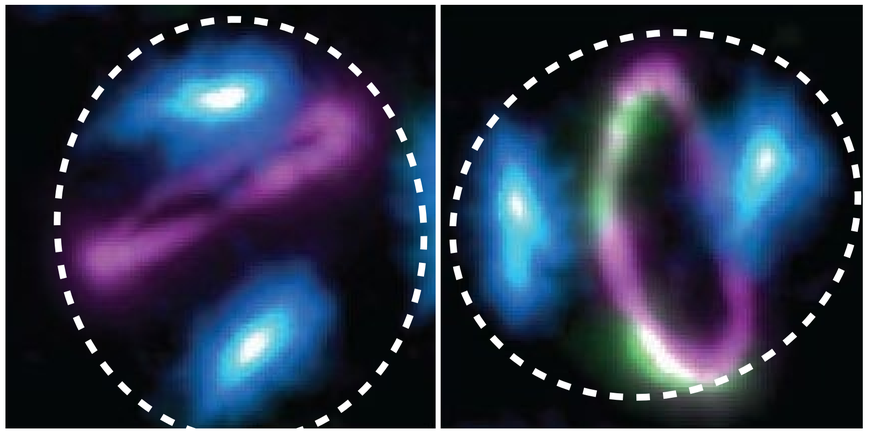
1st filament disassembles

with Buzz Baum

CELL DIVISION IN ARCHAEA

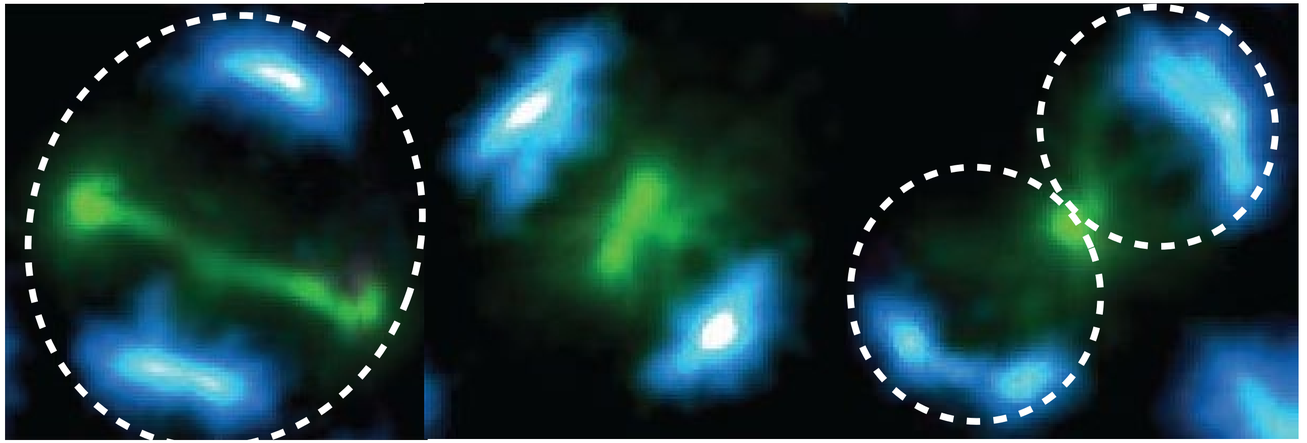
by chemically active filaments (ESCRT-III)

DNA

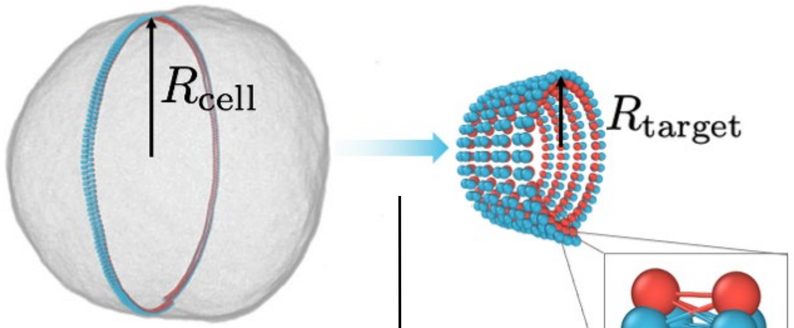


ATP

1st filament disassembles

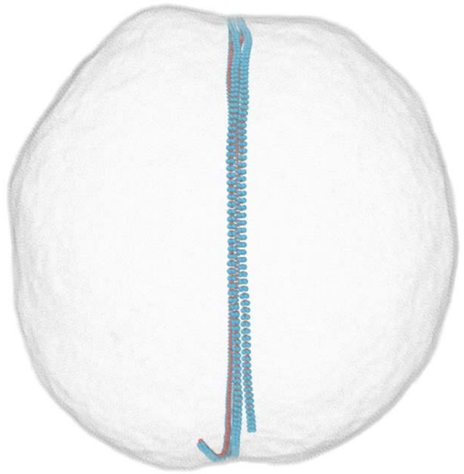


2nd filament divides the cell

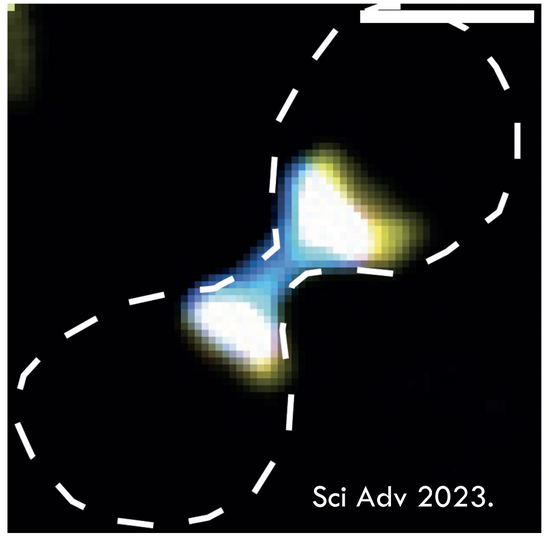


1st filament disassembles

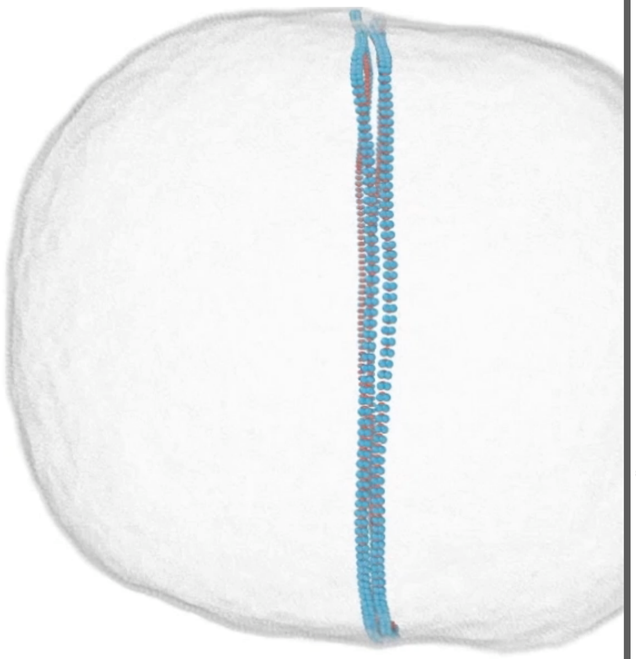
MODELLING DIVISION IN ARCHAEA



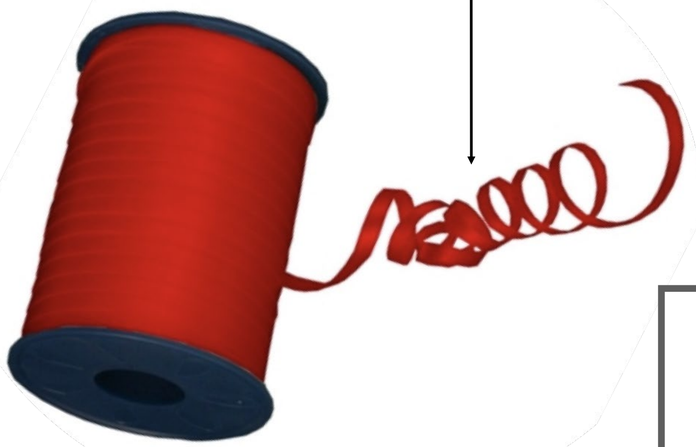
WITHOUT FILAMENT DISASSEMBLY DIVISION FAILS

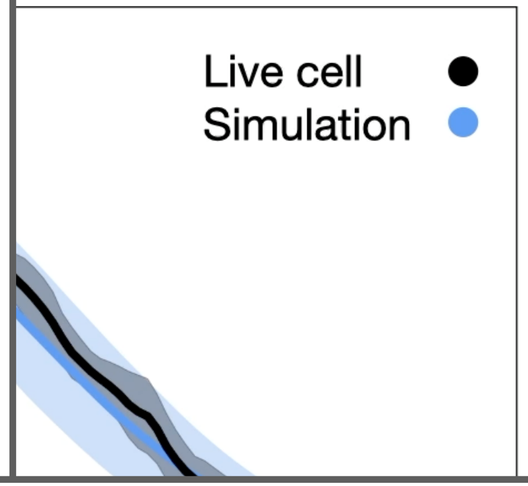


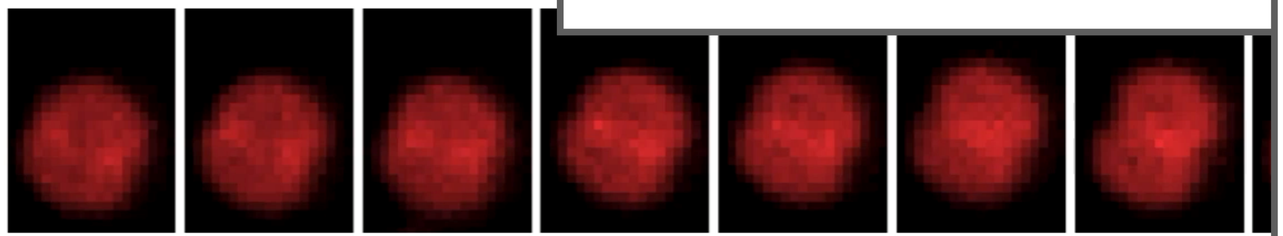
CELL DIVISION IN ARCHAEA



THE SAME PHYSICS AS:

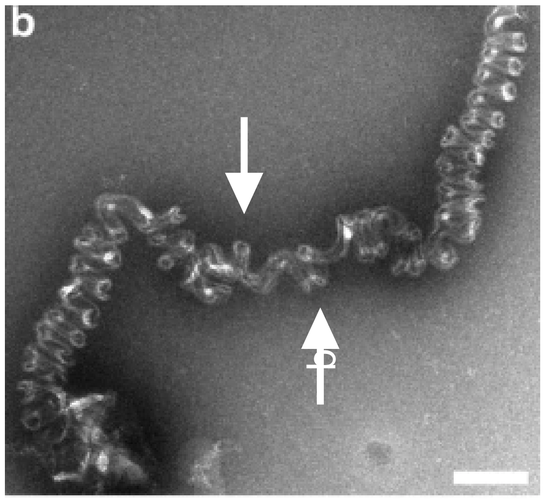






S. acidocaldarius

Human ESCRT-III



Risa, …, AŠ, Robinson, Baum, Science (2020).

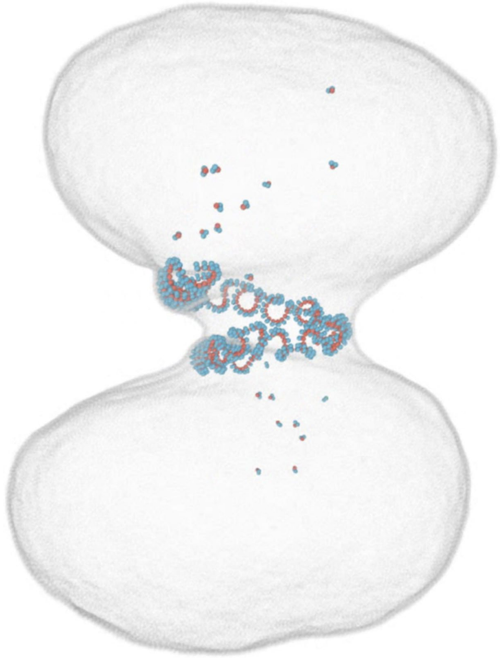
Harker-Kirschneck,…., AŠ, PNAS (2022).

Pfitzner,..., AŠ, Roux, Cell (2020).

Hurtig,..., AŠ, Vlijm, Baum, Sci Adv (2023).

Meadov

PHYSICAL PRINCIPLES OF ARCHAEAL DIVISION



- Active disassembly changes filament composition & geometry, which in turn reshapes the membrane.
- New type of the force production at the nanoscale.
- Minimal cell division system.
- Minimal beads & springs simulation to capture the cell.

Risa et al., Science (2020).
Pfitzner et al., Cell (2020).
Harker-Kirschneck et al., BMC Biology (2019).

Hurtig et al., Sci Adv (2023).
Harker-Kirschneck et al., PNAS (2022).

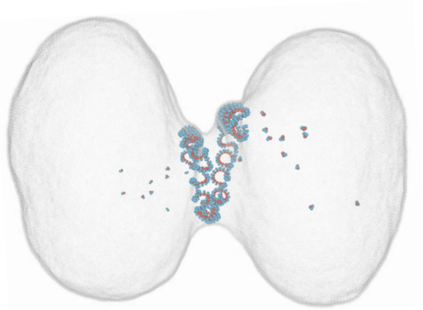
Meadowcroft et al., Phys Rev Lett (2022).
Jiang et al., PLOS Comp Biol (2022).

