Fluid flows shaping transport networks

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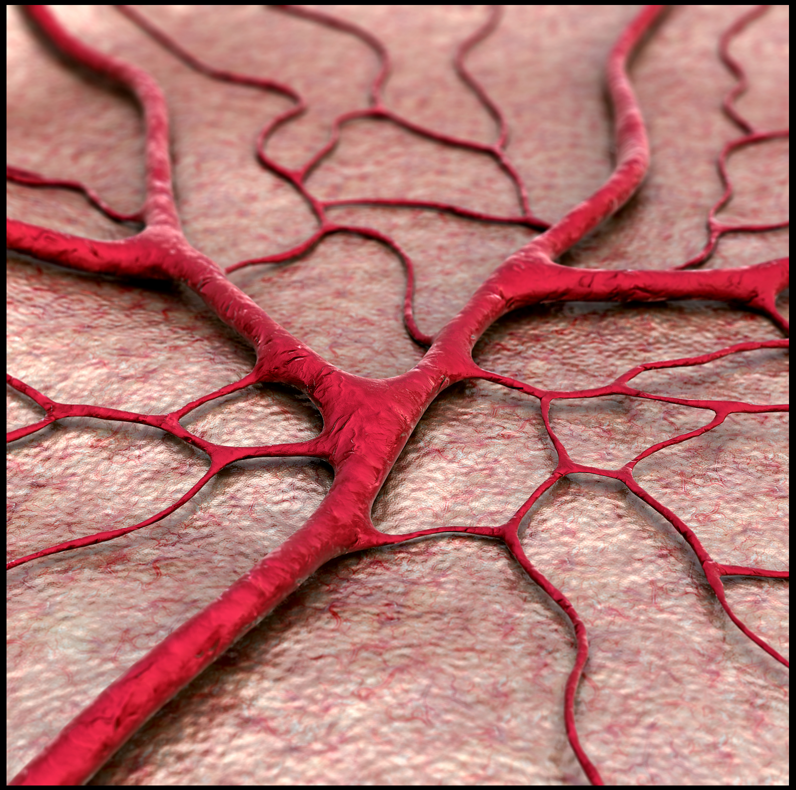
Biological Physics and Morphogenesis
Max Planck Institute for Dynamics and Self-Organization

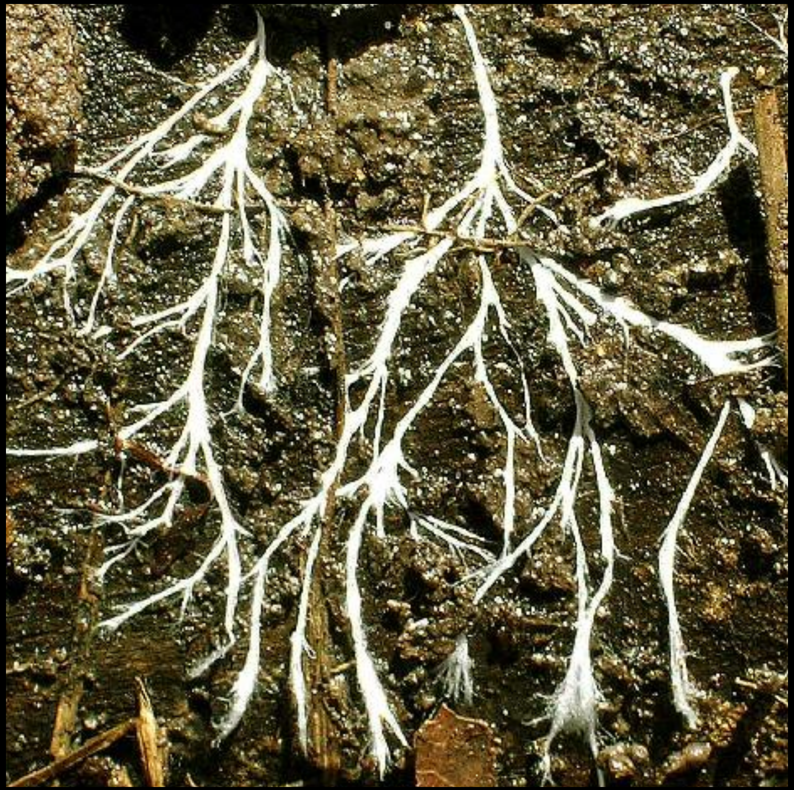
2nd August 2019

Fluid-filled networks abundant



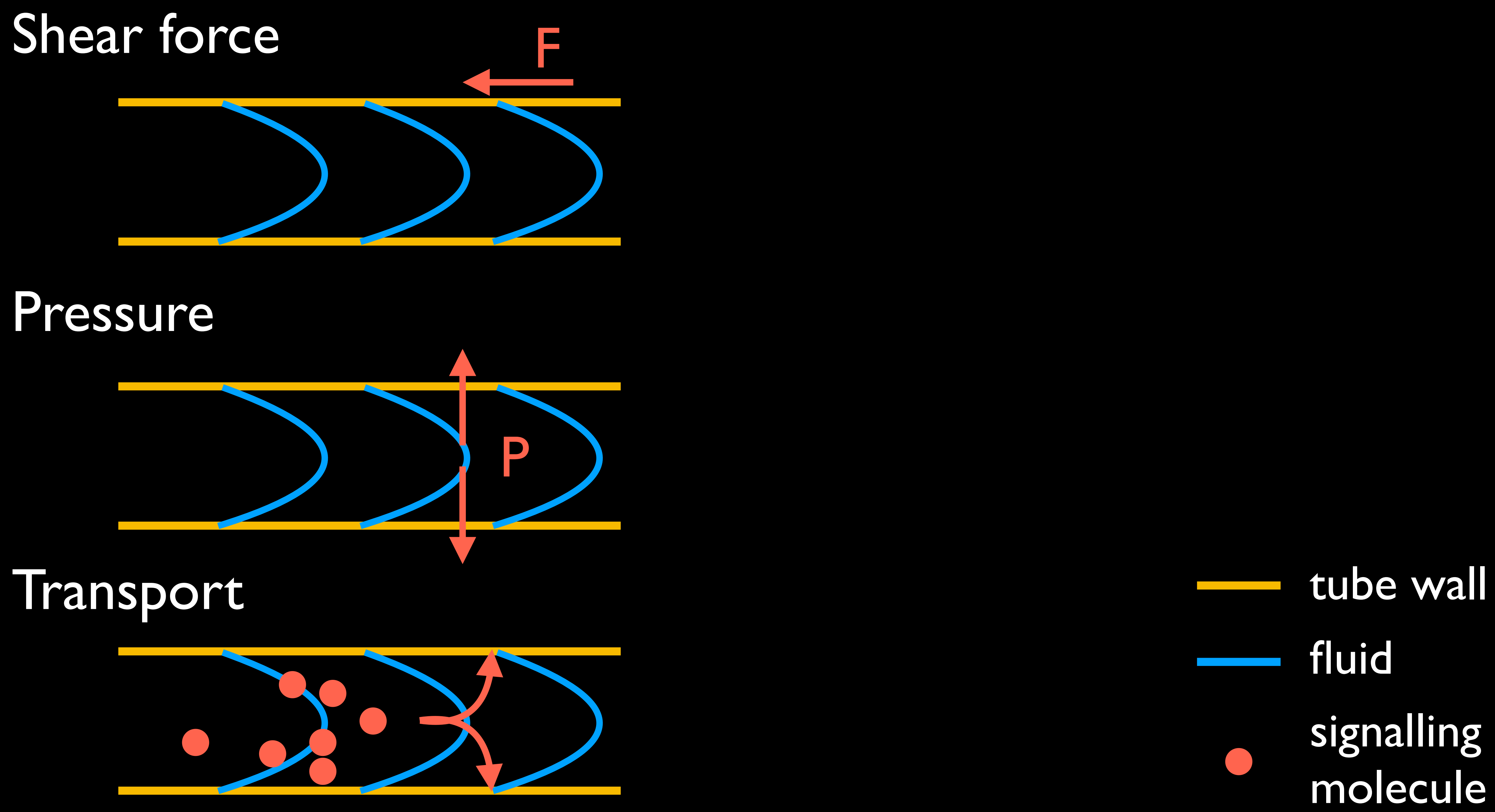
Animals

Plants



Fungi

Flows are information

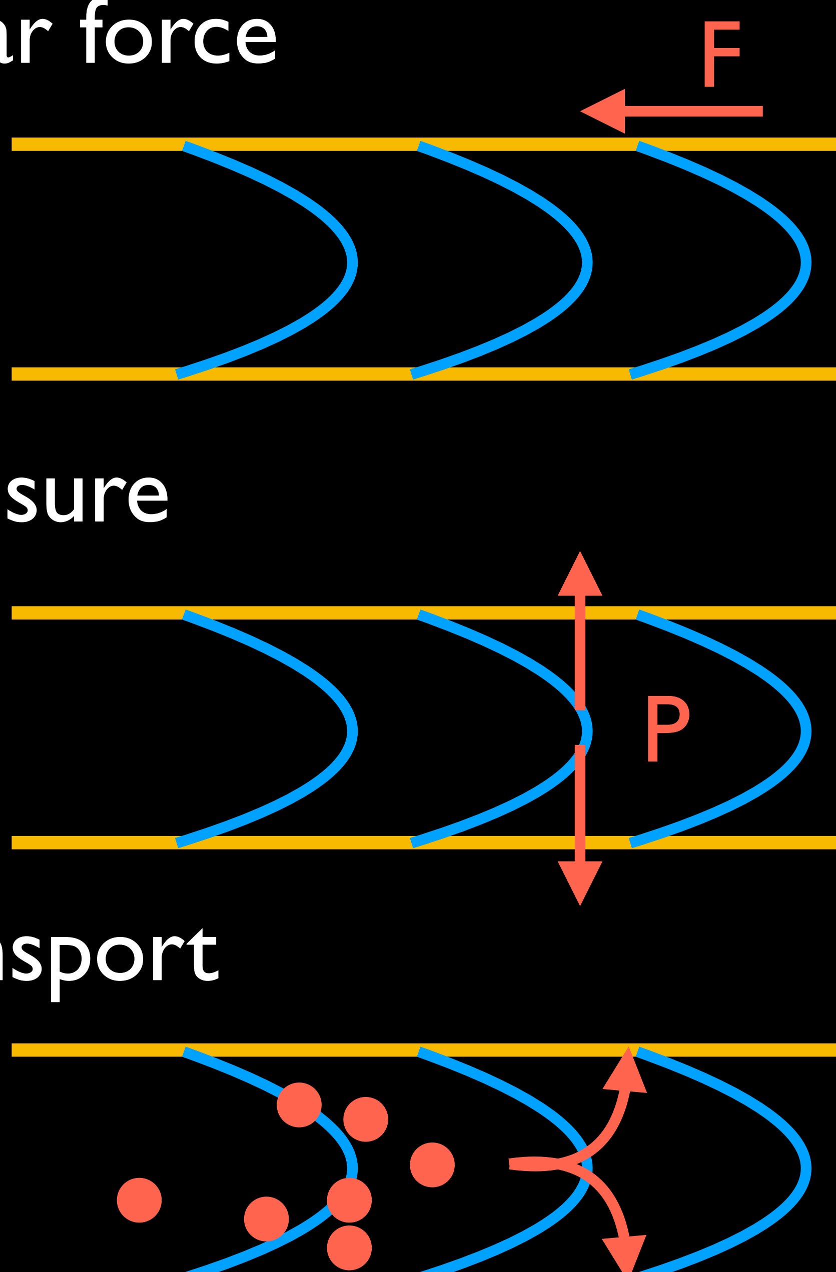


Flows are information

Shear force

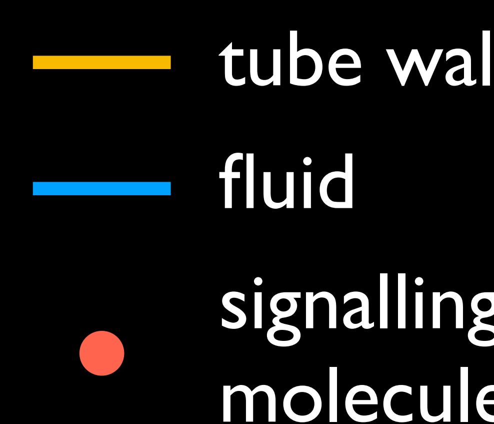
Pressure

Transport

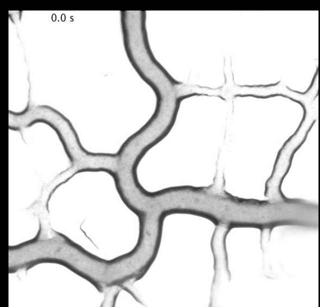


AND

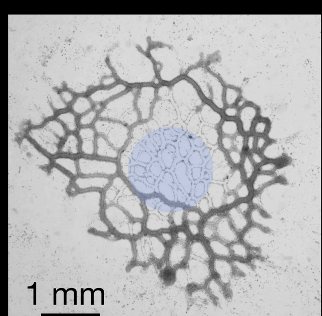
Tube walls are alive!



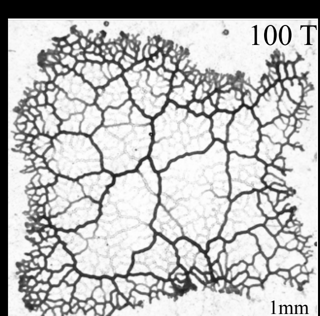
Flow ⟷ Morphology



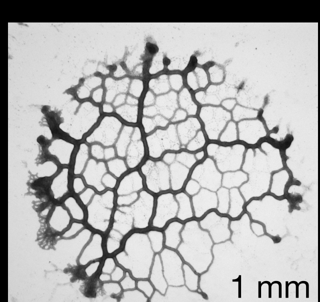
Flow control



Adaptability

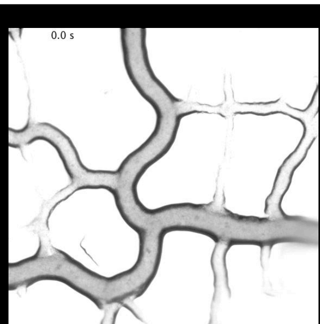


Topology

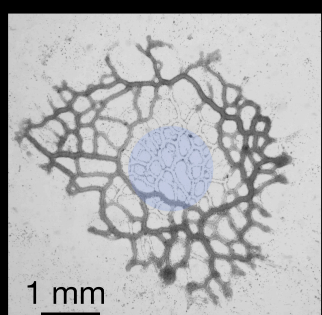


Hierarchy

Flow ⟲ Morphology



Flow control



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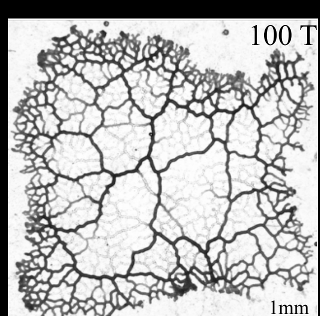

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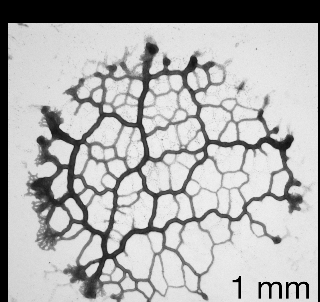
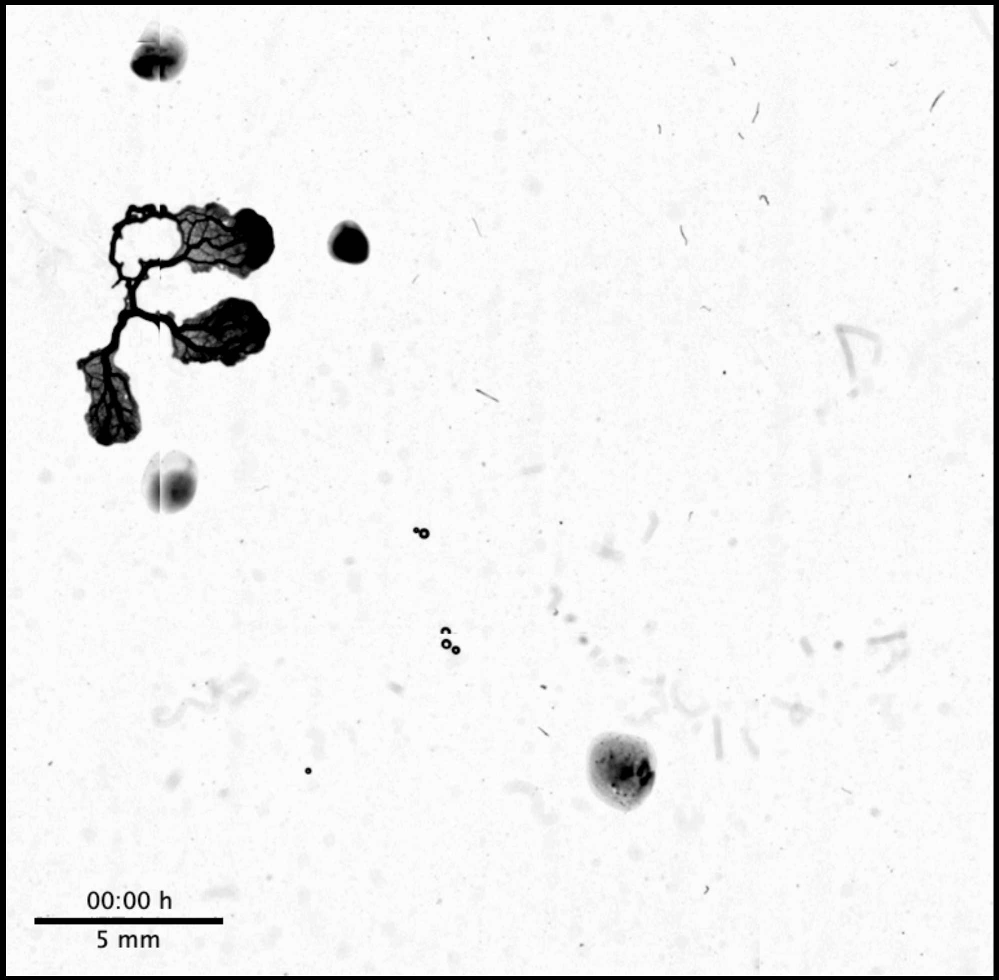


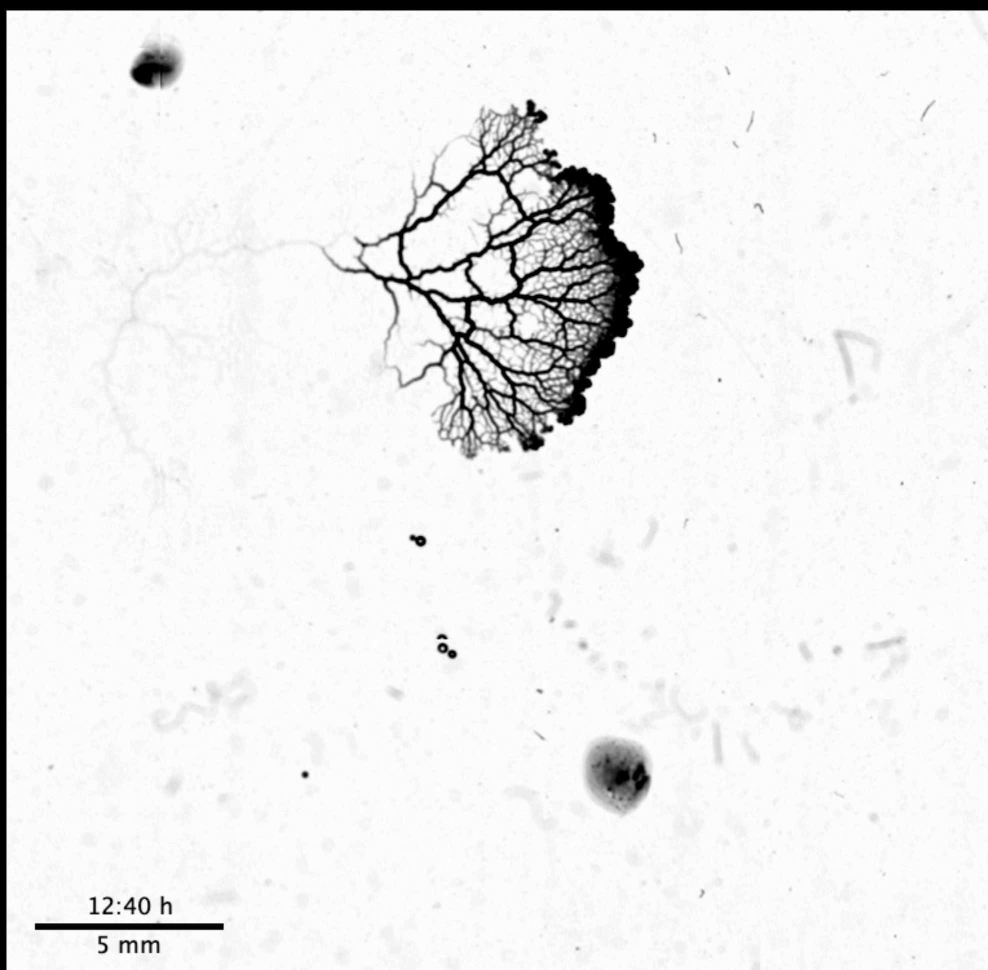
Hierarchy

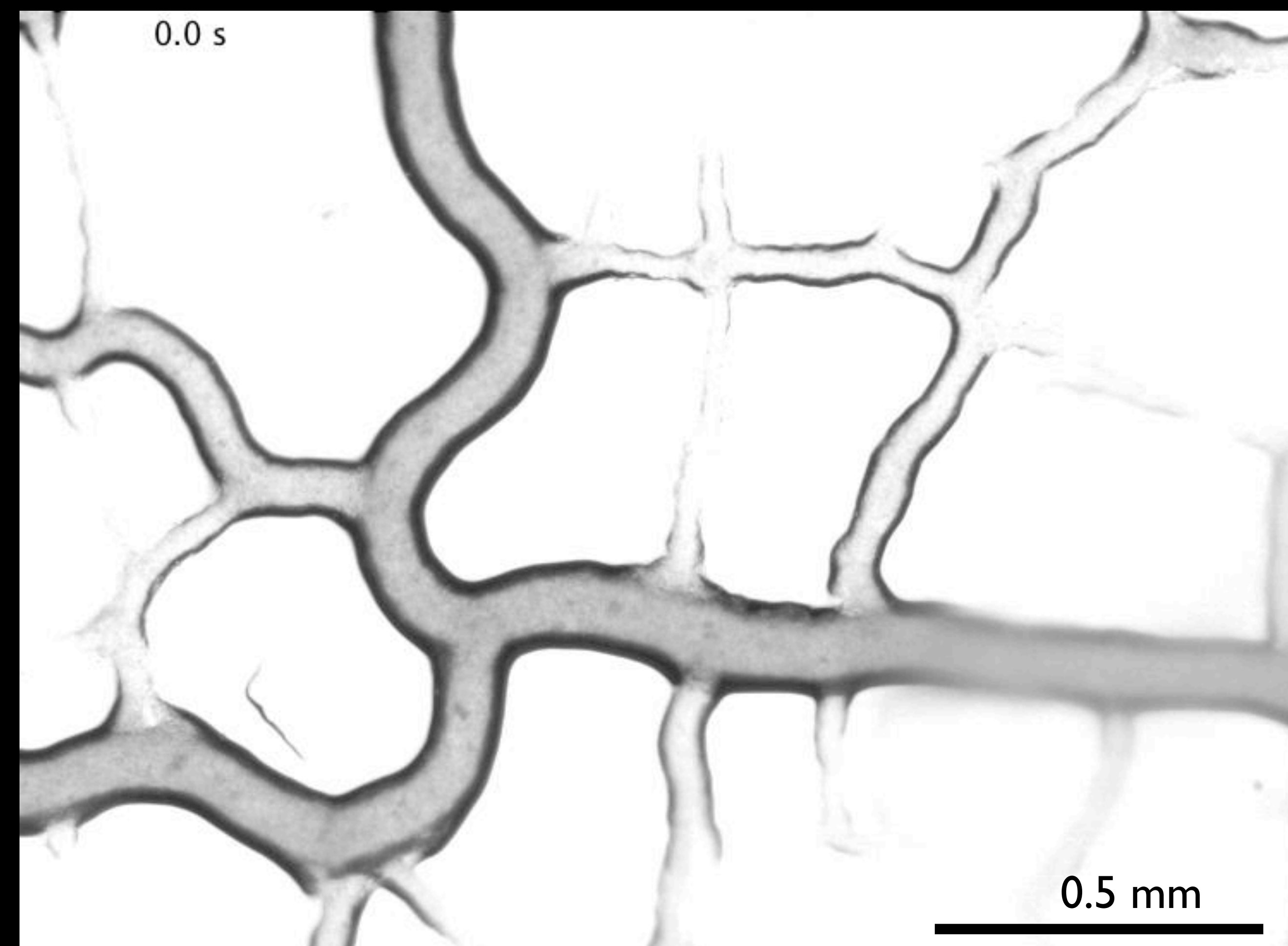
Model organism is network-shaped giant cell