TODAY

CELL SHAPE-SHIFTING ACROSS EVOLUTION

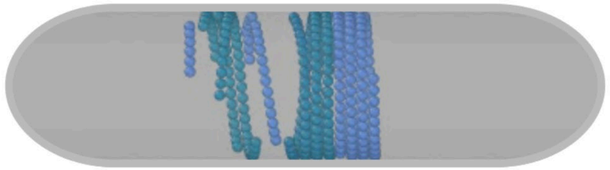
- DIVISION OF ARCHAEA

  (CHEMICALLY ACTIVE FILAMENTS)



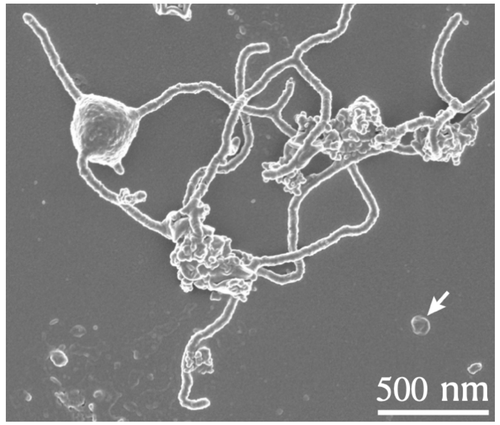
- DIVISION OF BACTERIA

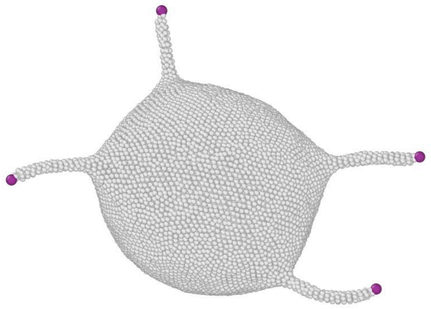
  (CHEMICALLY ACTIVE FILAMENTS)



- SYMBIOSIS OF ARCHAEA AND BACTERIA

  (CHEMICALLY ACTIVE MEMBRANES)





BACTERIAL DIVISION

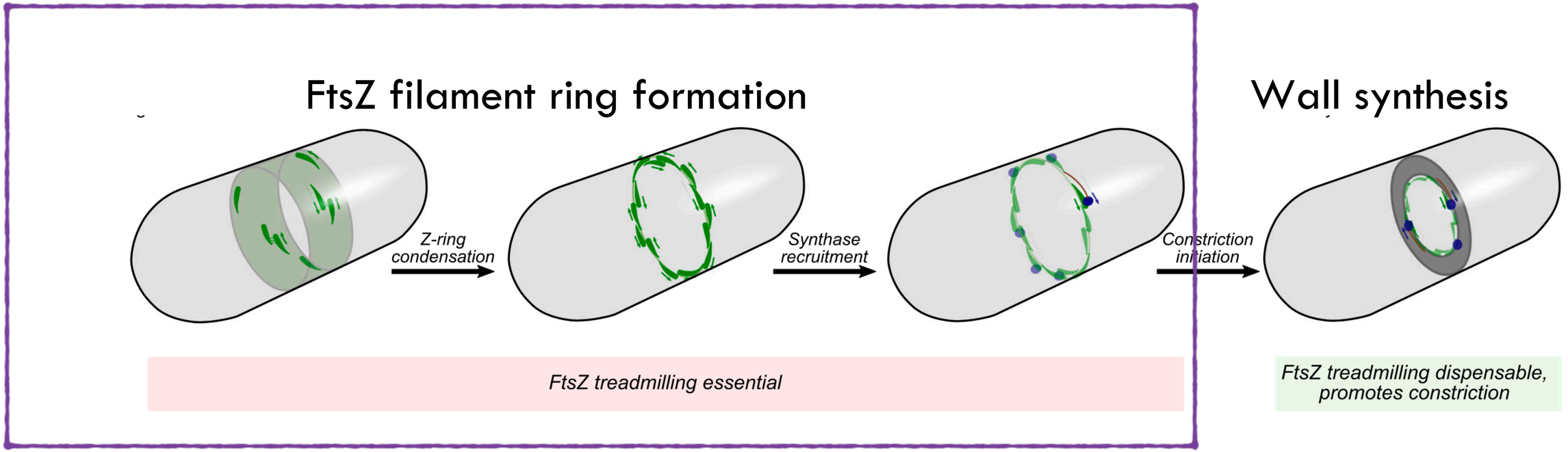
Dynamic FtsZ ring formation (GTP as a fuel)

Whitley et al., Nat Comm, 2021

Séamus Holden's group

BACTERIAL DIVISION RING

Chemically active FtsZ filaments + synthesis of the cell wall



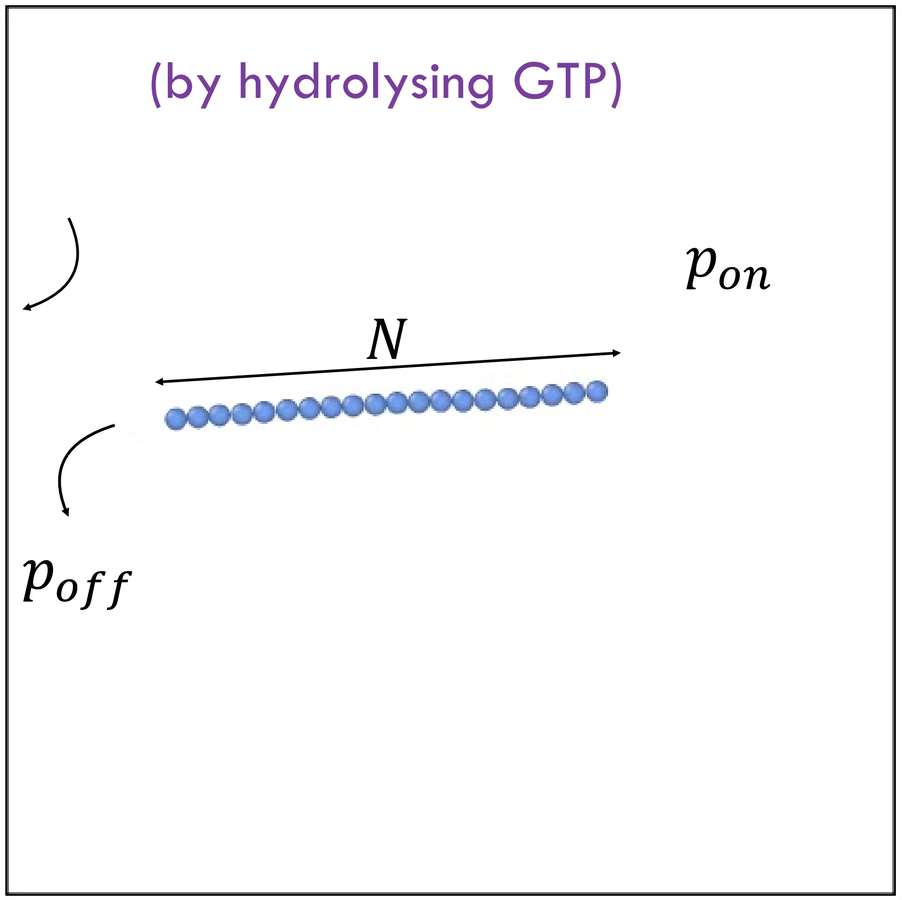
Whitley et al., Nat Comm, 2021

Why do filaments need to turnover to assemble?
WHY ALL THIS ENERGY?

with Séamus Holden & Martin Loose

MODELLING BACTERIAL DIVISION FtsZ RING FORMATION

SINGLE FILAMENT TREADMILLING



Three parameters for filament dynamics:

$r_{\mathrm{nuc}} \rightarrow$ nucleation rate

$r_{on} \rightarrow$ polymerisation rate

$r_{off}(\tau_{hyd}, t_{det}) \rightarrow$ depolymerisation rate, depends on GTP hydrolysis rate

$r_{off}(\tau_{hyd}, t_{det})$ r_{on}

Biologically relevant scales:

$N \sim 30 - 40$ monomers $\sim 120 - 200$ nm

$v \sim 25 - 30$ nm/s in vivo

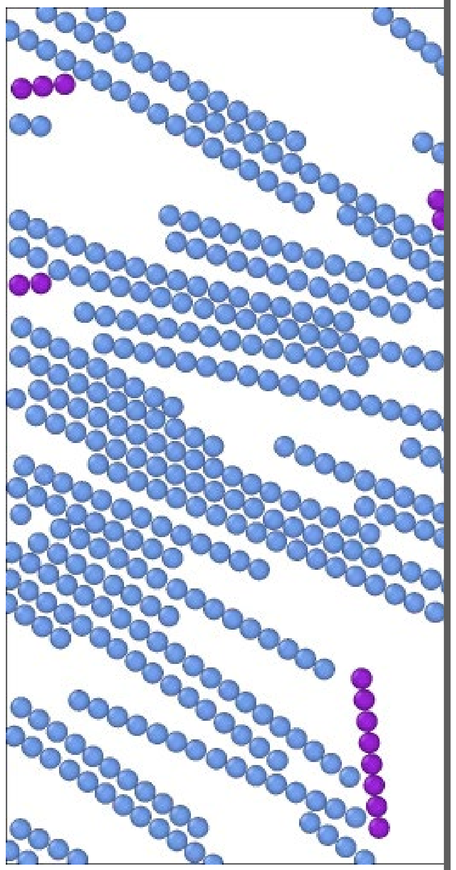
WHY THIS TURNOVER?

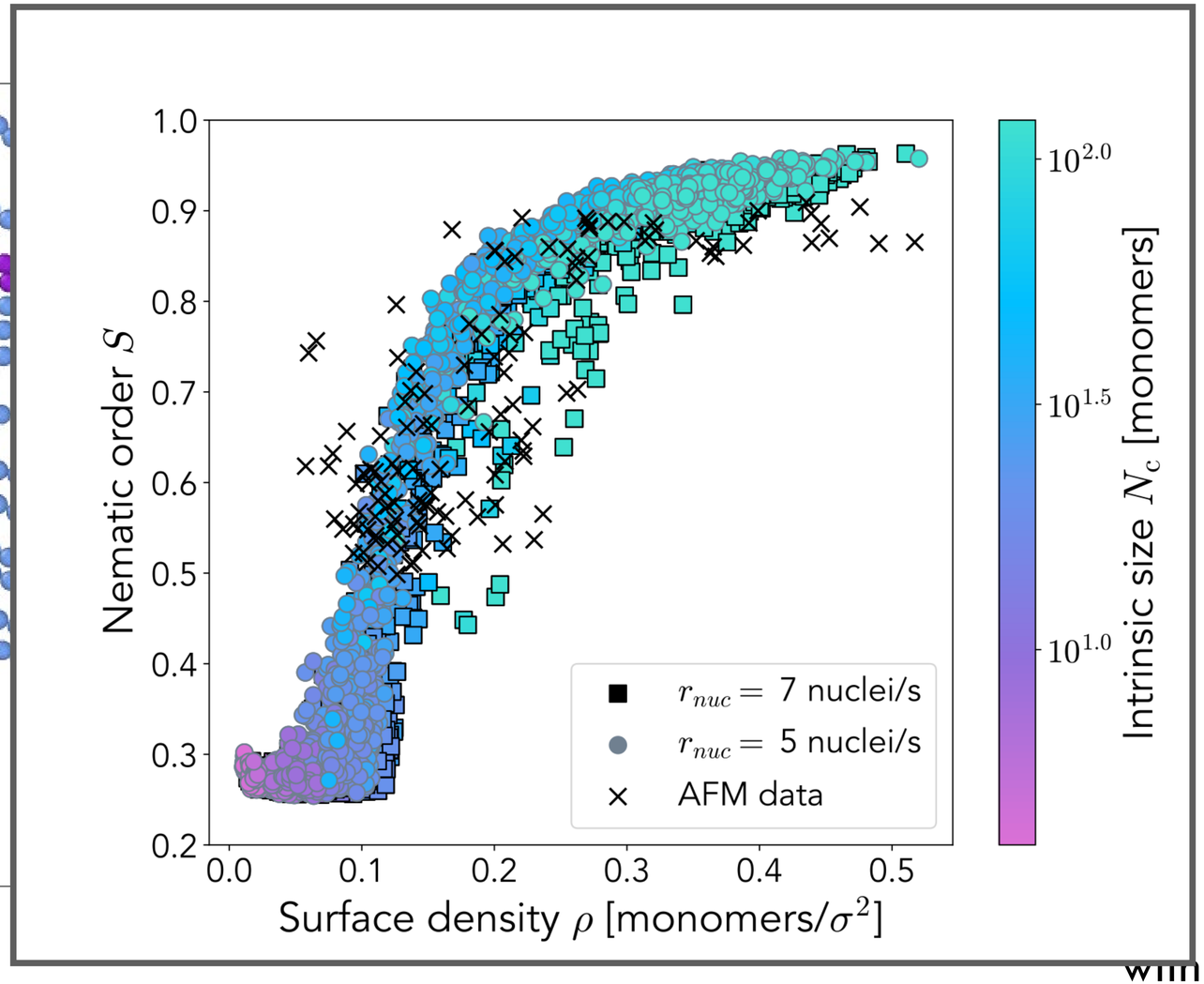
with S. Holden & M. Loose

MODELLING BACTERIAL DIVISION FtsZ RING FORMATION

MANY FILAMENTS ALIGN!

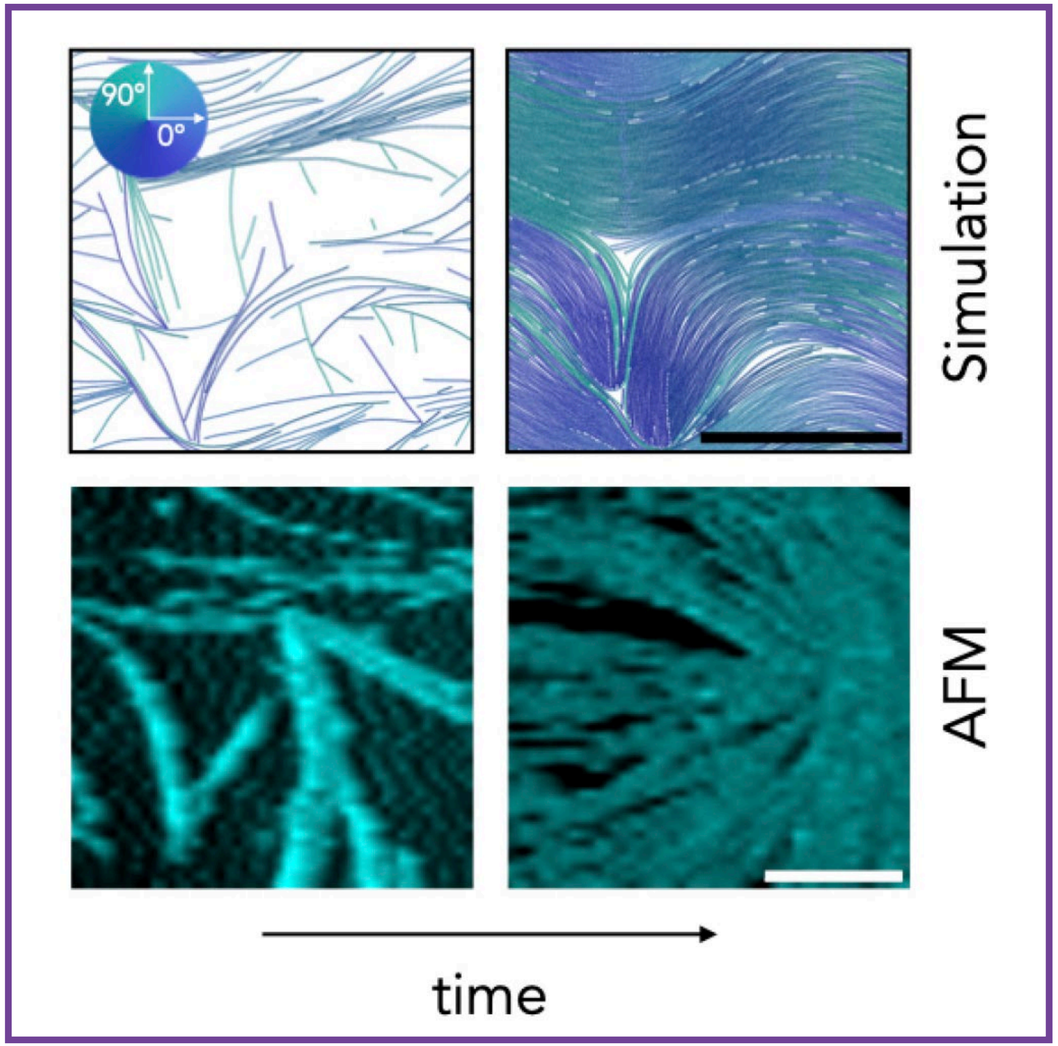
Simulation:

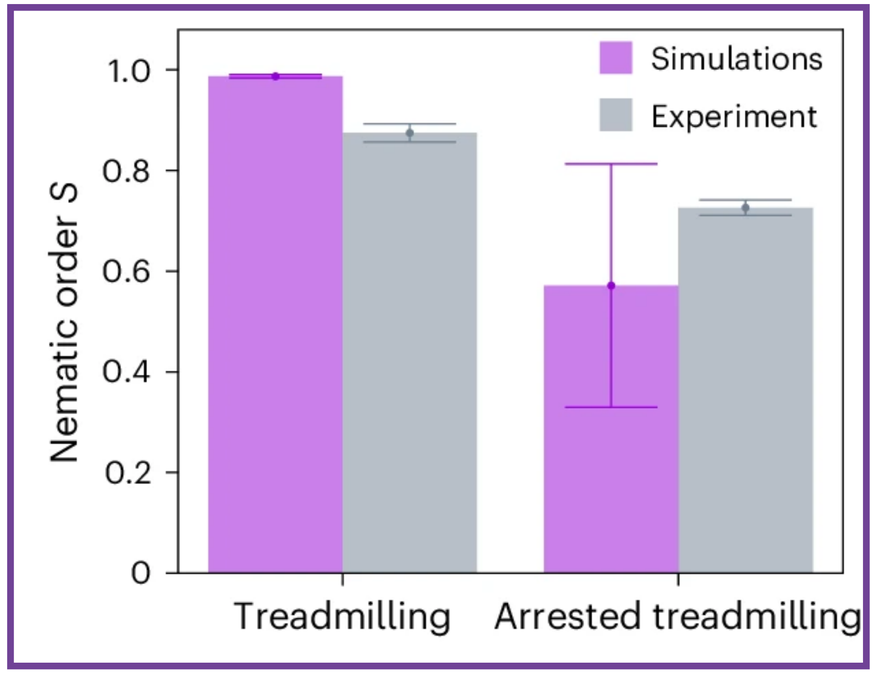




with S. Holden & M. Loose

NON-TREADMILLING FILAMENTS CANNOT ALIGN

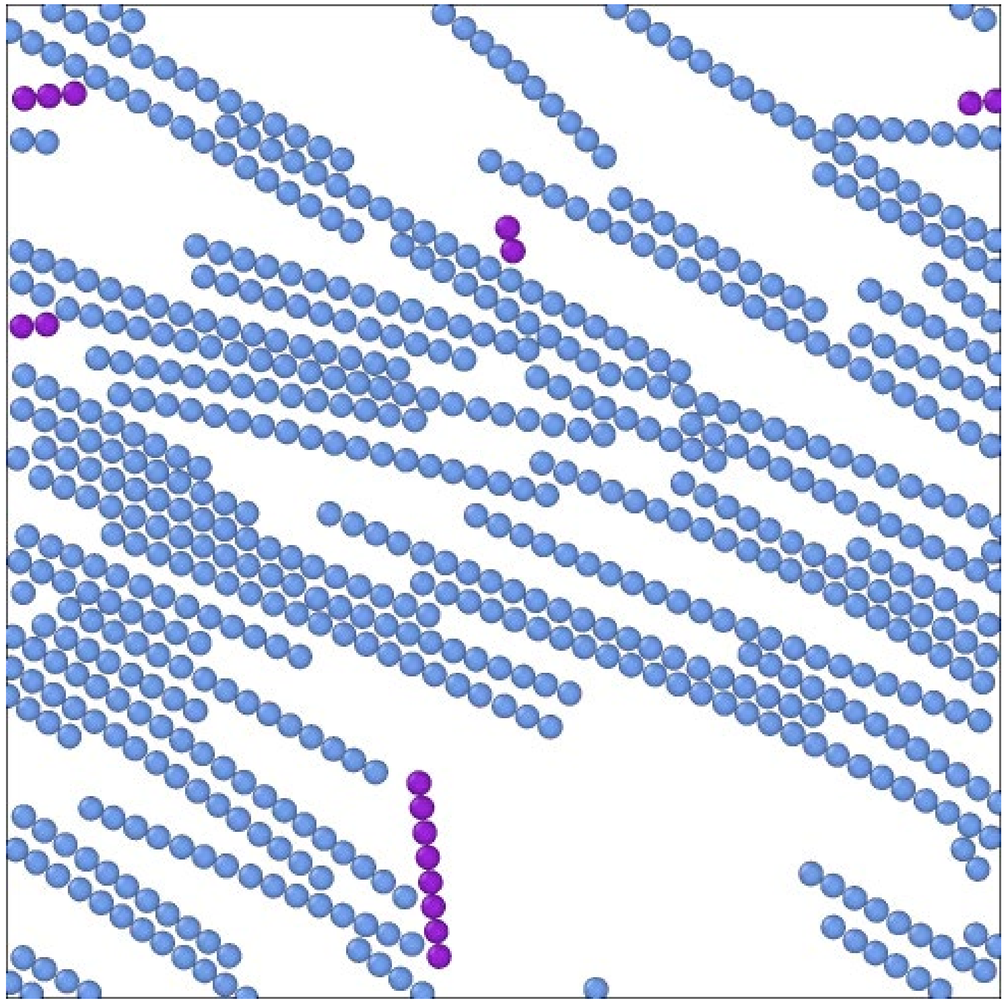




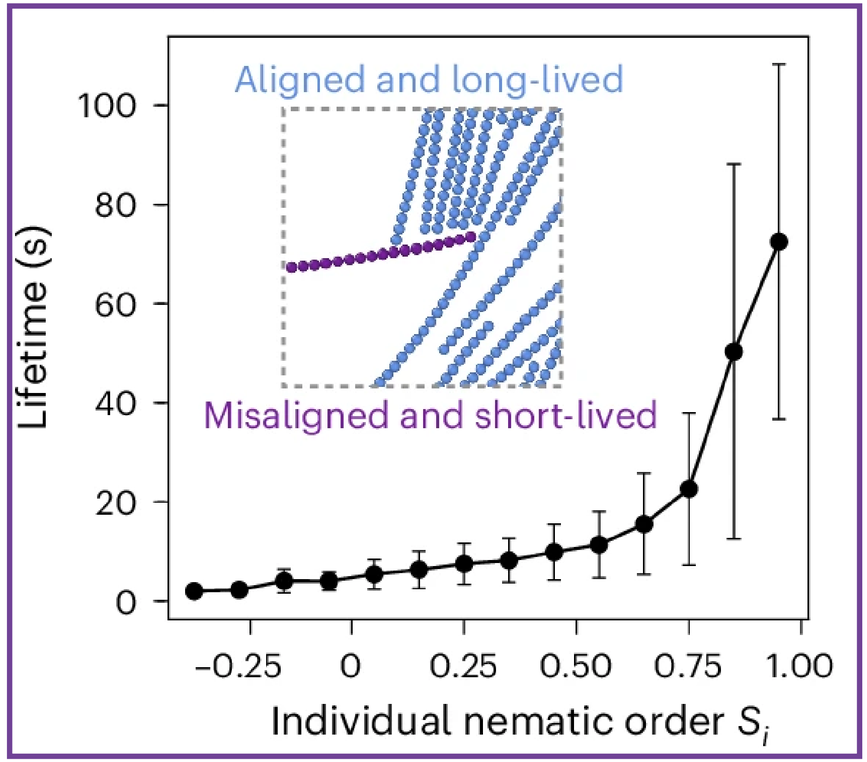
by Martin Loose's group

PHYSICAL MECHANISM

ALIGNMENT BY TURNOVER



MISALIGNED FILAMENTS DIE OUT



Vanhille-Campos, …, AŠ, Nature Physics (2024).

HOW TO MAKE A RING?

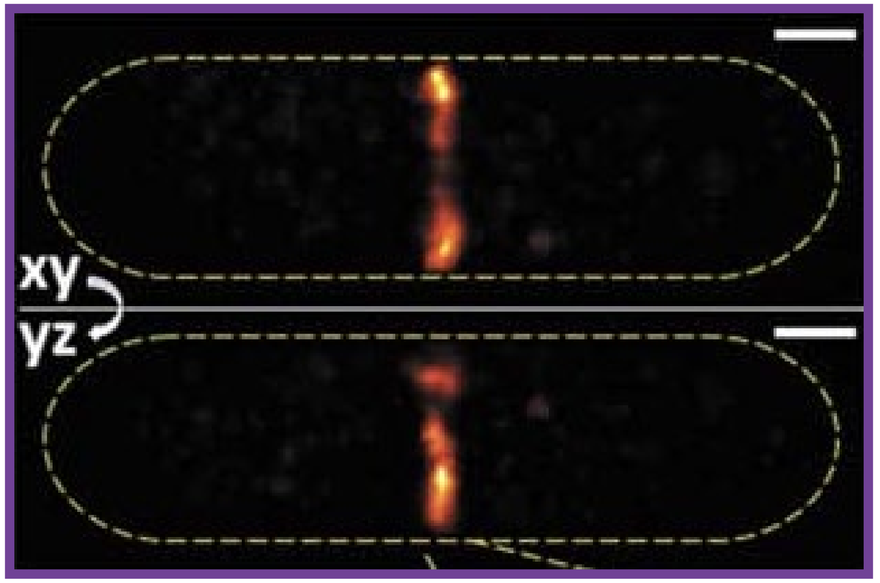
TREADMILLING

+

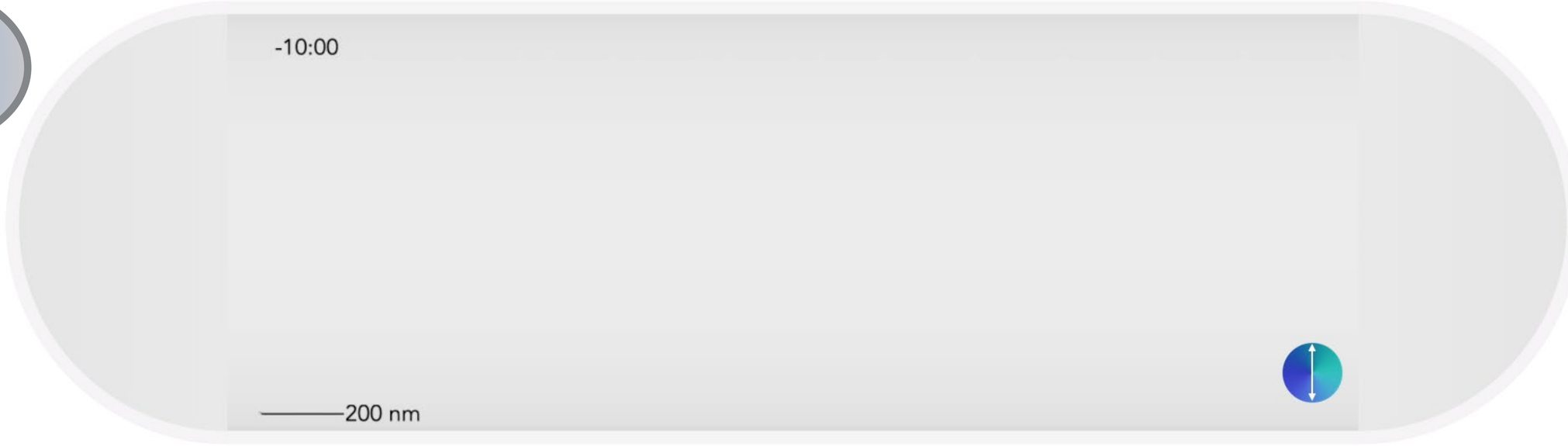
FILAMENT CURVATURE

+

CHEMICAL PATTERN



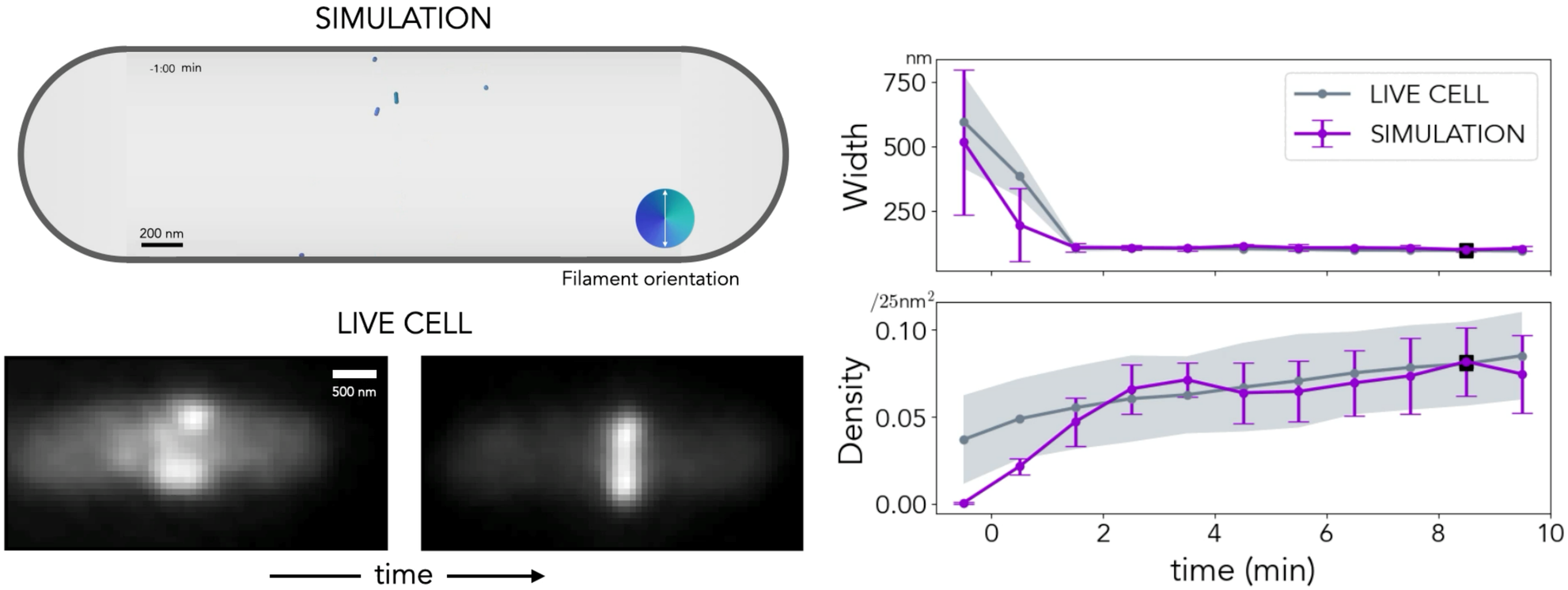
Jie Xiao lab, Johns Hopkins U



COMPARISON
TO
IN VIVO
(*B. Subtilis*)