Physarum polycephalum

Model organism is network-shaped giant cell

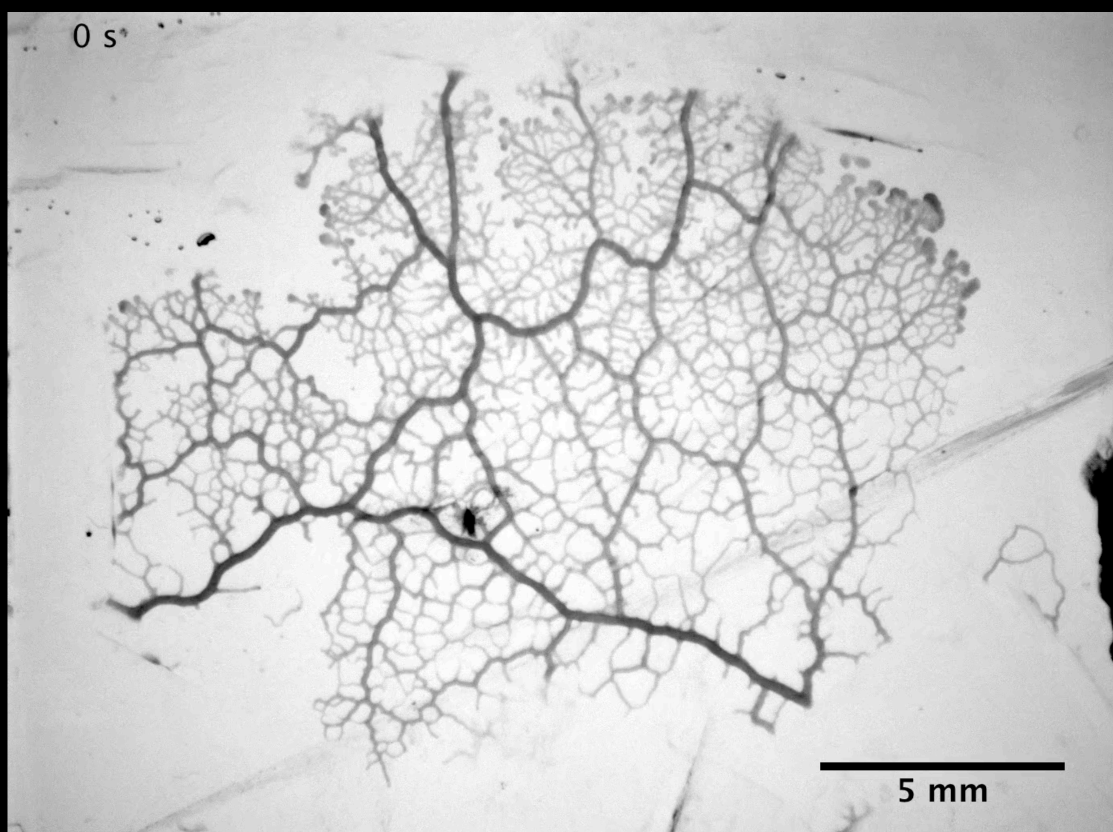


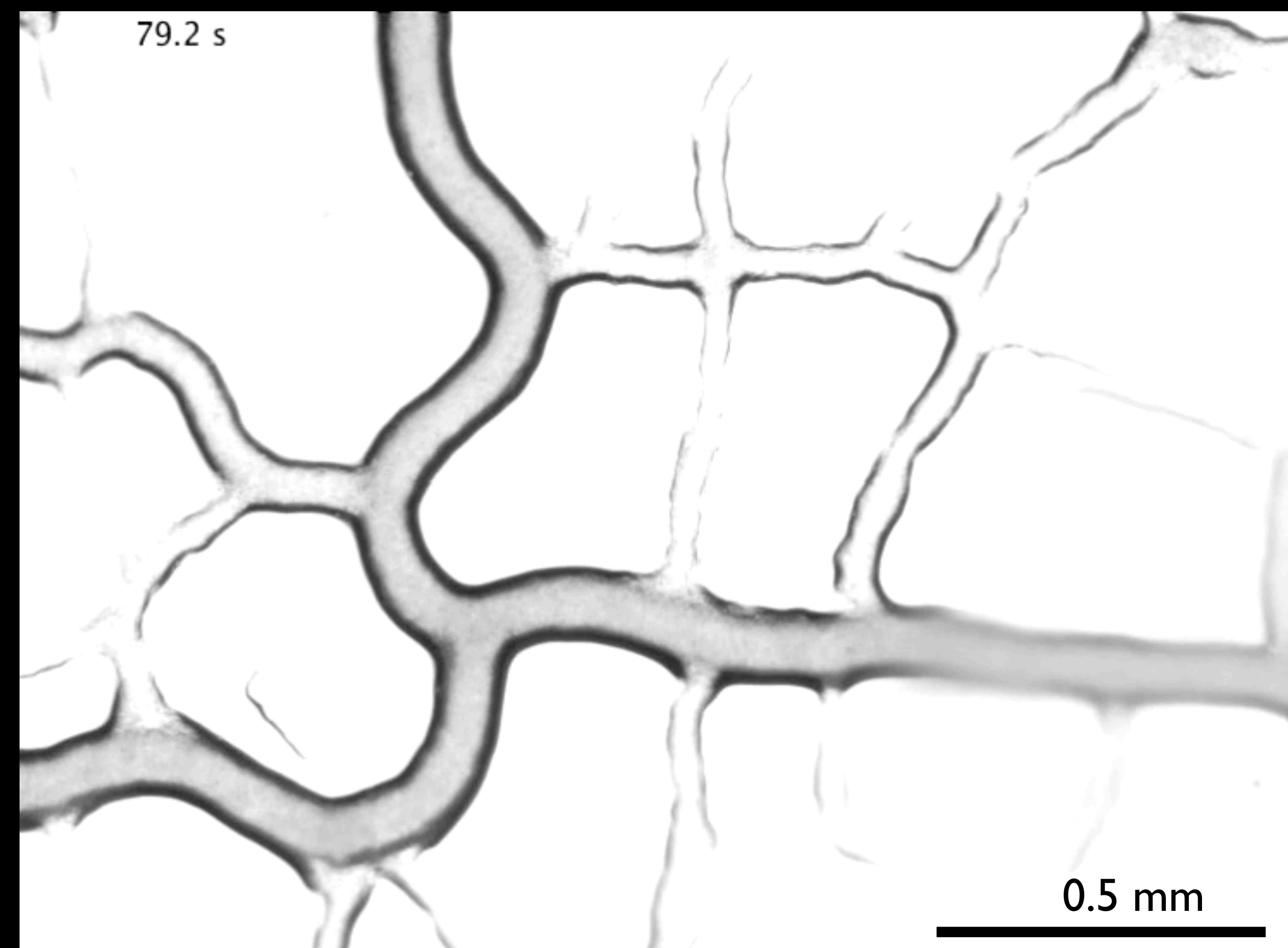


Physarum polycephalum

- Actin cortex as tube wall
- Contracting tubes drive cytoplasm flow

Model organism is network-shaped giant cell





Physarum polycephalum

- Actin cortex as tube wall
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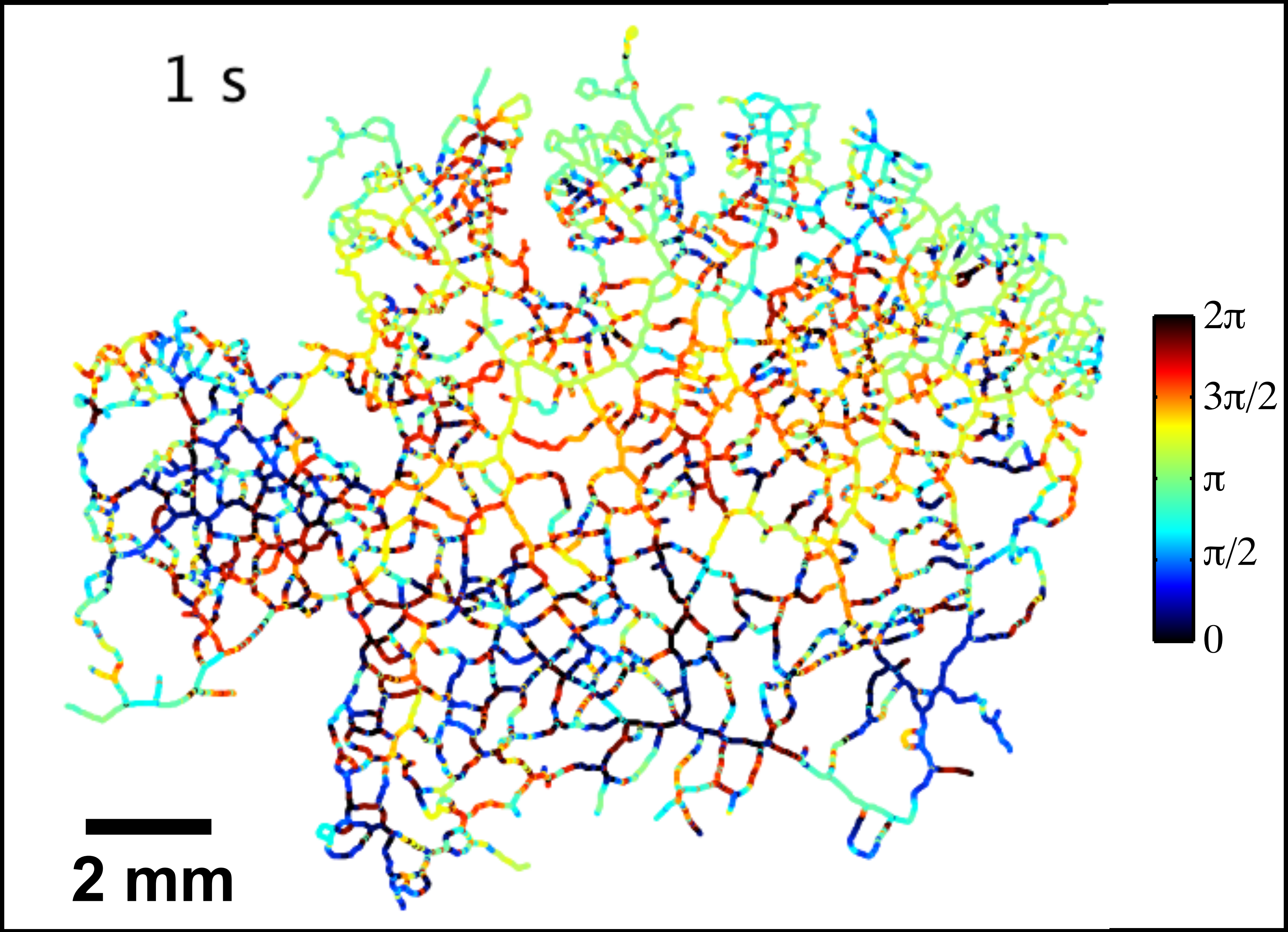
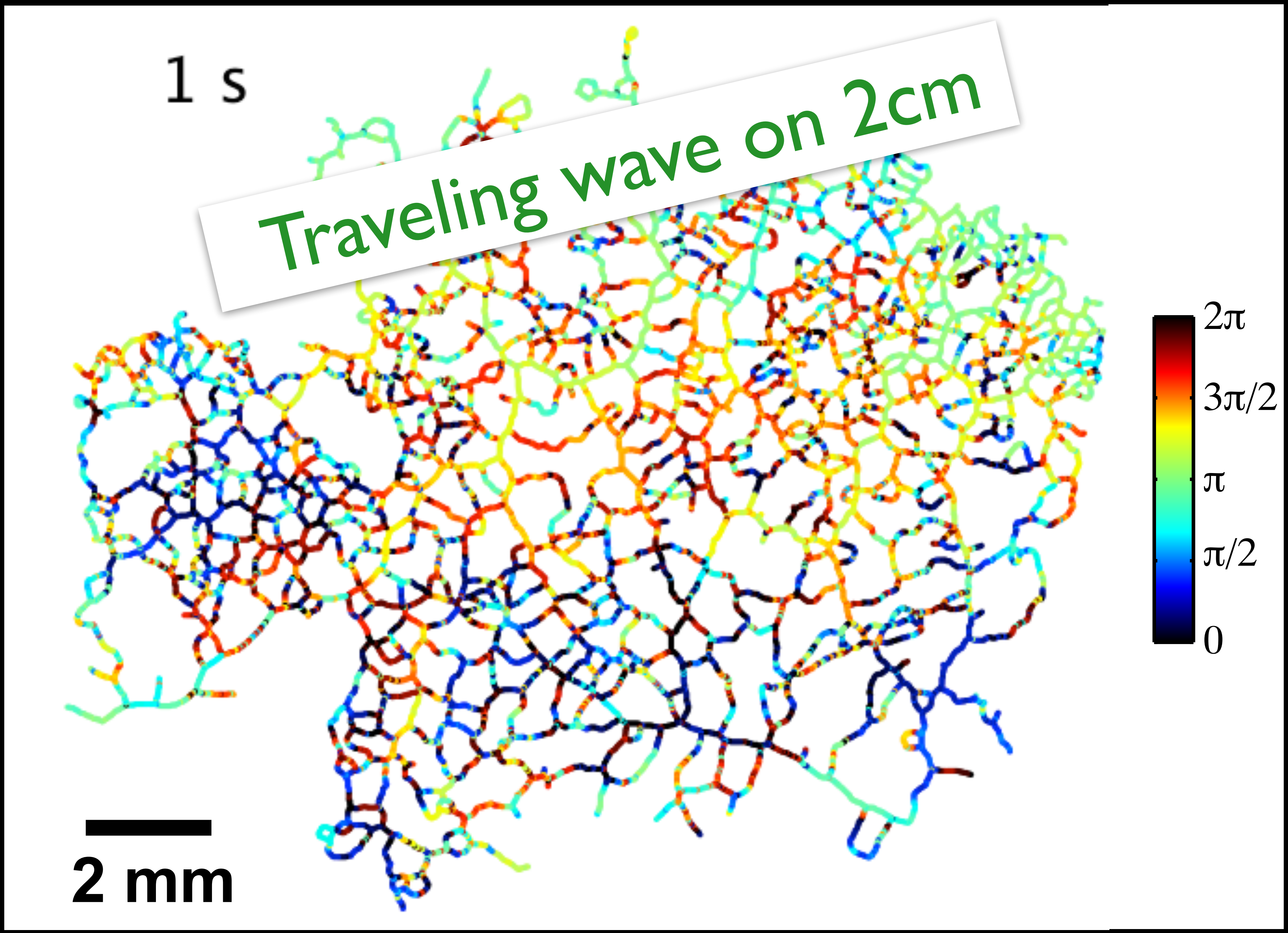
Contraction wavelength scales with network size



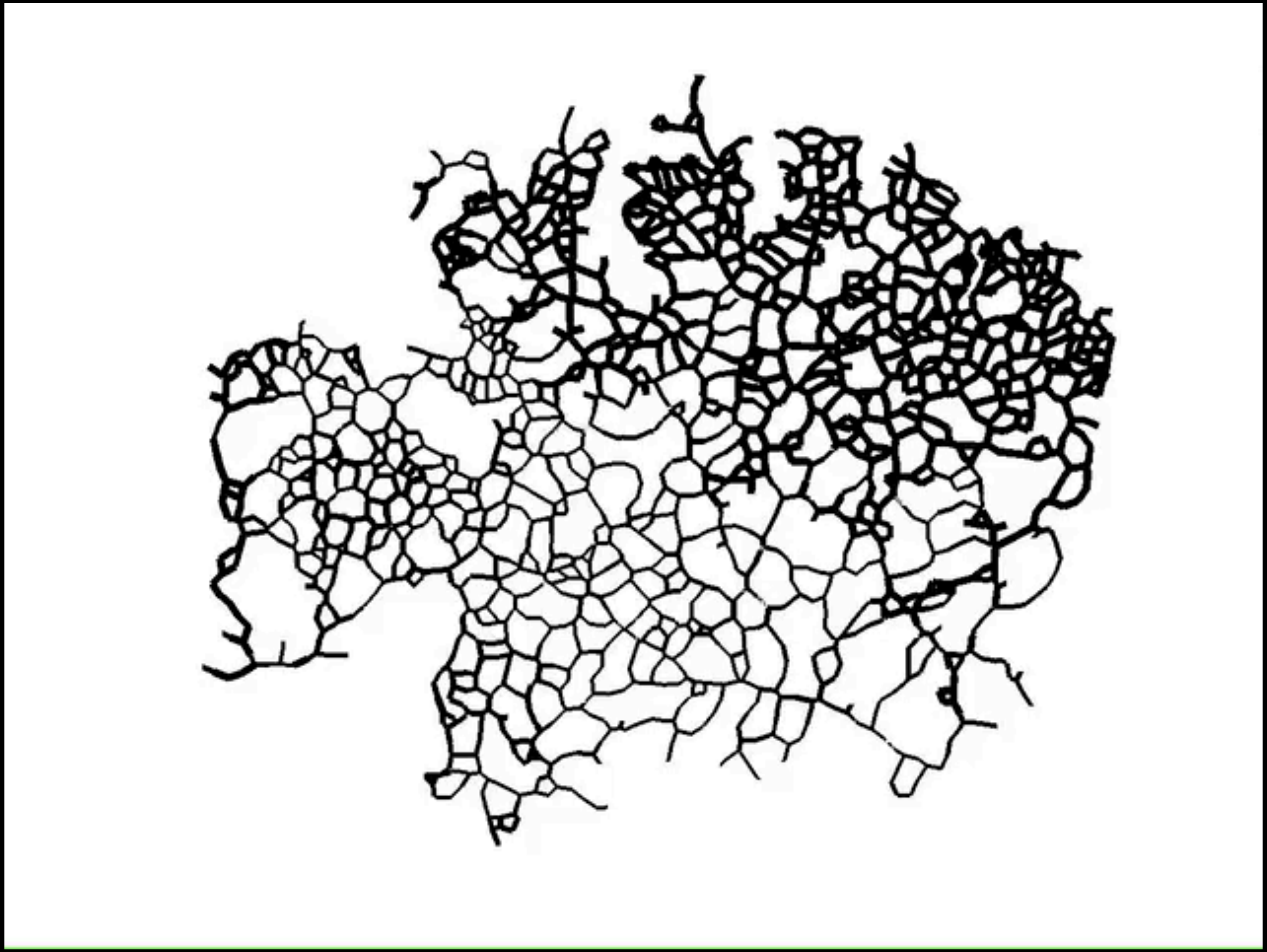
Alim et al. PNAS (2012)

Contraction wavelength scales with network size



Alim et al. PNAS (2012)

Peristaltic wave for efficient transport by Taylor dispersion

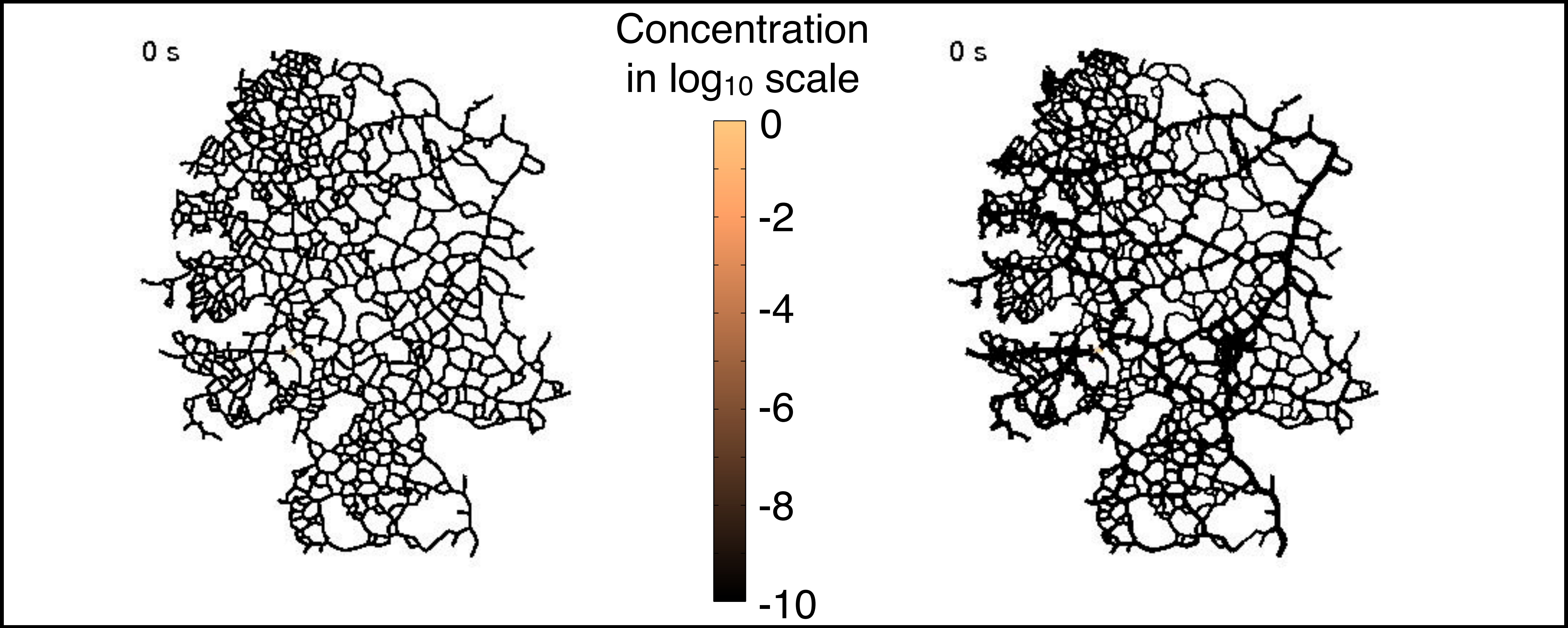


Simulation

Alim, Amselem, Peaudecerf, Brenner, Pringle PNAS (2013)

Tube radii are patterned to enhance transport

Sophie Marbach



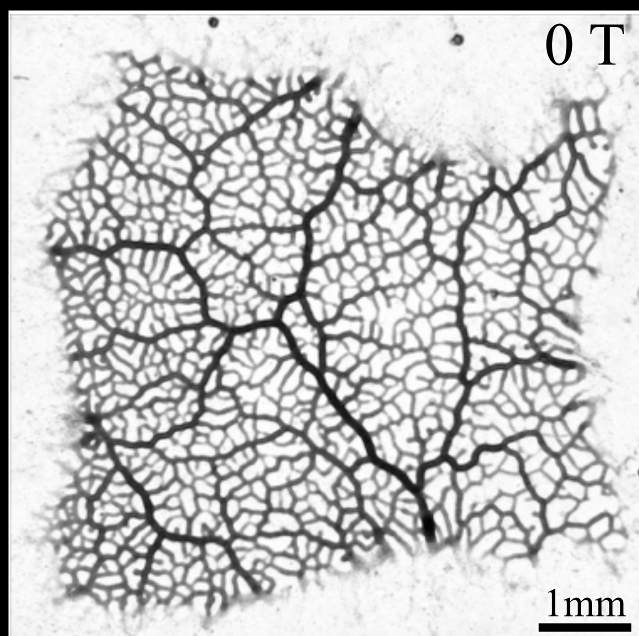
Uniform radii

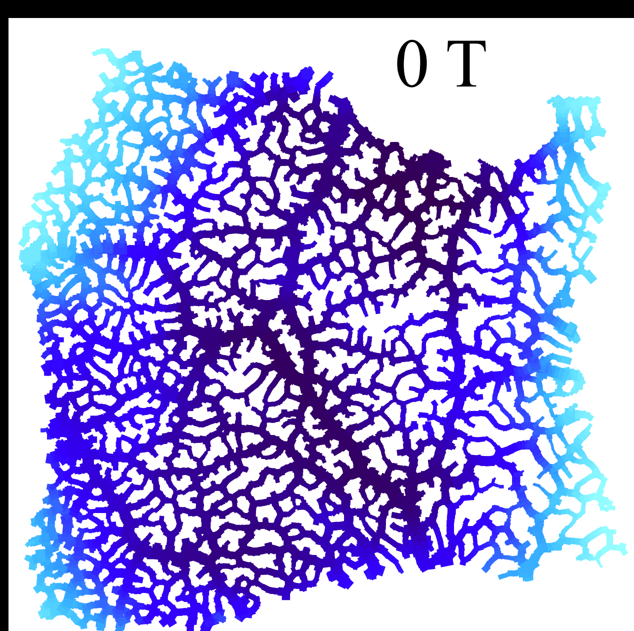
Measured radii

Simulation

Marbach, **Alim**, Andrew, Pringle, Brenner PRL (2016)