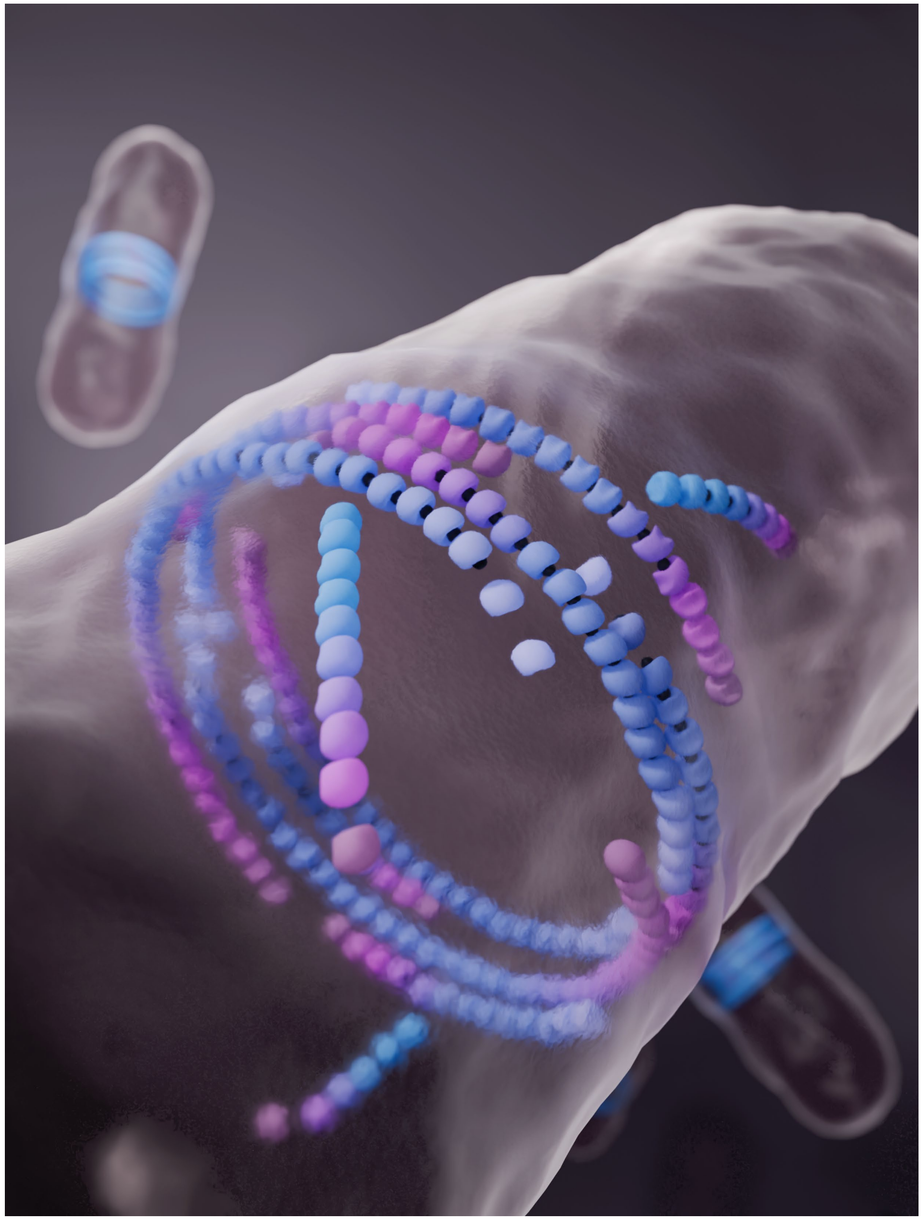
CELL DIVISION IN BACTERIA

FORMATION OF BACTERIAL DIVISION RING: in silico vs in vivo



Vanhille-Campos et al., Nature Physics (2024).

BACTERIAL DIVISION RING FORMATION

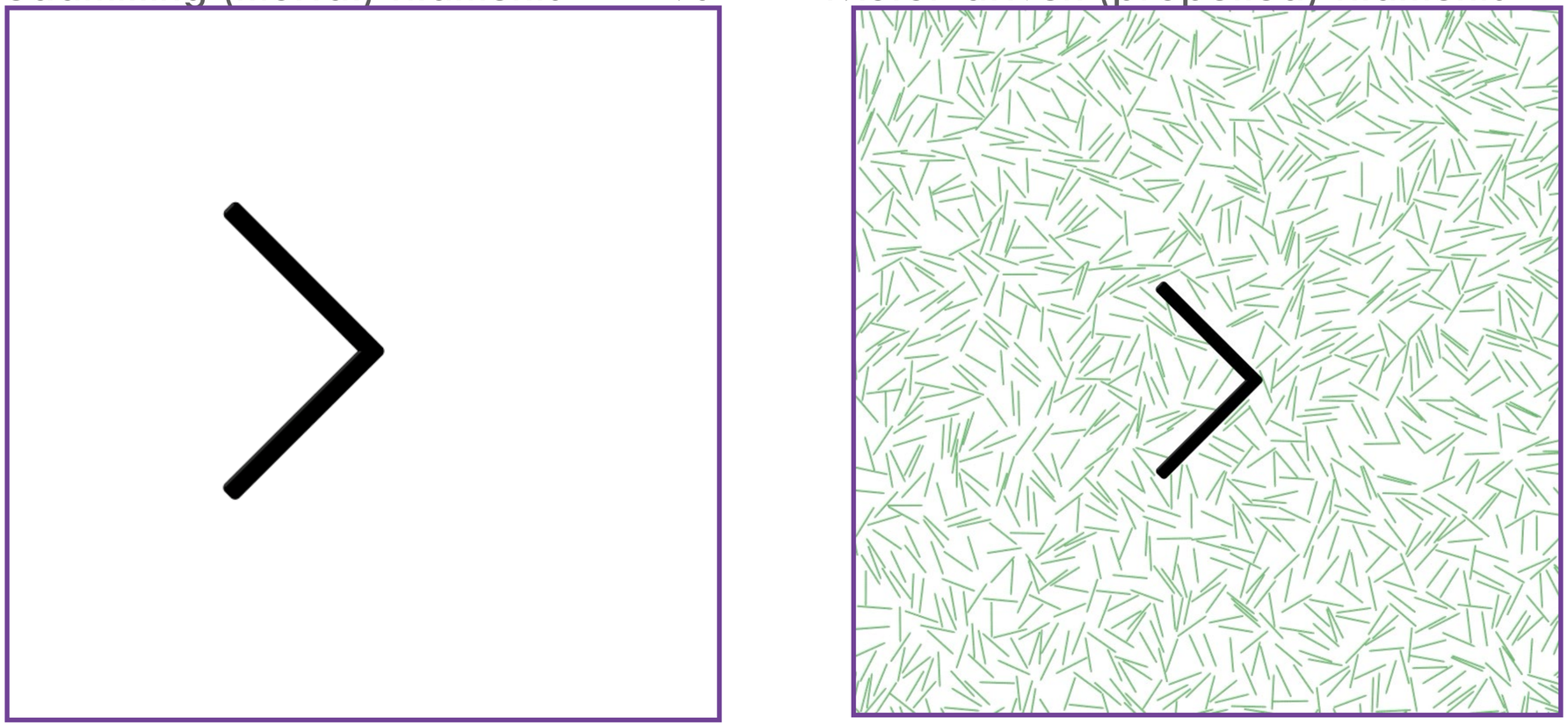


- SURVIVAL OF THE PARALLEL via dynamic growth and shrinkage of filaments
- Order cannot form without disassembly!
- Filament curvature + underlying chemical pattern + treadmilling: ring formation

FUN WITH PHYSICS:
SELF-ORGANISATION OF TREADMILLING FILAMENTS

OBSTACLE COURSE

Treadmilling (mortal) filaments Vs Motor-driven (propelled) filaments



AVOIDS OBSTACLES

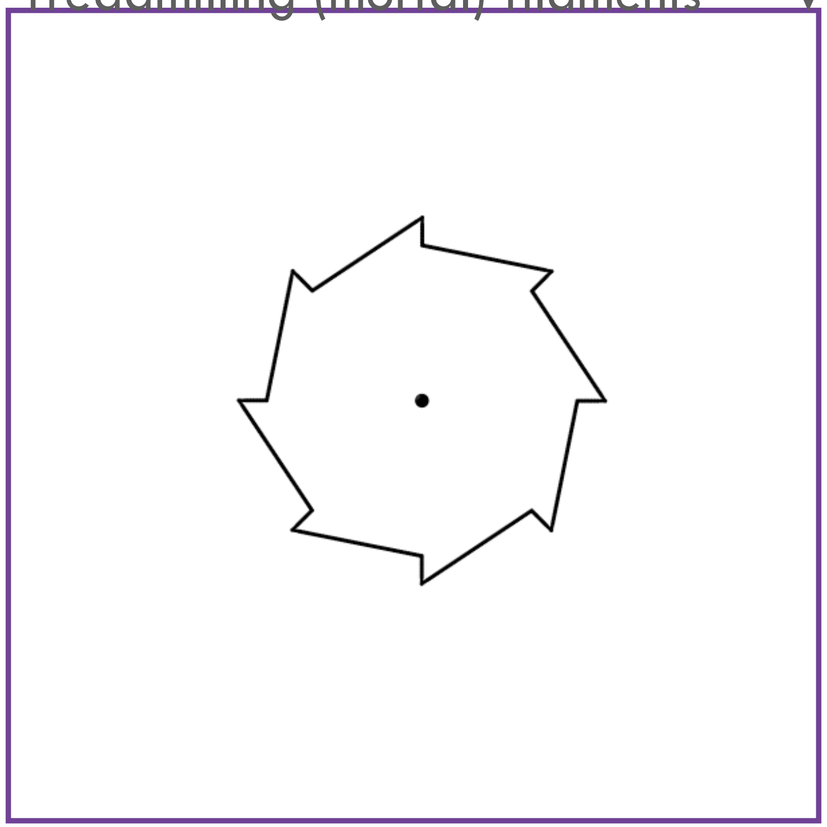
STUCK IN OBSTACLES

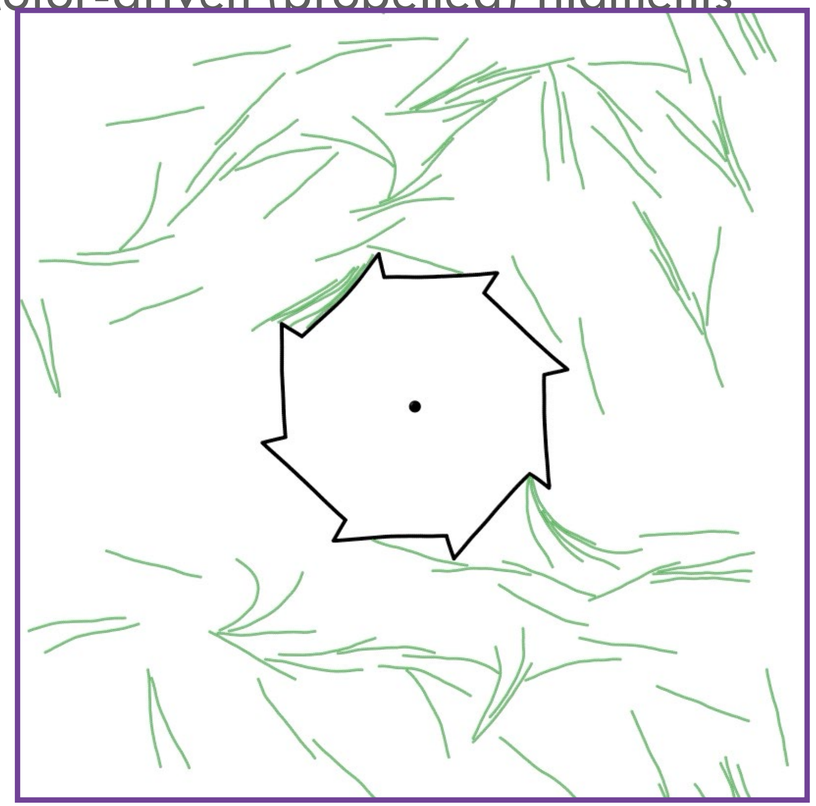
unpublished

FUN WITH PHYSICS:
SELF-ORGANISATION OF TREADMILLING FILAMENTS

SPIN THE WHEEL

Treadmilling (mortal) filaments Vs Motor-driven (propelled) filaments





SPINS CLOCKWISE

SPINS COUNTER-CLOCKWISE

unpublished

SELF-ORGANISATION OF TREADMILLING FILAMENTS: PHYSICAL PROPERTIES

Filaments shorter on the inside of a cluster

Defect healing

(DIFFERENT TYPE OF) ACTIVE MATTER

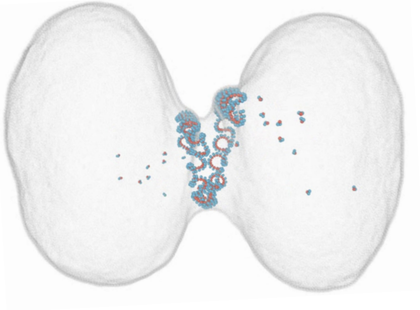
unpublished

TODAY

CELL SHAPE-SHIFTING ACROSS EVOLUTION

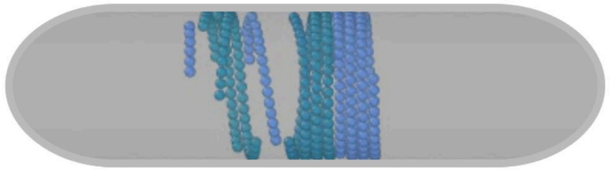
- DIVISION OF ARCHAEA

  (CHEMICALLY ACTIVE FILAMENTS)



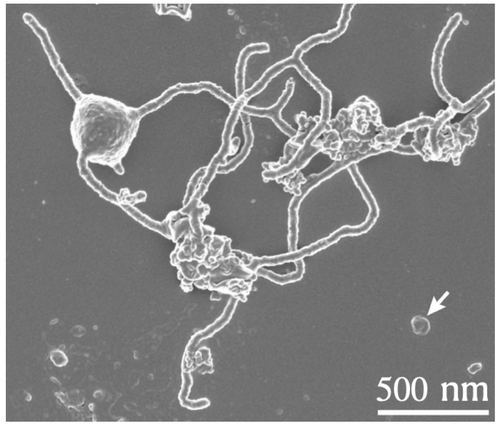
- DIVISION OF BACTERIA

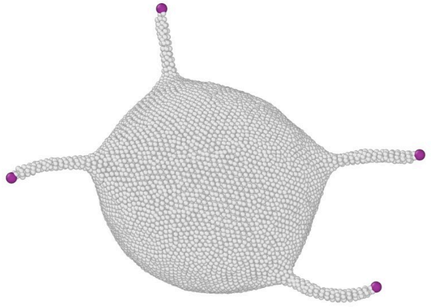
  (CHEMICALLY ACTIVE FILAMENTS)