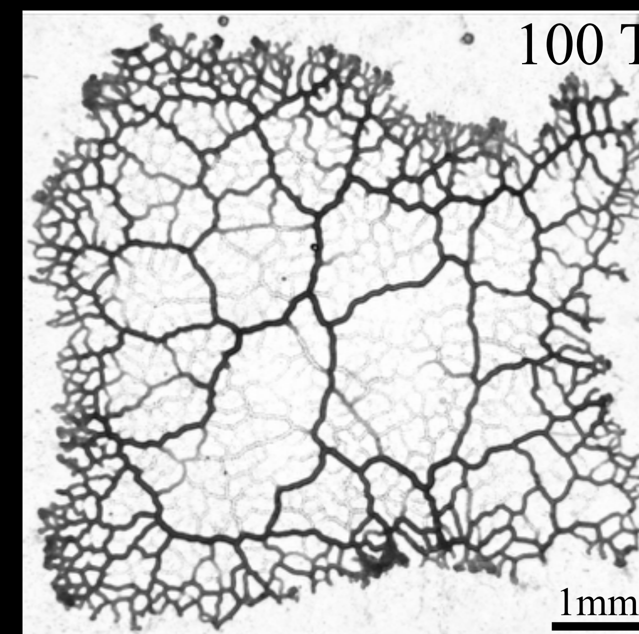
Pruning to increase Taylor dispersion

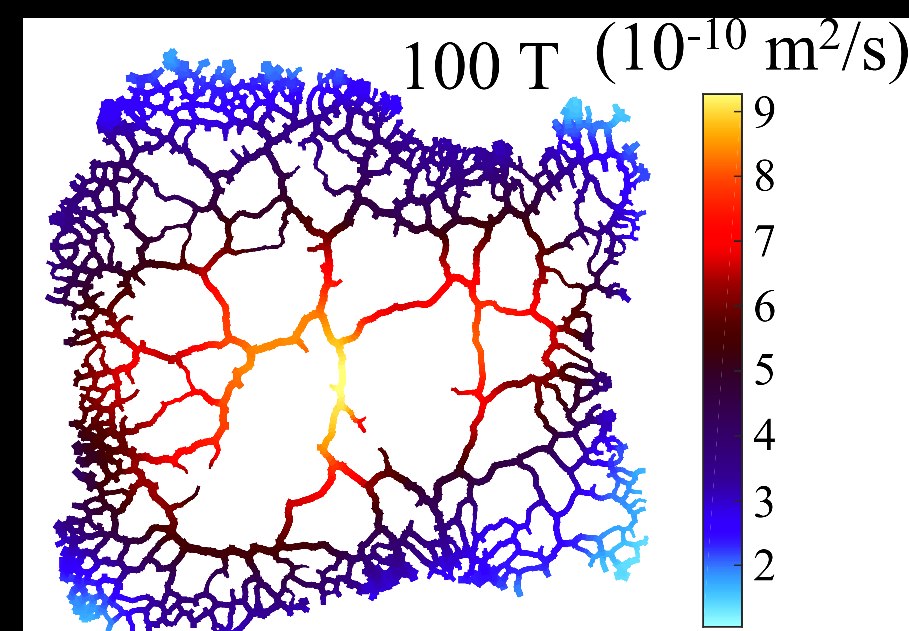




pruning in response to starvation

dispersion increases 40%



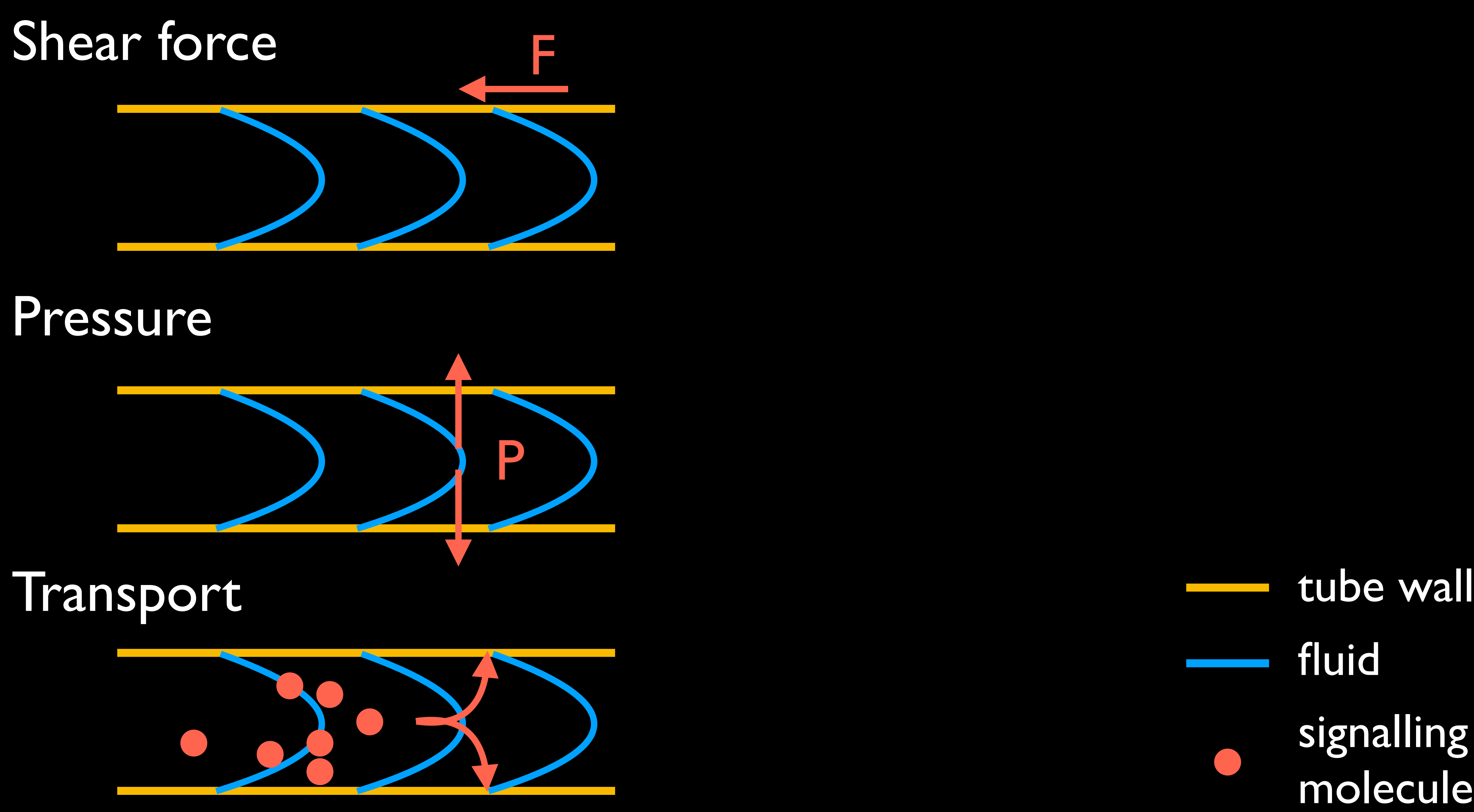


Data

Simulation

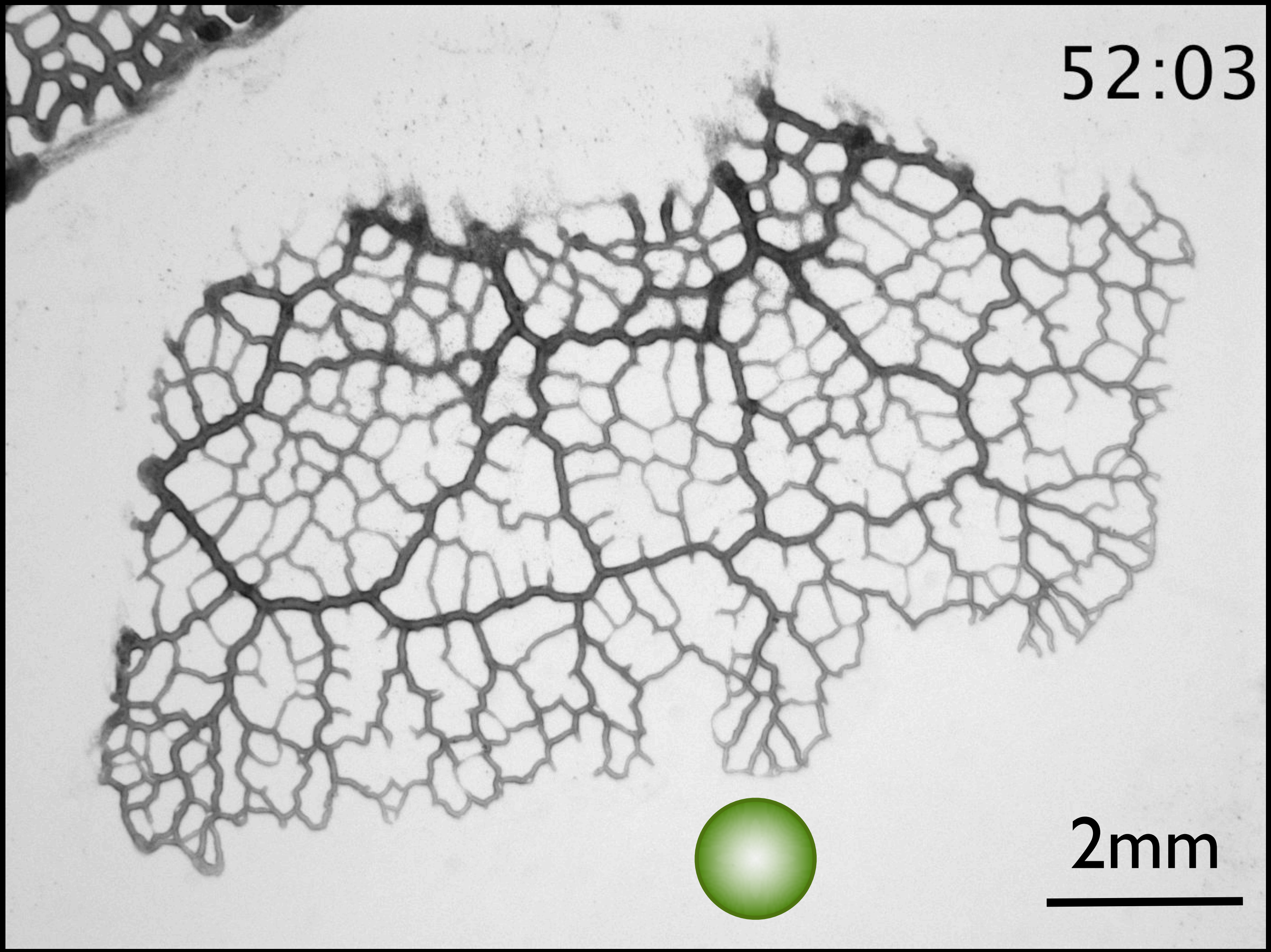
Marbach, **Alim**, Andrew, Pringle, Brenner PRL (2016)

Flows are information



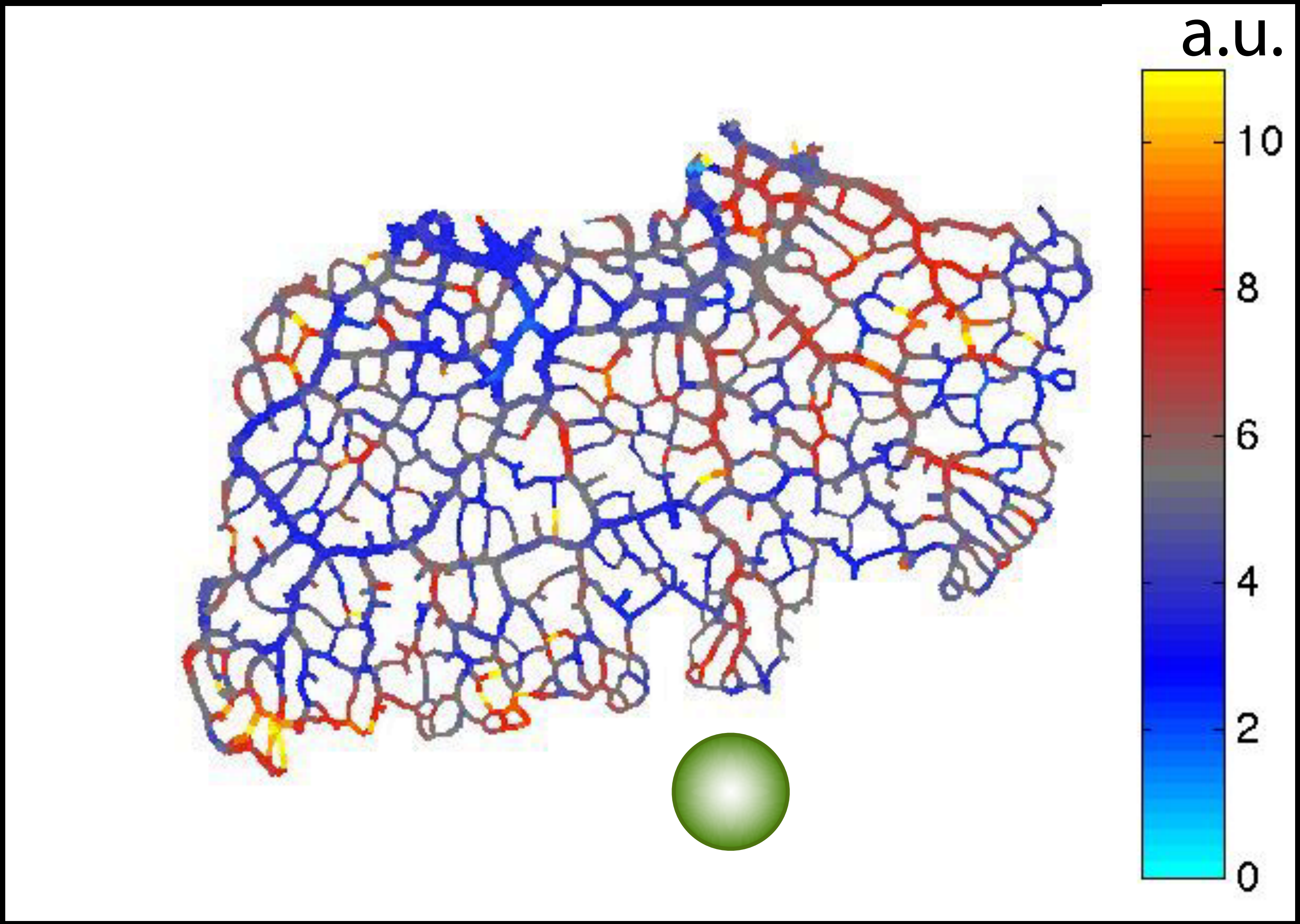
How does information propagate?

Natalie
Andrew



Alim, Andrew, Pringle, Brenner PNAS (2017)

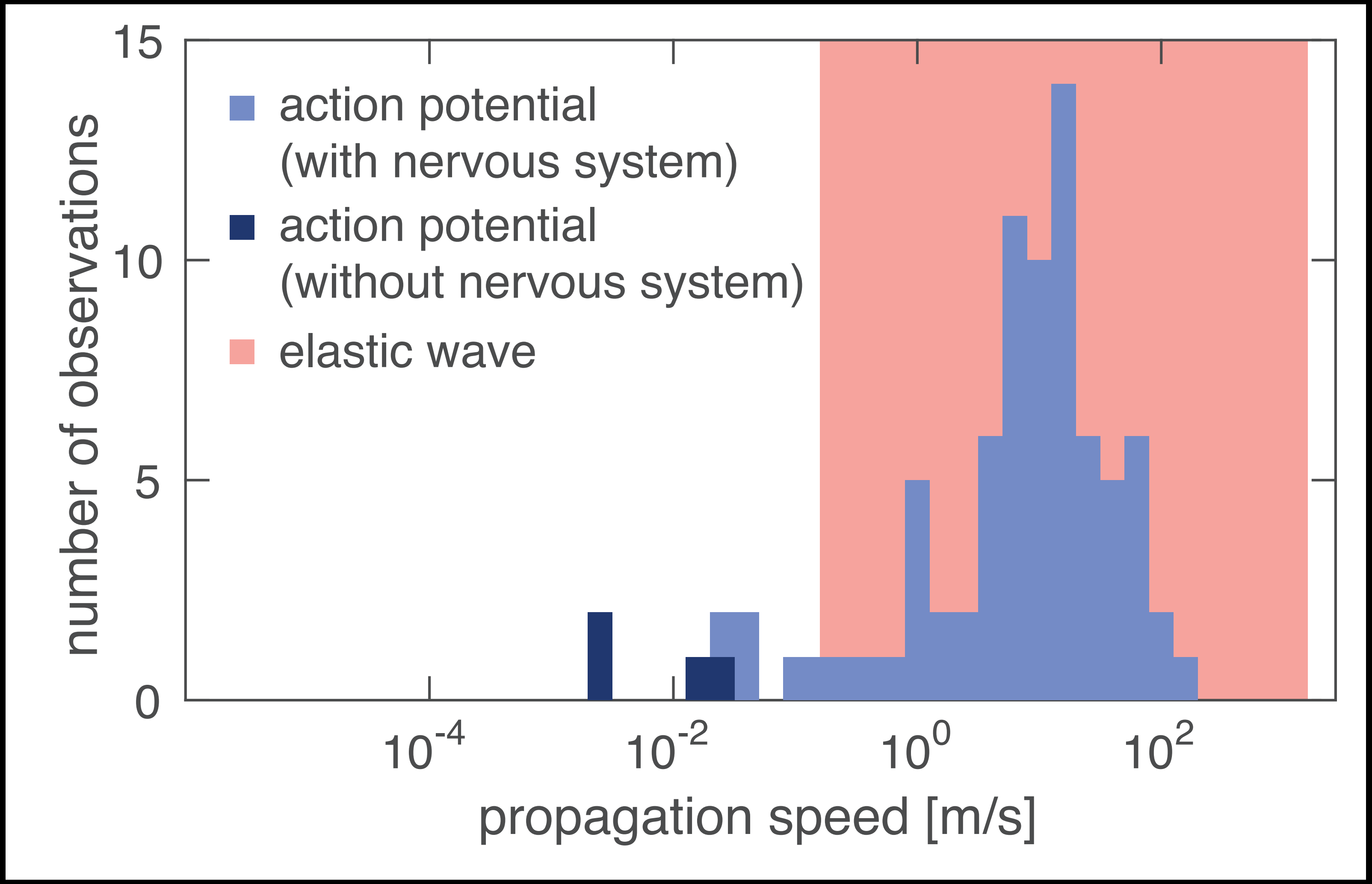
Stimulus spread marked by increase in amplitude



Alim, Andrew, Pringle, Brenner PNAS (2017)

Signal way slower than elastic wave or action pot.

comparison of propagation speed of possible mechanisms



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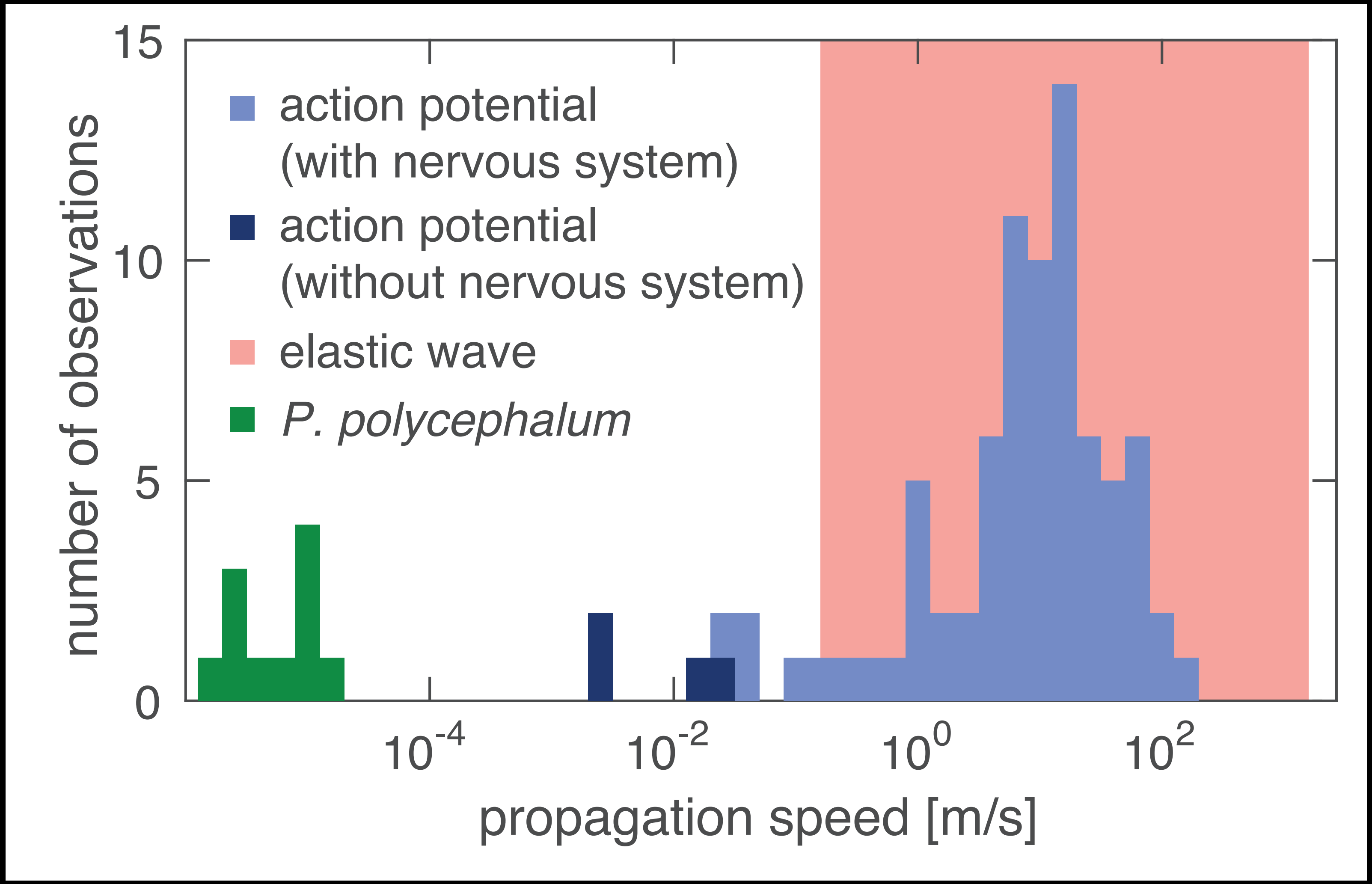

Alim, Andrew, Pringle, Brenner PNAS (2017)