- SYMBIOSIS OF ARCHAEA AND BACTERIA

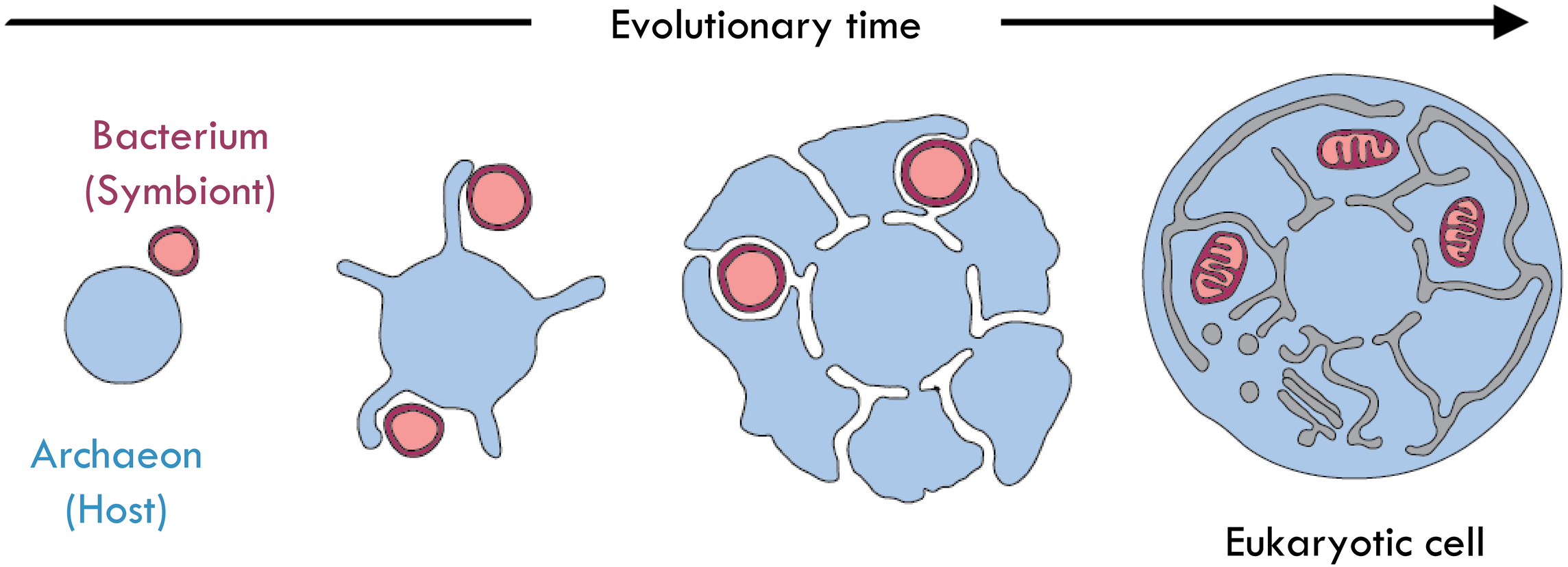
  (CHEMICALLY ACTIVE MEMBRANES)





THE MERGER THAT MADE US

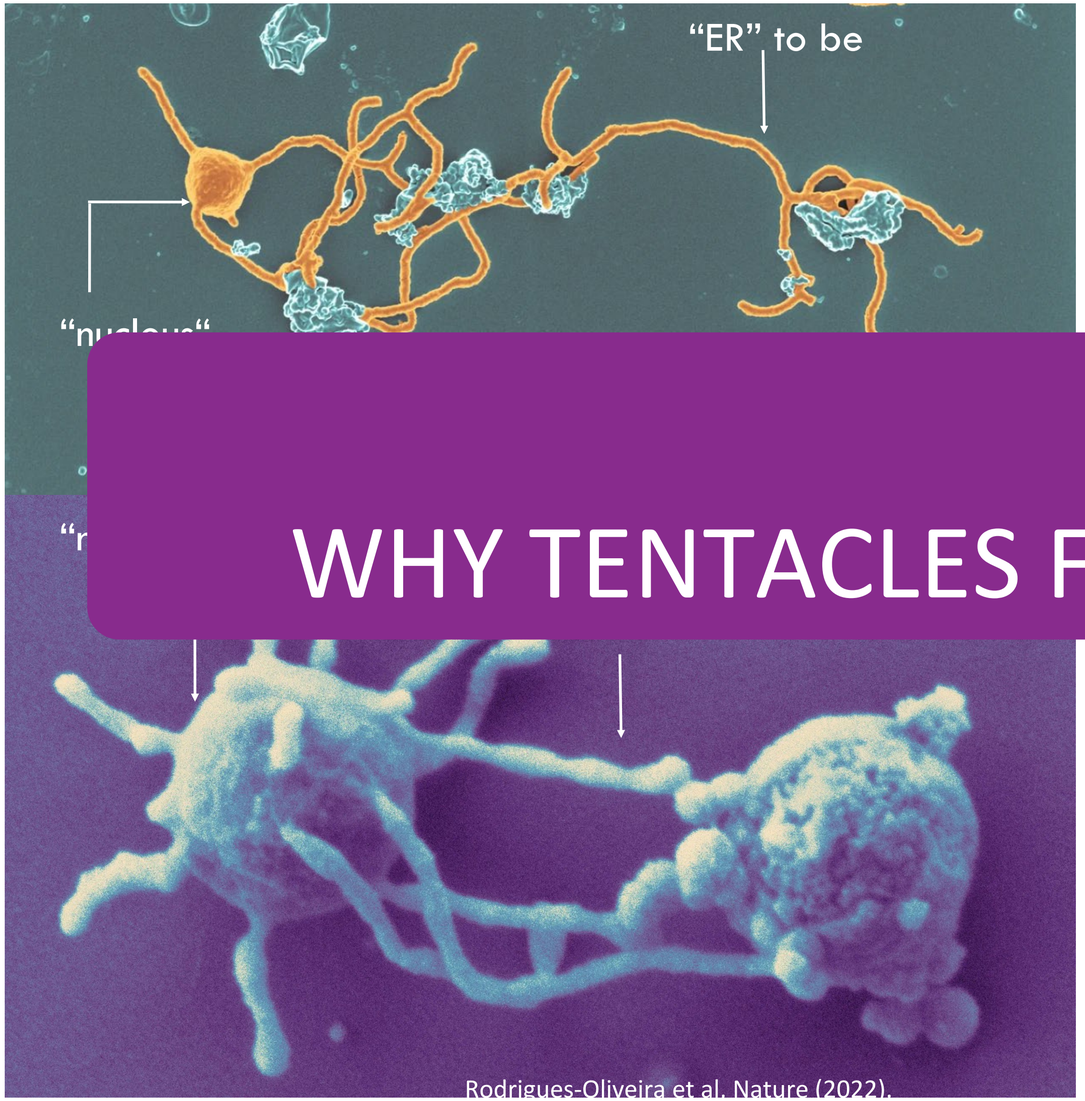
The (most important) transition in evolution of complex life



Watson, Nature (2019); Eme et al., Nature (2023); Spang et al, Nature (2015); Baum & Baum, BMC Biol (2020)

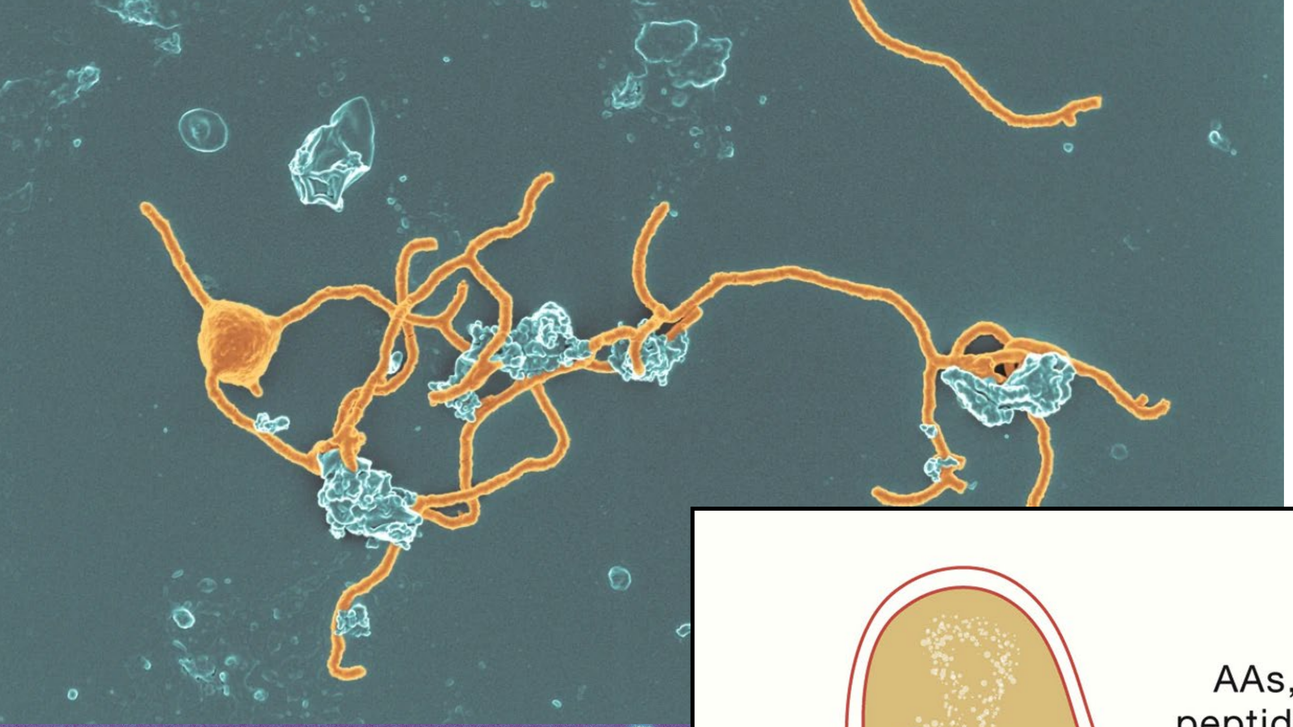
ASGARD ARCHAEA in EUKARYOGENESIS

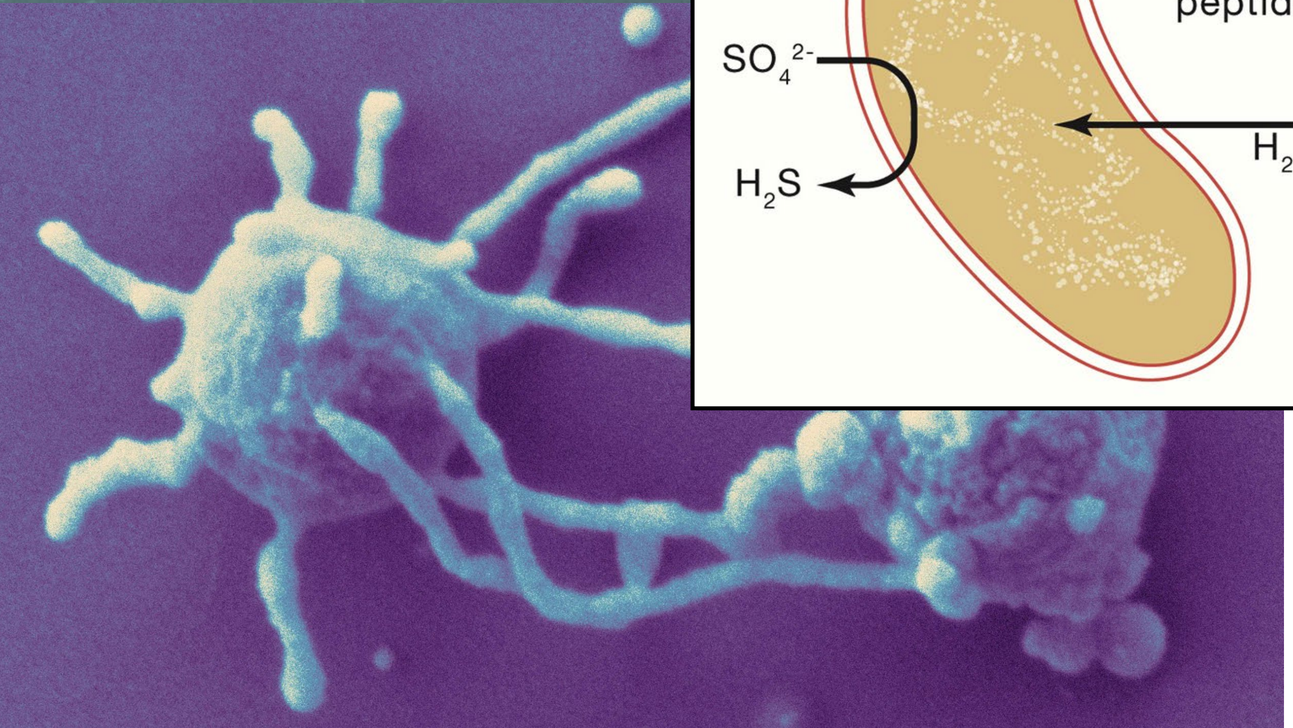
Recently isolated symbiosis between Loki archaea and bacteria



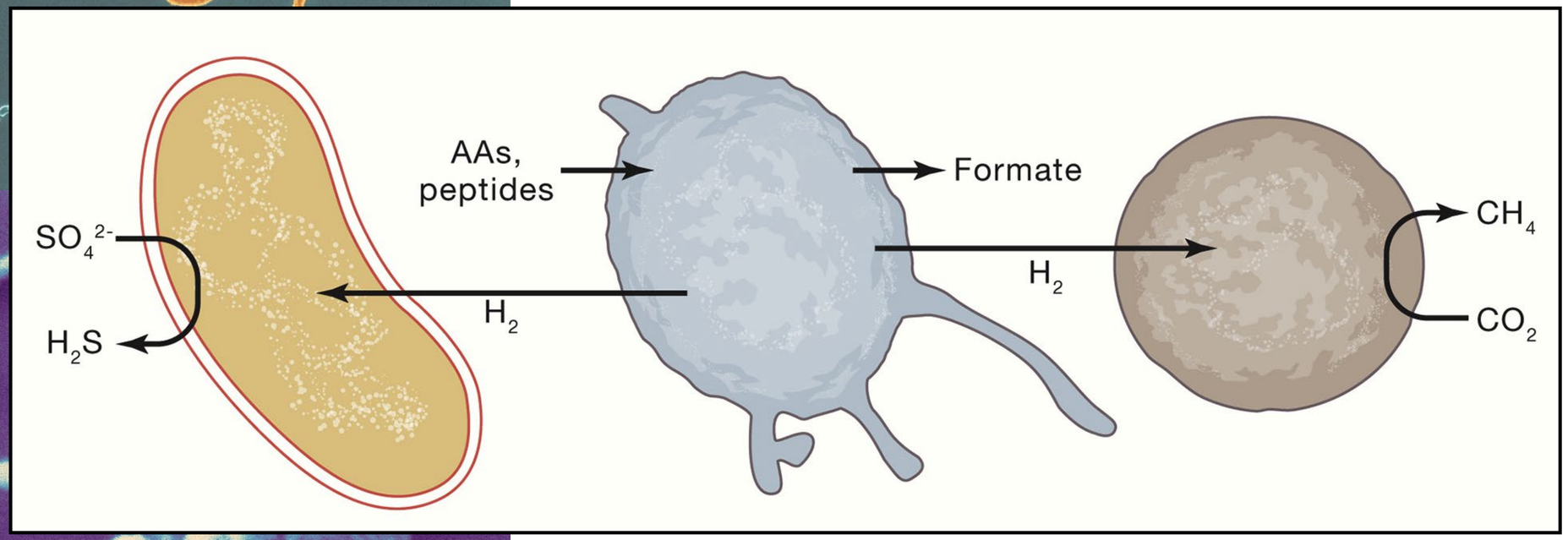
Rodrigues-Oliveira et al. Nature (2022).