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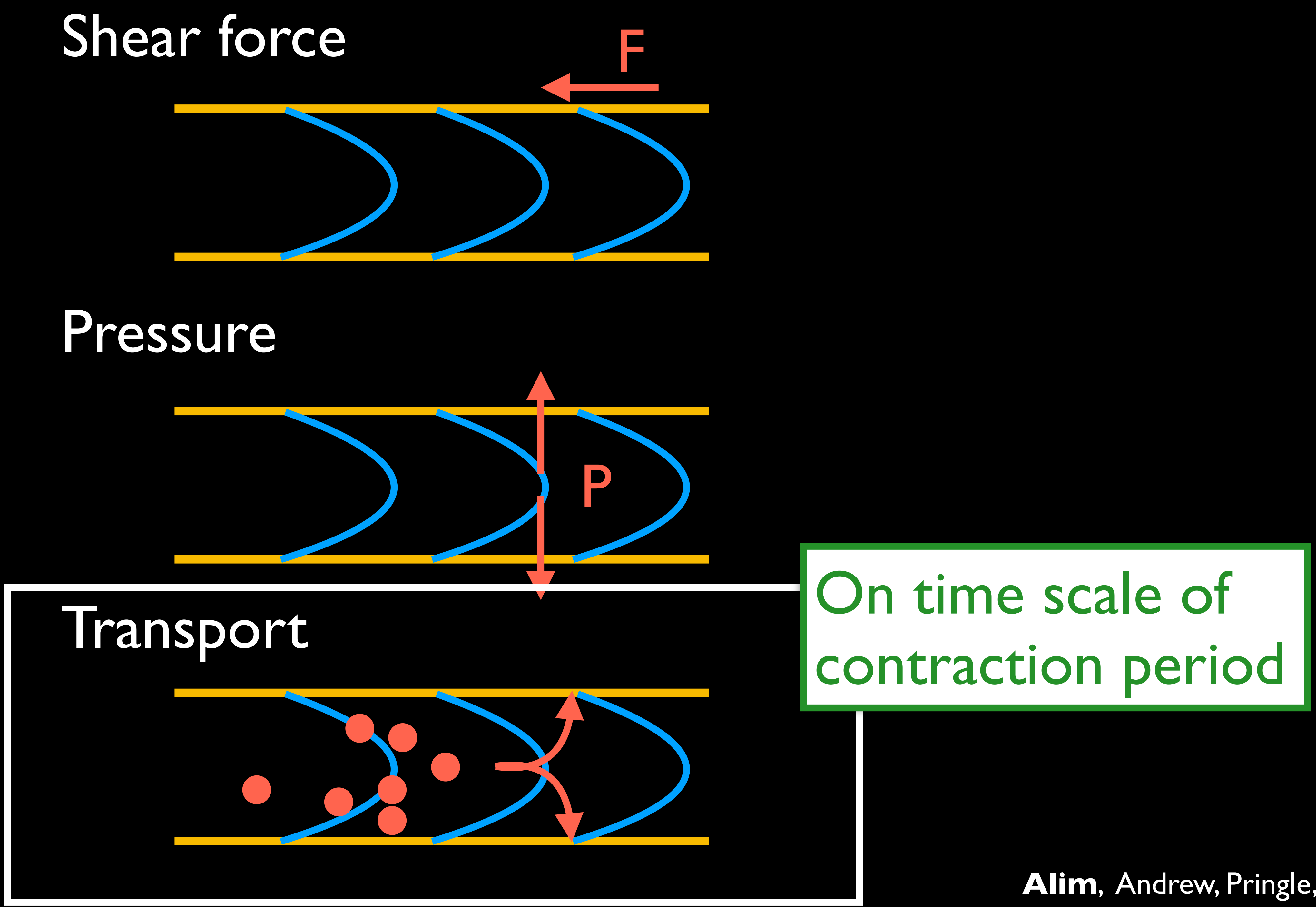
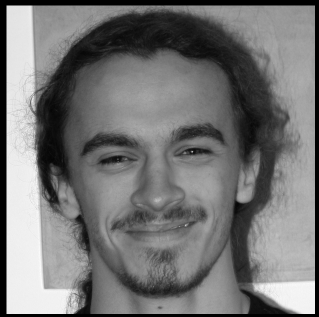


Alim, Andrew, Pringle, Brenner PNAS (2017)

Coupling contractions by transport of Calcium

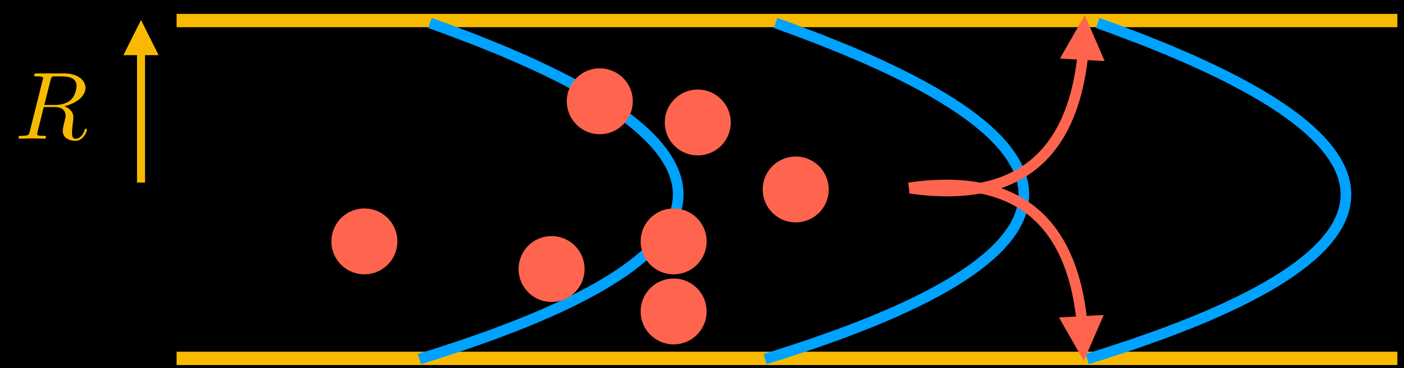


Jean-Daniel Julien

visco-elastic restoring stress σ_e

Calcium controlled contractile stress σ_C

stretch-activated Calcium inflow



Oster, Odell Cell Motil (1984)
Lee et al. Nature (1999)

Julien, **Alim**, PNAS (2018)

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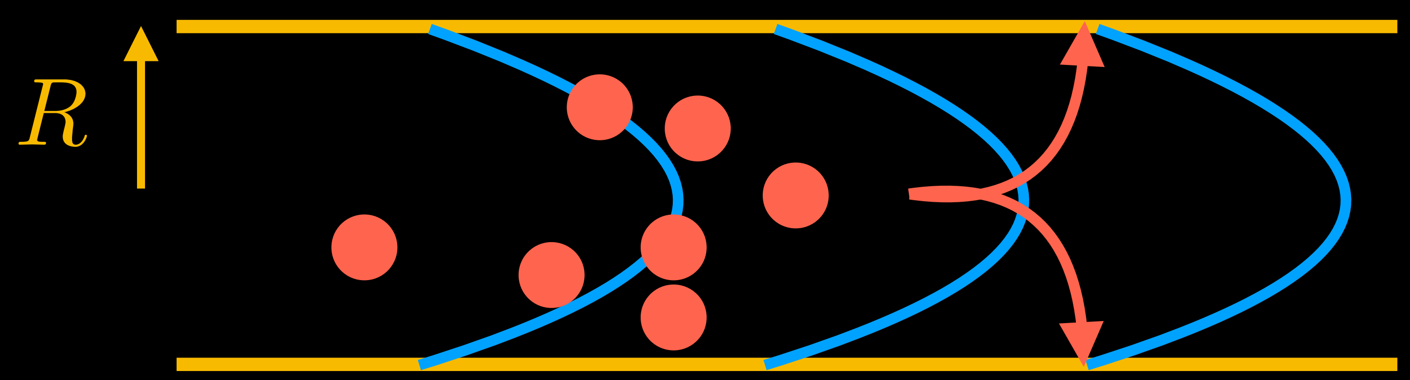

Oster, Odell Cell Motil (1984)
Lee et al. Nature (1999)

re-capture of Calcium drives relaxation

$$\frac{\partial C}{\partial t} = 2\pi R \left[p_c \left(1 + \frac{R - R^0}{\epsilon_c} \right) - d_c \frac{C}{\pi R^2} \right]$$

Julien, **Alim**, PNAS (2018)

Coupling contractions by transport of Calcium

visco-elastic restoring stress σ_e

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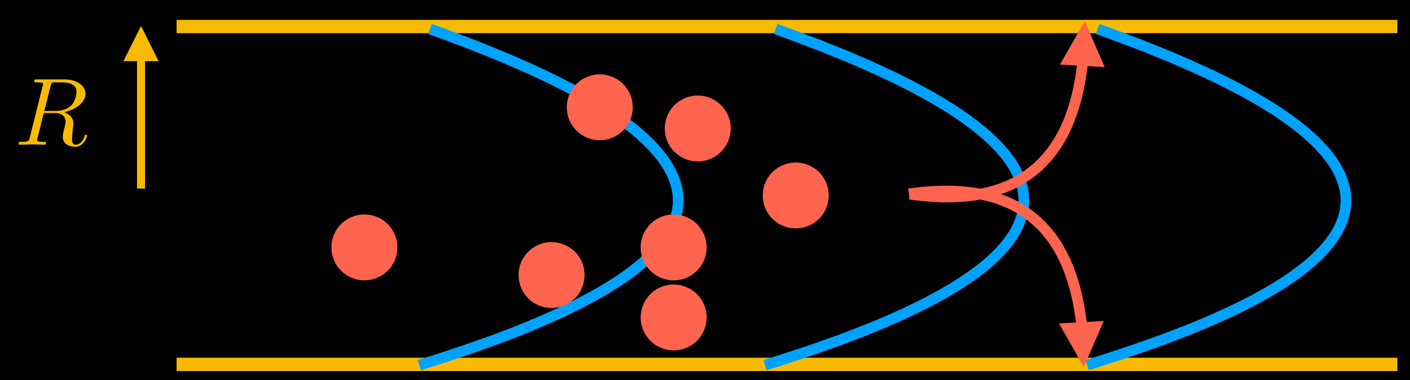

Oster, Odell Cell Motil (1984)
Lee et al. Nature (1999)

contractions drive fluid flow

$$\bar{u} = -\frac{R^2}{8\mu}\frac{\partial}{\partial z}\left(\sigma_e + \sigma_C\right)$$

$$\frac{\partial R^2}{\partial t} = -\frac{\partial}{\partial z}\left(R^2 \bar{u}\right)$$

Julien, **Alim**, PNAS (2018)

Coupling contractions by transport of Calcium

visco-elastic restoring stress σ_e

Calcium controlled contractile stress σ_C

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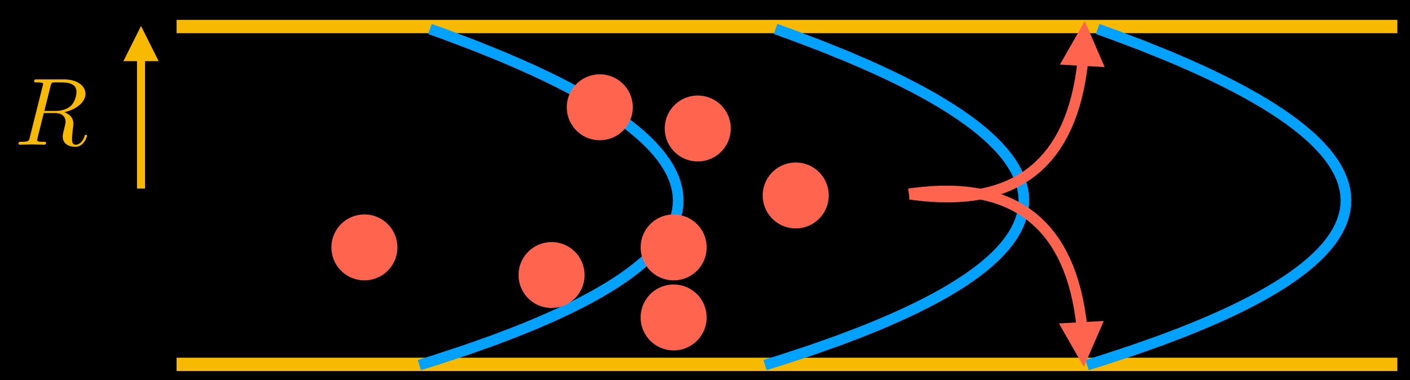


Oster, Odell Cell Motil (1984)
Lee et al. Nature (1999)