WHY TENTACLES FOR SYMBIOSIS?





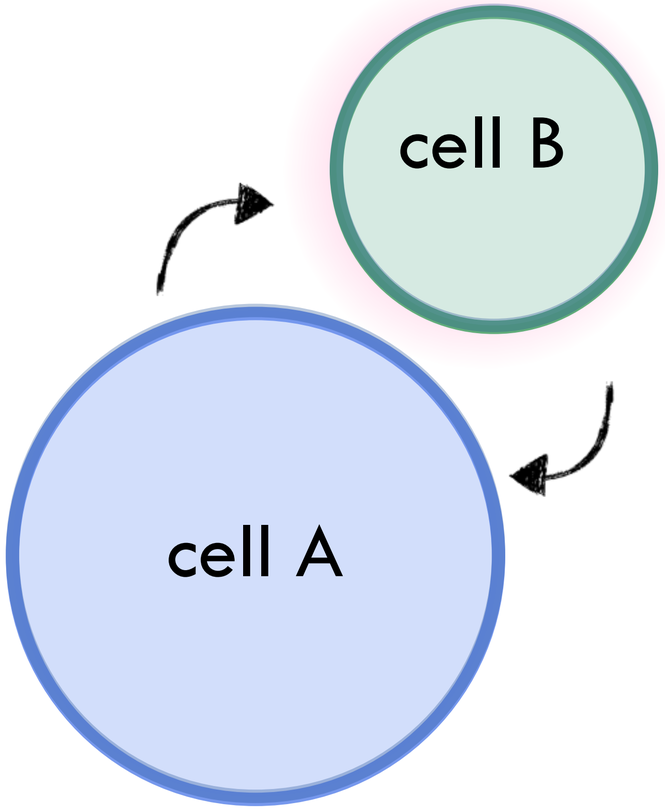
THESE CELLS EXCHANGE METABOLITES!



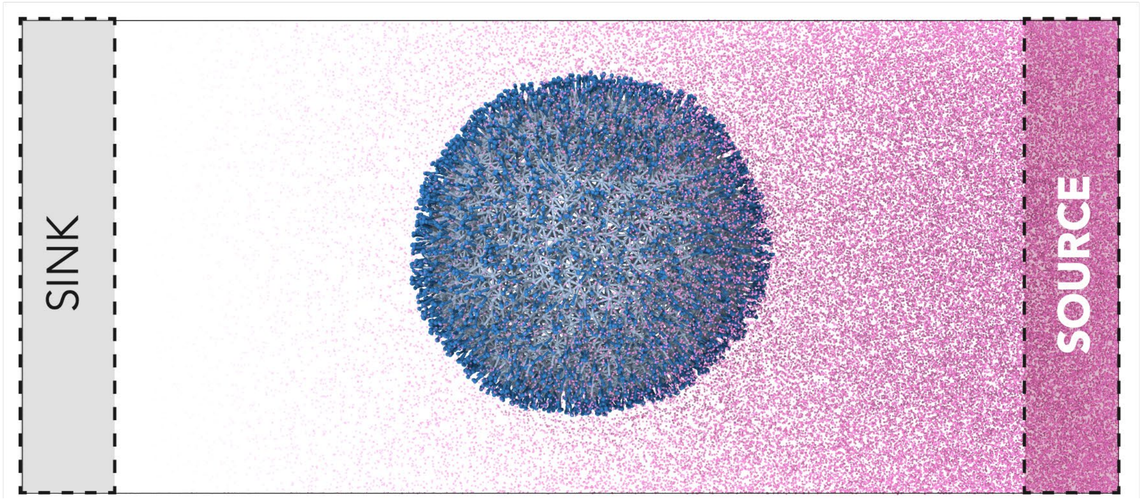
Imachi et al, Nature (2020)

Computational model of chemically coupled membranes

Deformable membrane consuming reactants

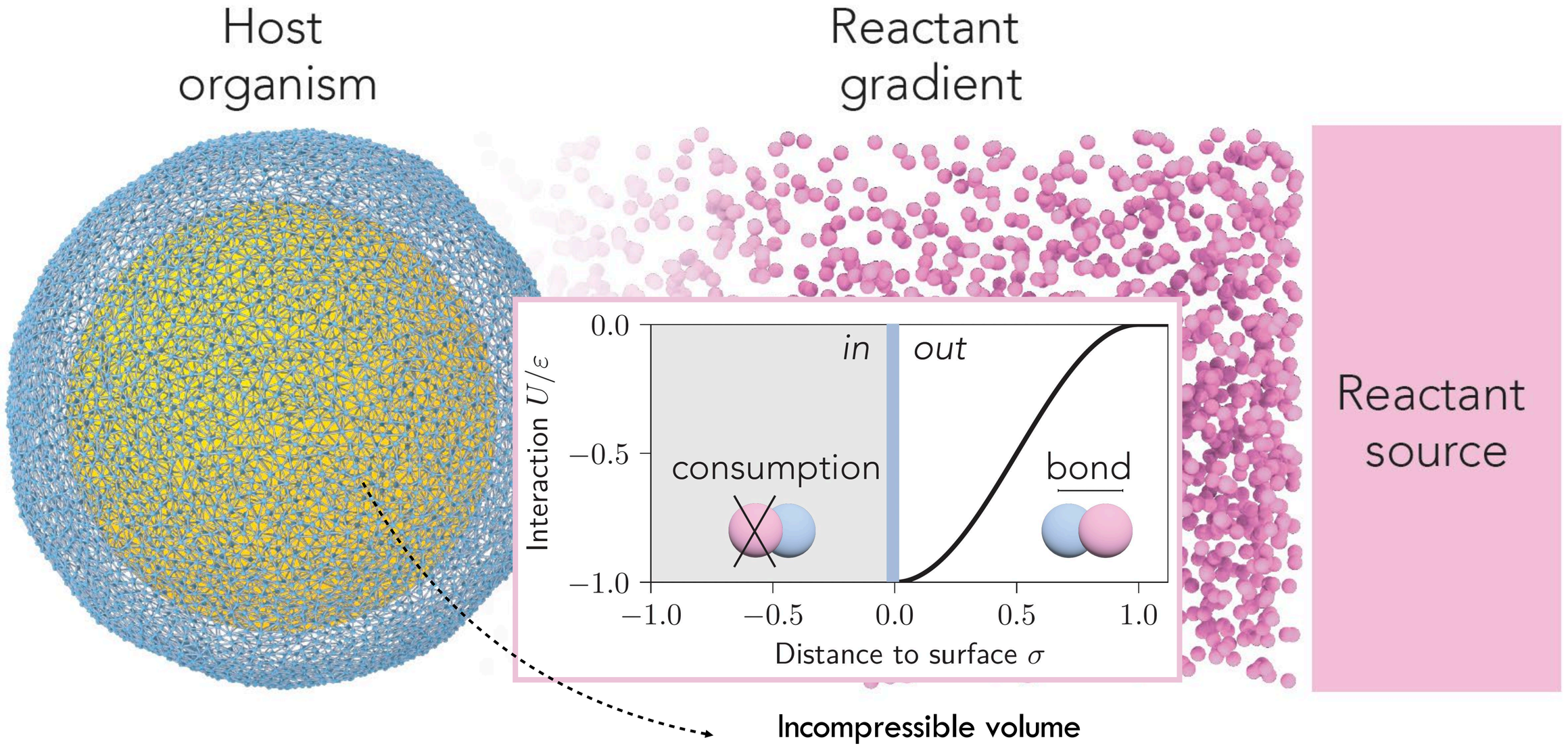


Boundary-driven NEMD simulations
Langevin dynamics (implicit solvent)



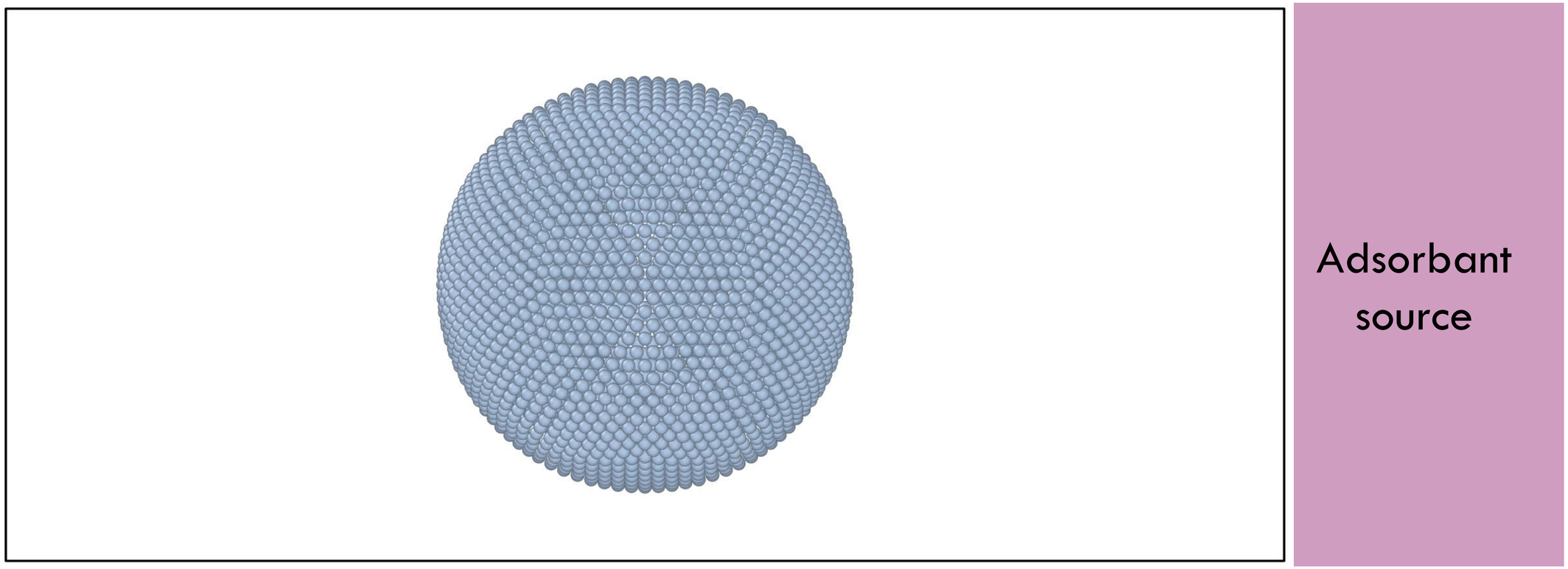
Computational model of chemically coupled membranes

Deformable membrane consuming reactants



Chemically coupled membranes

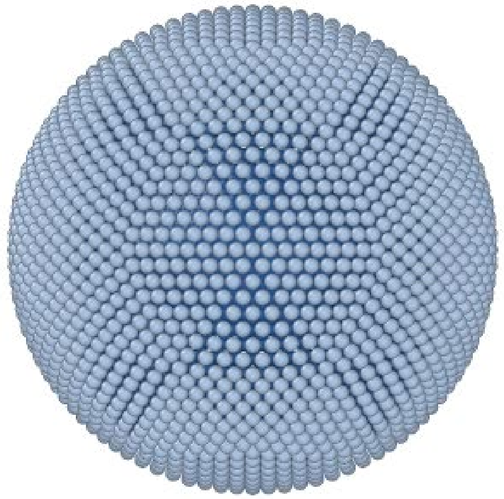
CONTROL: ADSORPTION, BUT NO CONSUMPTION



BORING EQUILIBIRUM.

Chemically coupled membranes

NOW: ADSORPTION AND CONSUMPTION

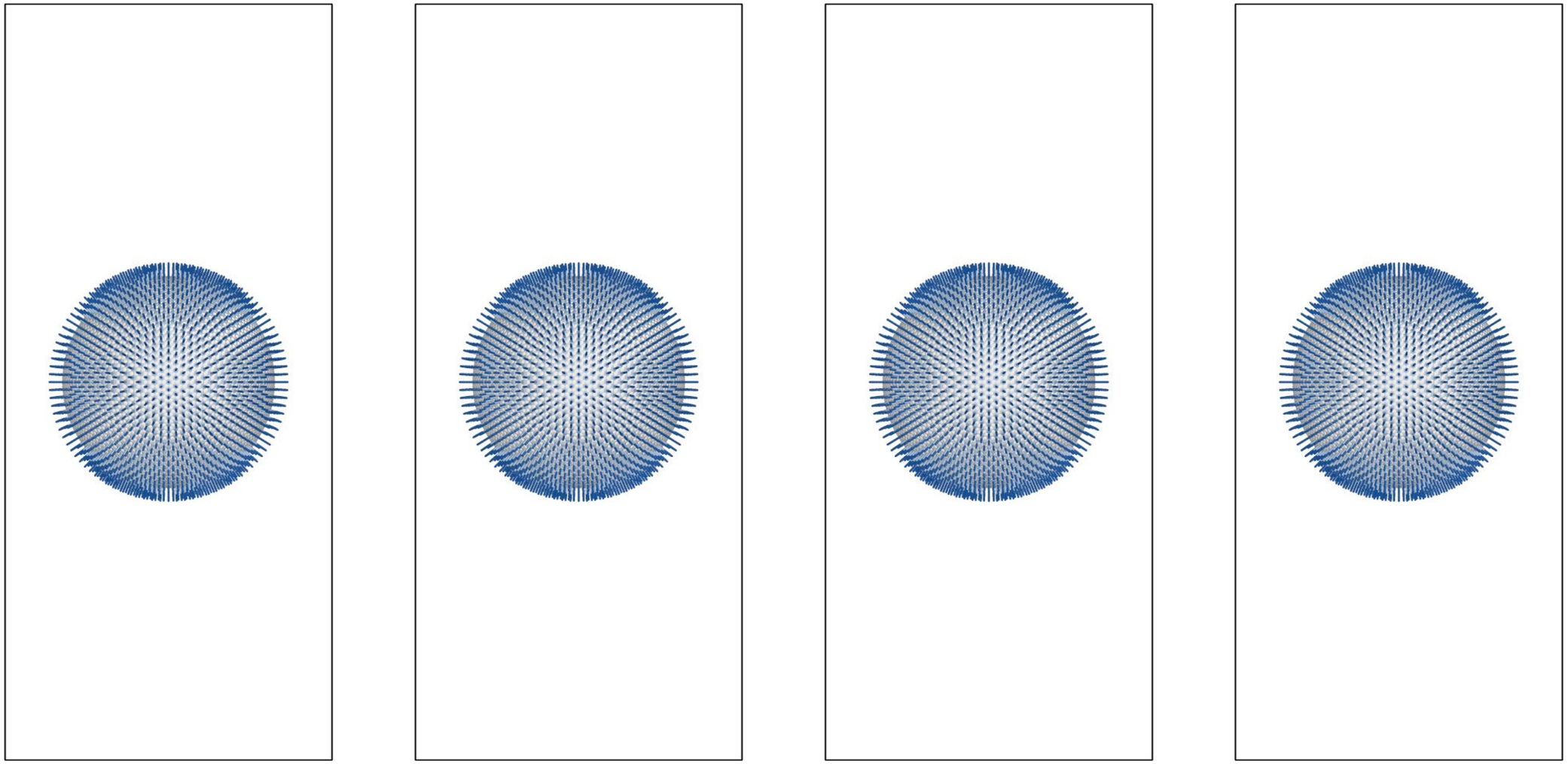


Reactant source

TENTACLE GROWTH!
(ALSO “SEARCH”)

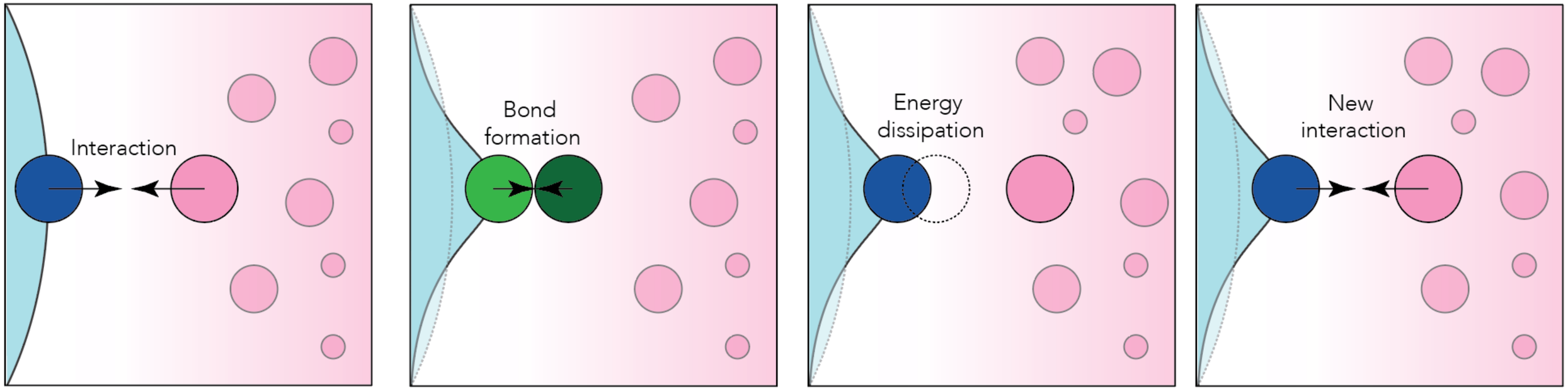
unpublished

CONSUMPTION ON THE MEMBRANE NEEDS TO BE FAST



Turn-over rate on the membrane

Mechanism of reshaping of chemically active membranes

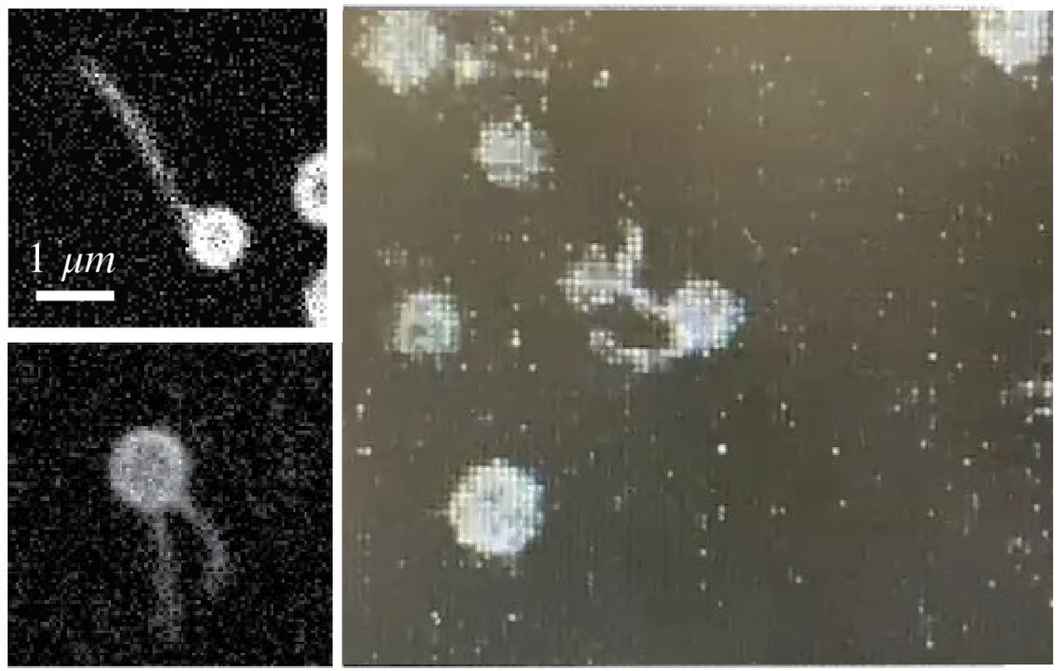


Ratcheting in a fluctuating asymmetric potential.

reminiscent of Ajdari & Prost (1992) “Drift induced by a spatially periodic potential of low symmetry”

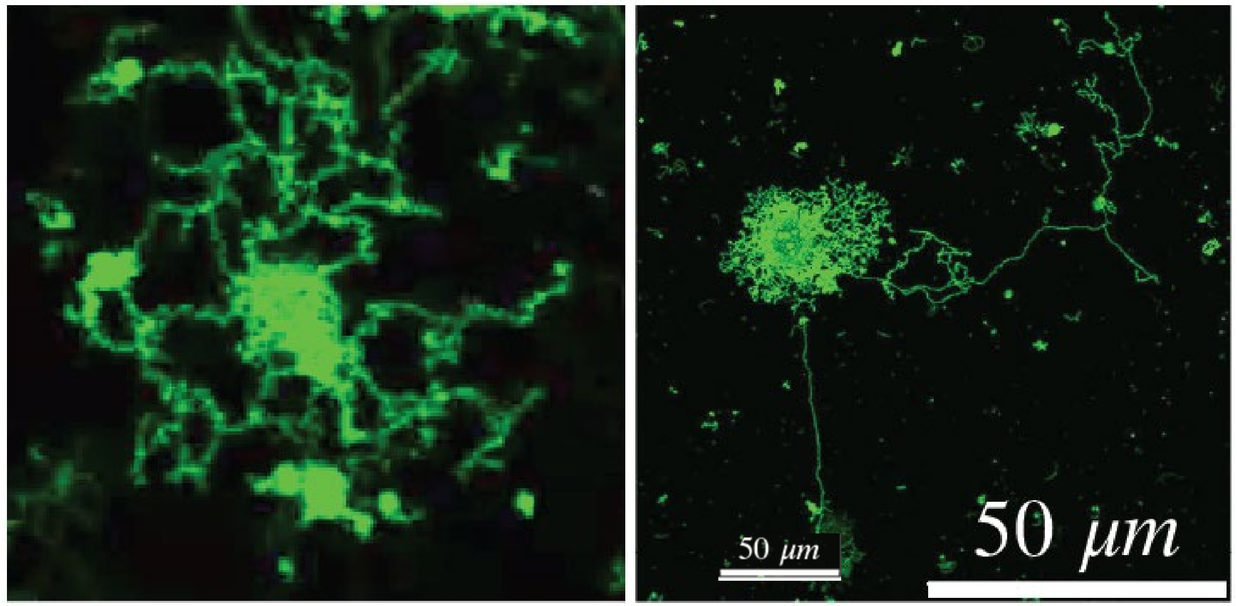
DEFORMATION OF CHEMICALLY ACTIVE MEMBRANES

IN VIVO & IN VITRO



IN VIVO, by B. Baum, MRC LMB

Sulfolobus archaea protrusions
unpublished

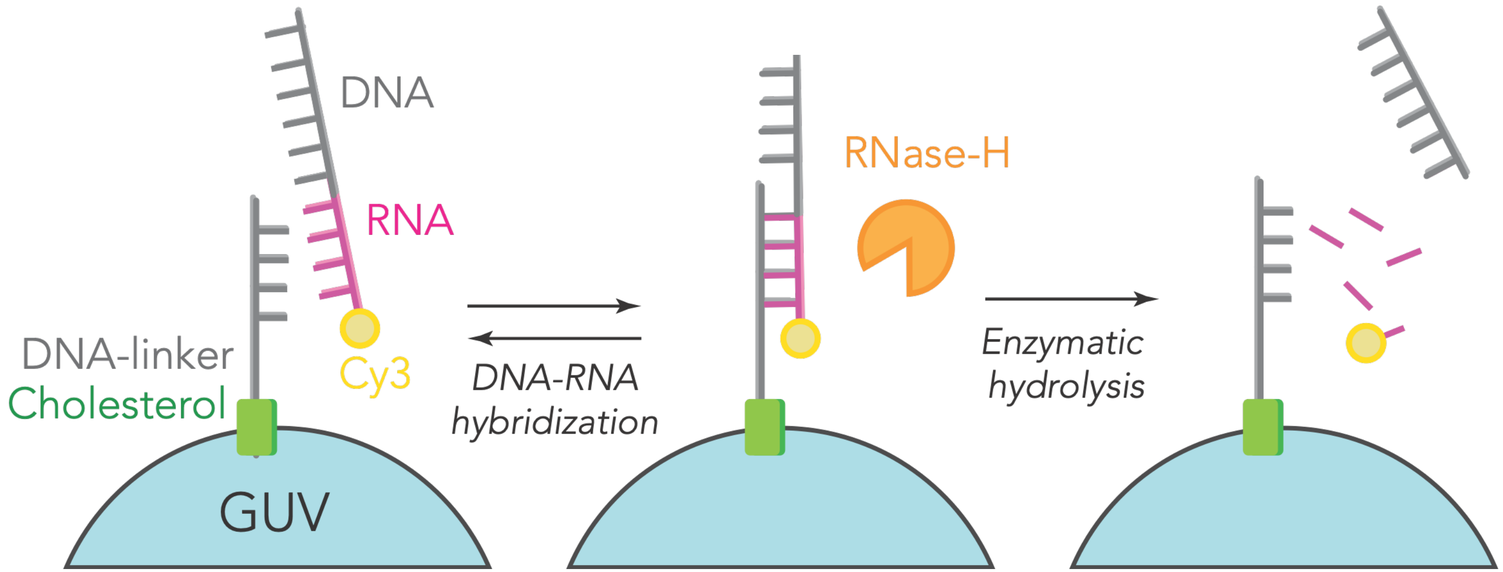


IN VITRO, by K. Göpfrich, U Heidelberg

Chemically consuming synthetic vesicles form tentacles
unpublished

DEFORMATION OF CHEMICALLY ACTIVE MEMBRANES *in vitro*

ssDNA + ssRNA ⟶ DNA-RNA hybrid + RNase H ⟶ ssDNA



by K.Göpfrich, Heidelberg Uni

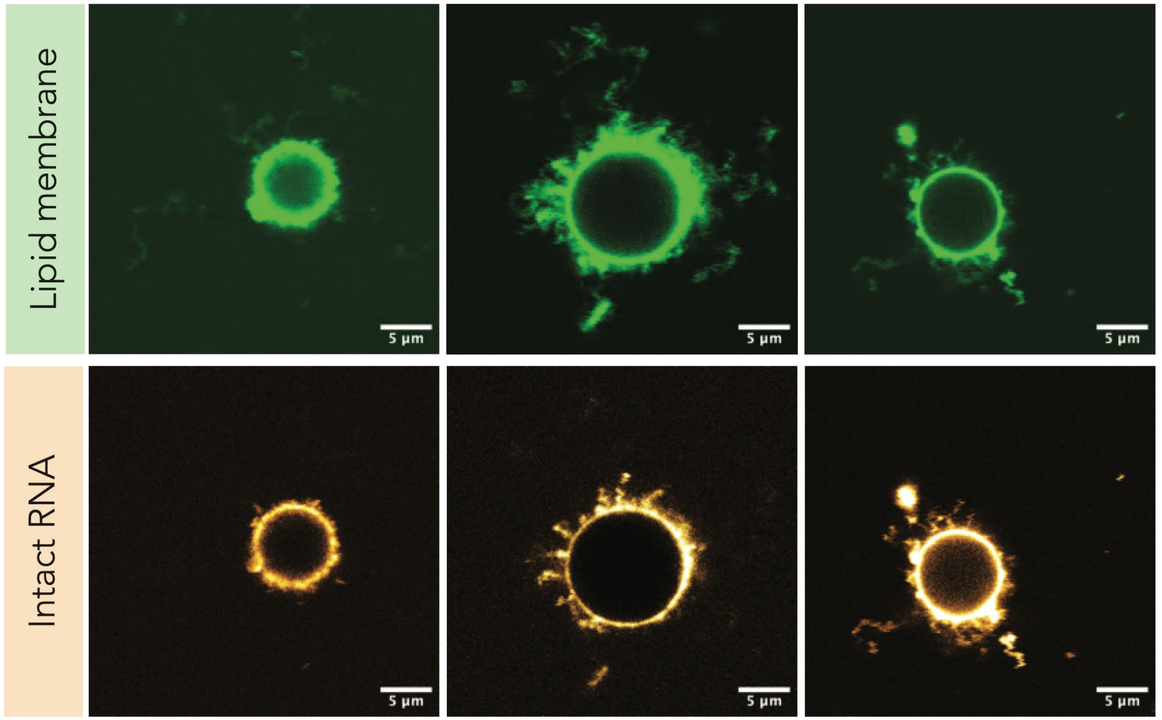
In preparation, 2025

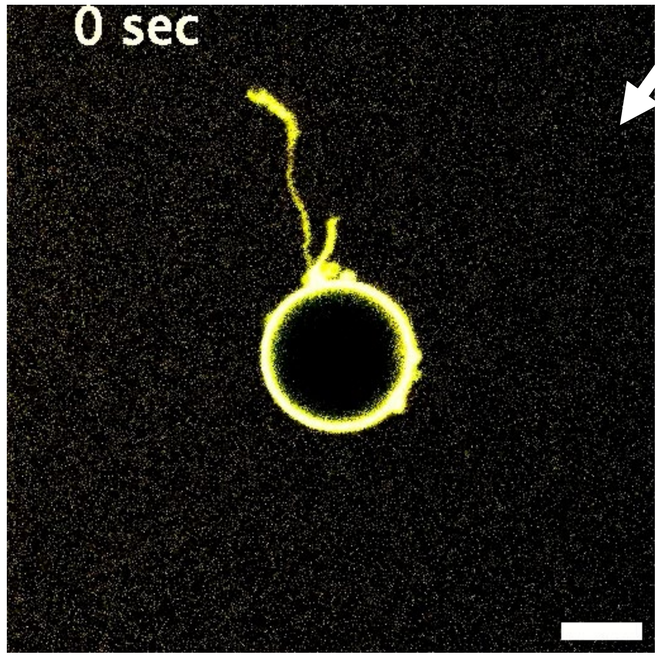
Homogeneous reactant field

Deformation of chemically-active vesicles

ssDNA + ssRNA ⟶ DNA-RNA hybrid + RNase H ⟶ ssDNA

A+B → AB + enzyme → A + bbbb..





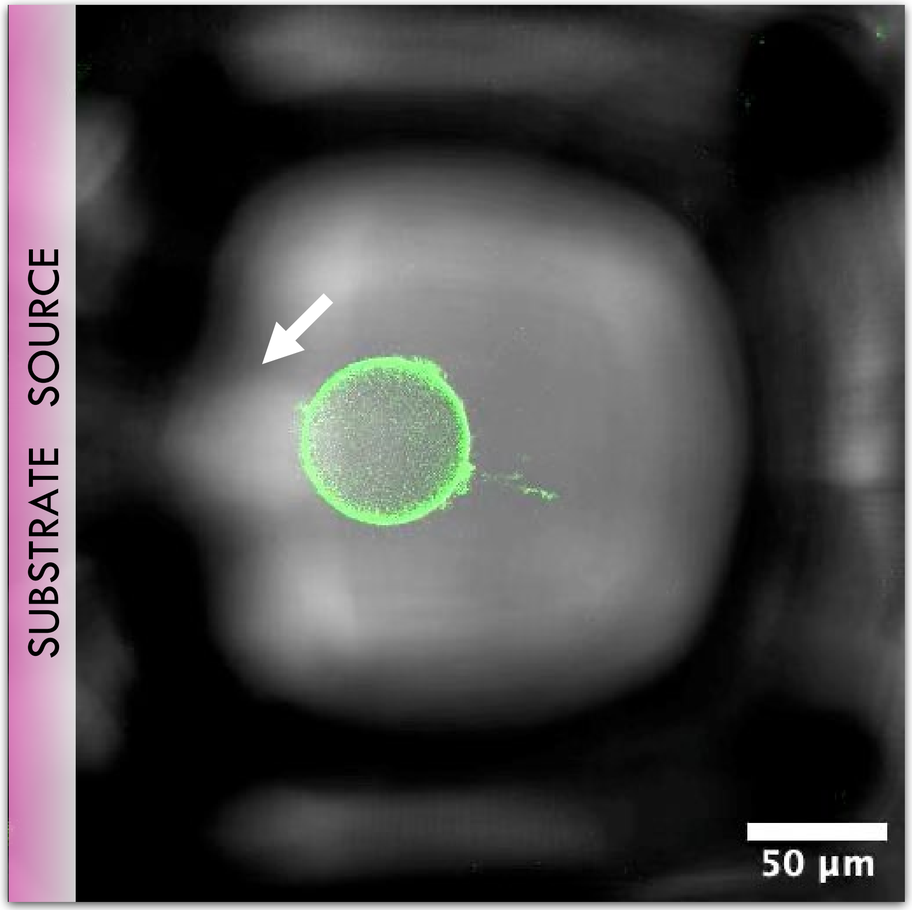
Homogeneous reactants around the vesicle.

In preparation, 2025

Localised reactant field

Deformation of chemically-active vesicles

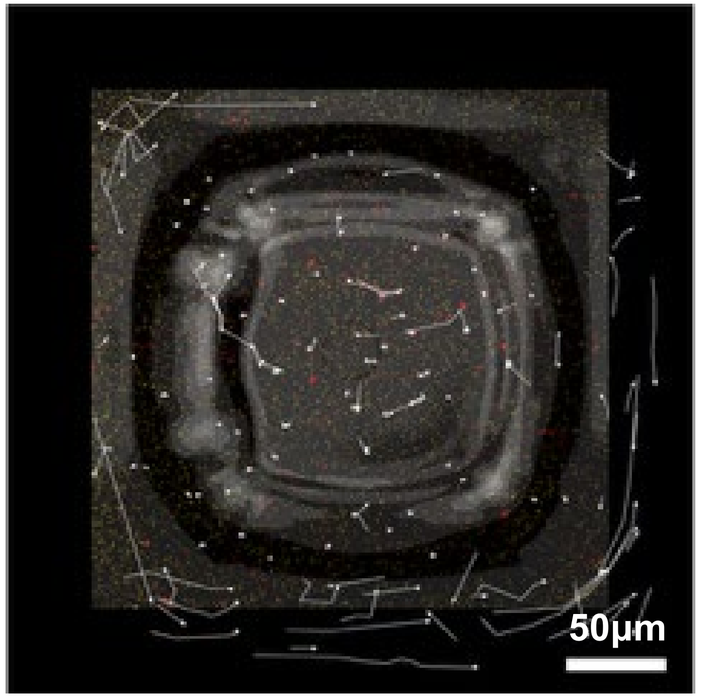
Video: M. Emmert (Göprich group)



Localised reactant source.

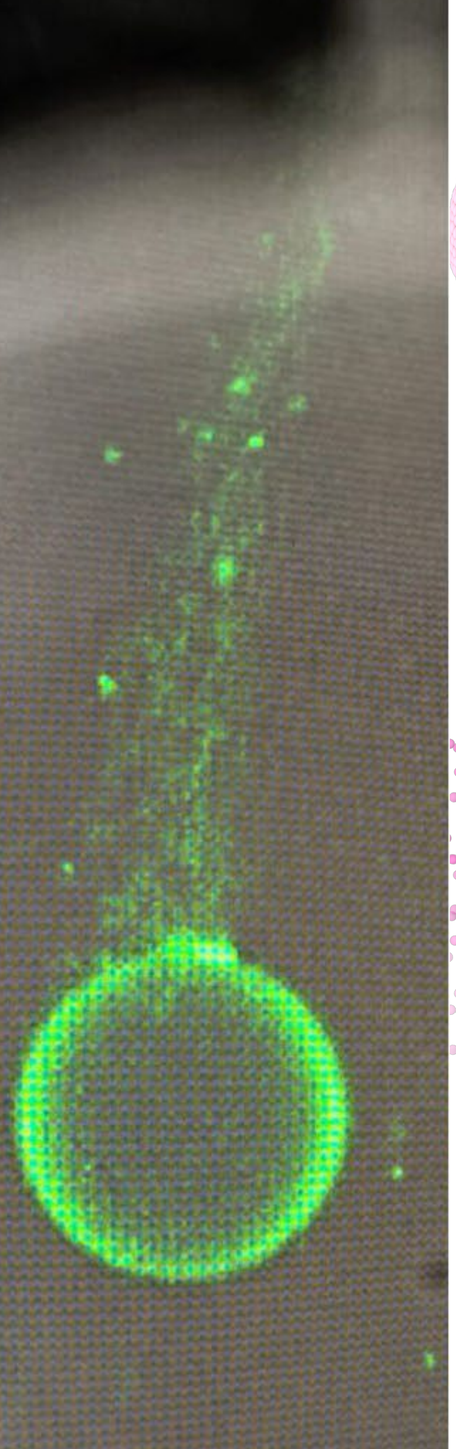
Negative controls

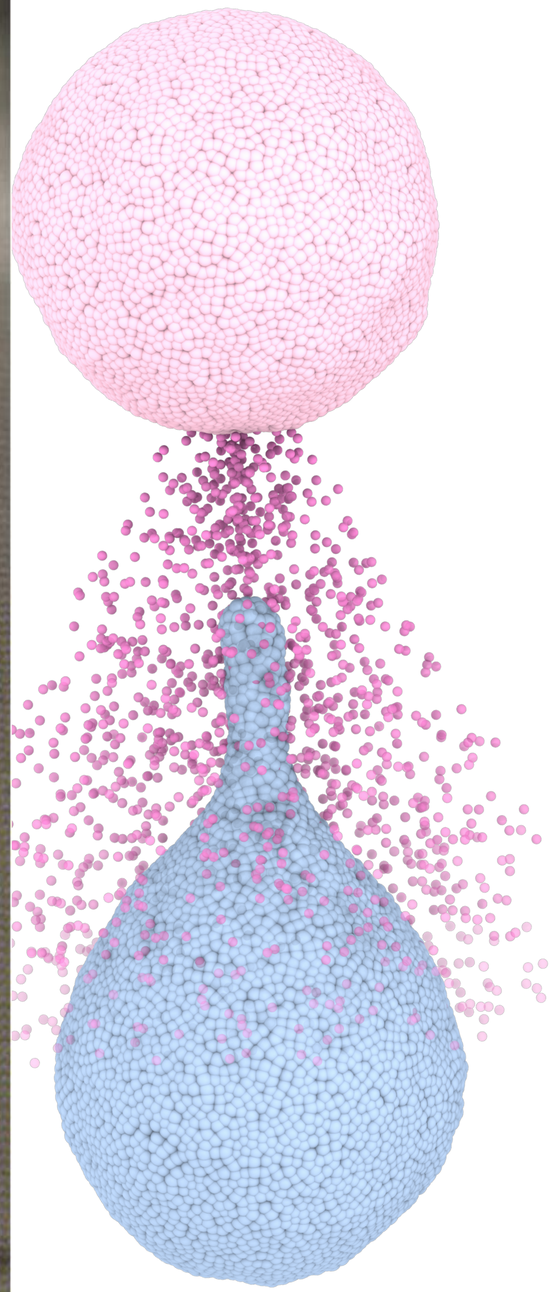
- Enzyme needed
- Reaction must be localised on membrane
- Not an osmotic effect
- No flows present



Tracer particles show no flows.

In preparation, 2025

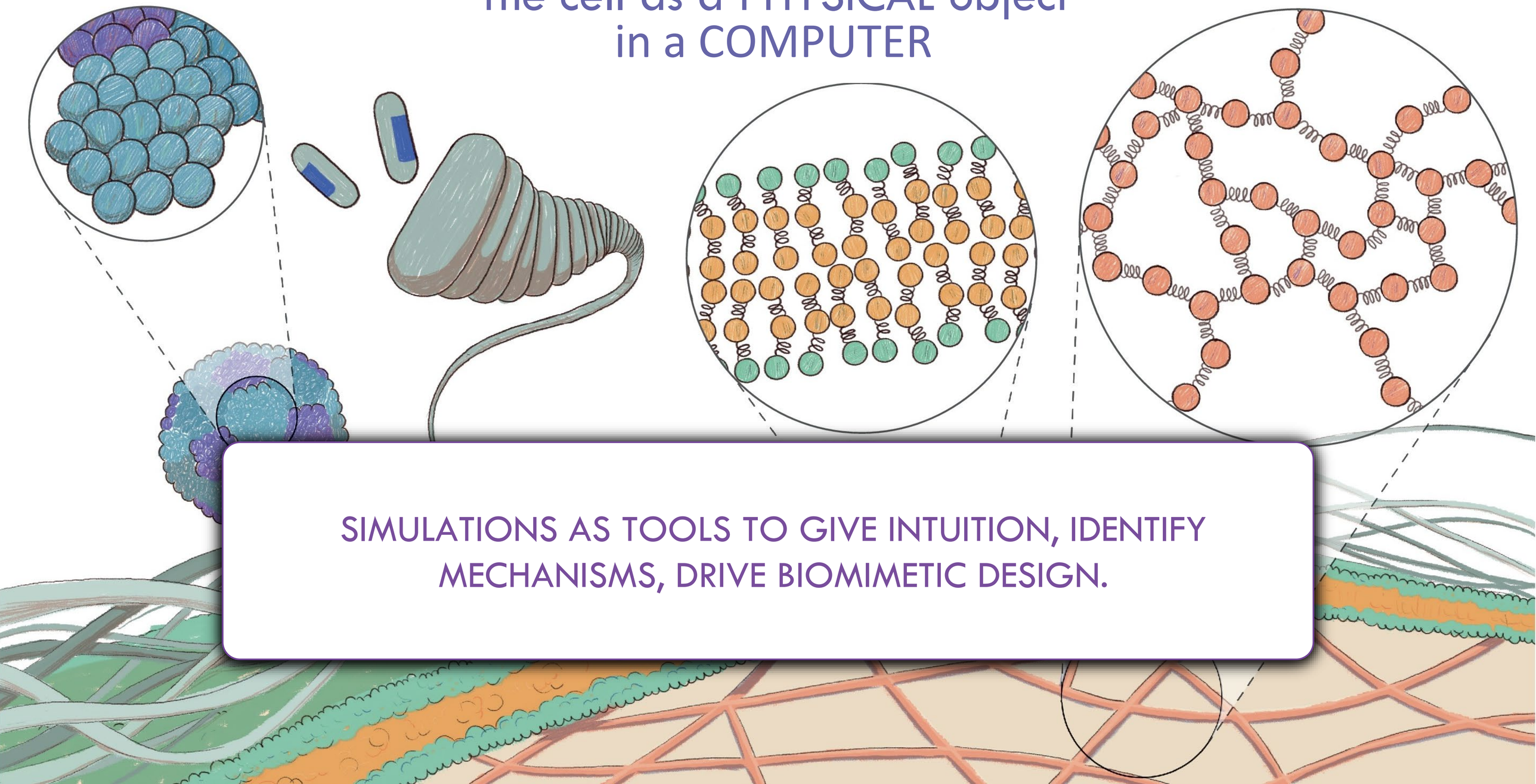




RESHAPING MEMBRANES BY CHEMICAL ACTIVITY

- Metabolite consumption on the membrane can reshape membrane.
- Why tubes? Fluid membrane responds to local force by forming tubes.
- Chemically active tubes can drive search & symbiosis, in archaea and beyond.

The cell as a PHYSICAL object in a COMPUTER



SIMULATIONS AS TOOLS TO GIVE INTUITION, IDENTIFY MECHANISMS, DRIVE BIOMIMETIC DESIGN.

THANKS TO:

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