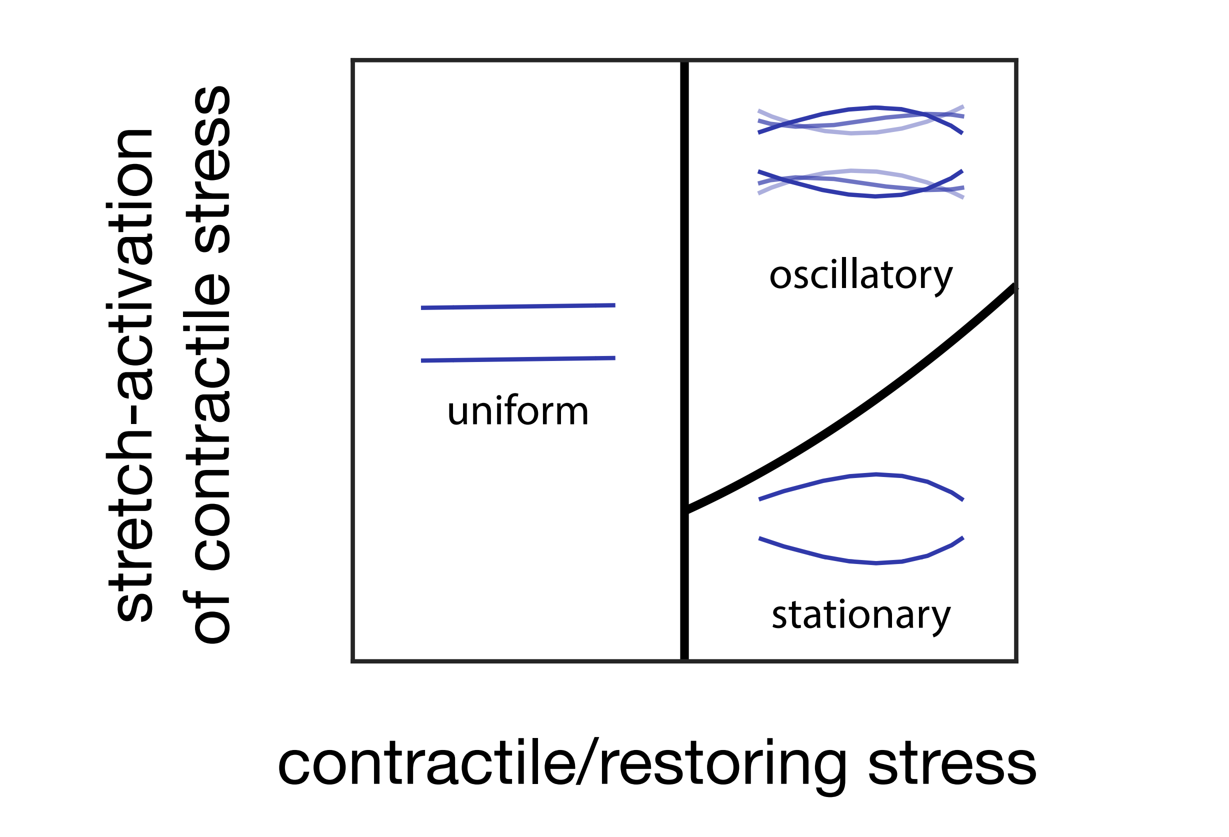
+ Transport of Calcium with flow

$$\frac{\partial C}{\partial t} = \ldots \qquad \frac{\partial R}{\partial t} = \ldots$$

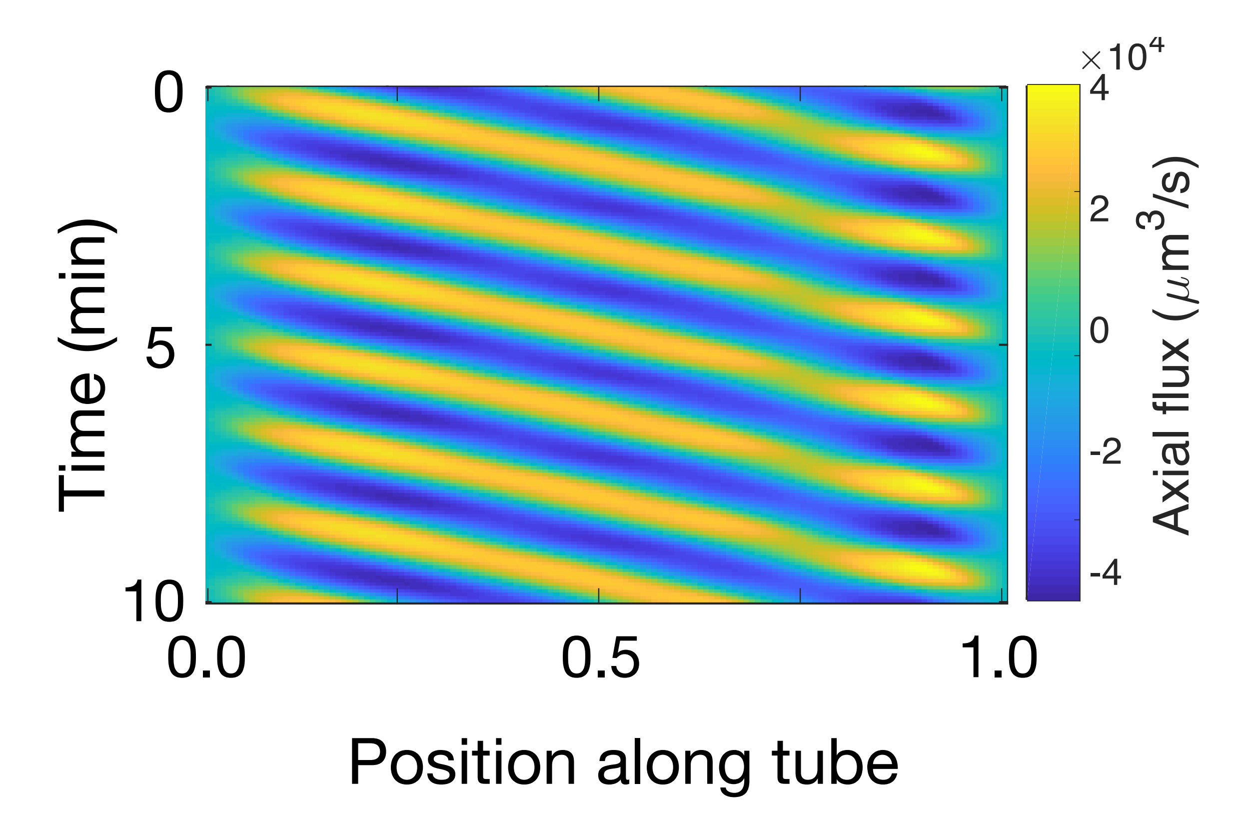
Julien, **Alim**, PNAS (2018)

Oscillations predicted in physical parameter regime

Phase diagram



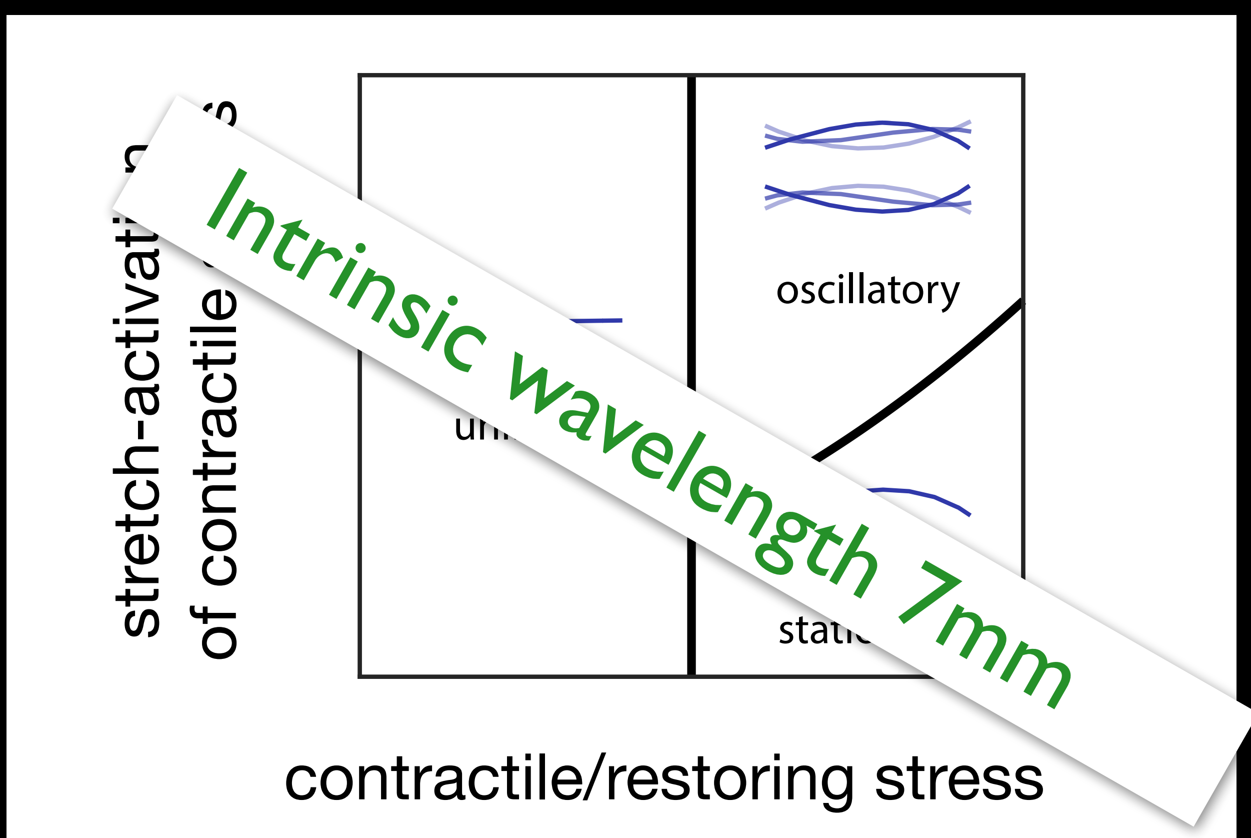
Traveling wave



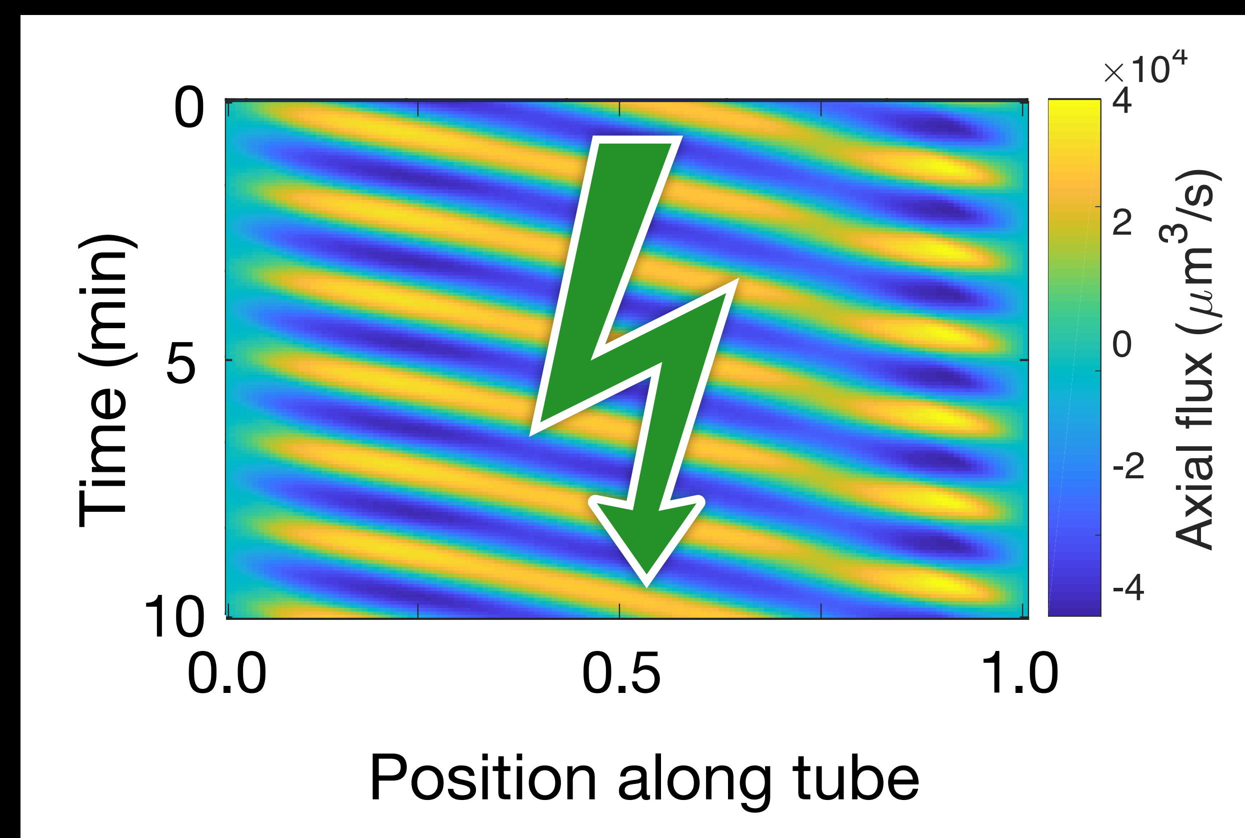
Julien, **Alim**, PNAS (2018)

Traveling wave predicted in physical parameter regime

Phase diagram



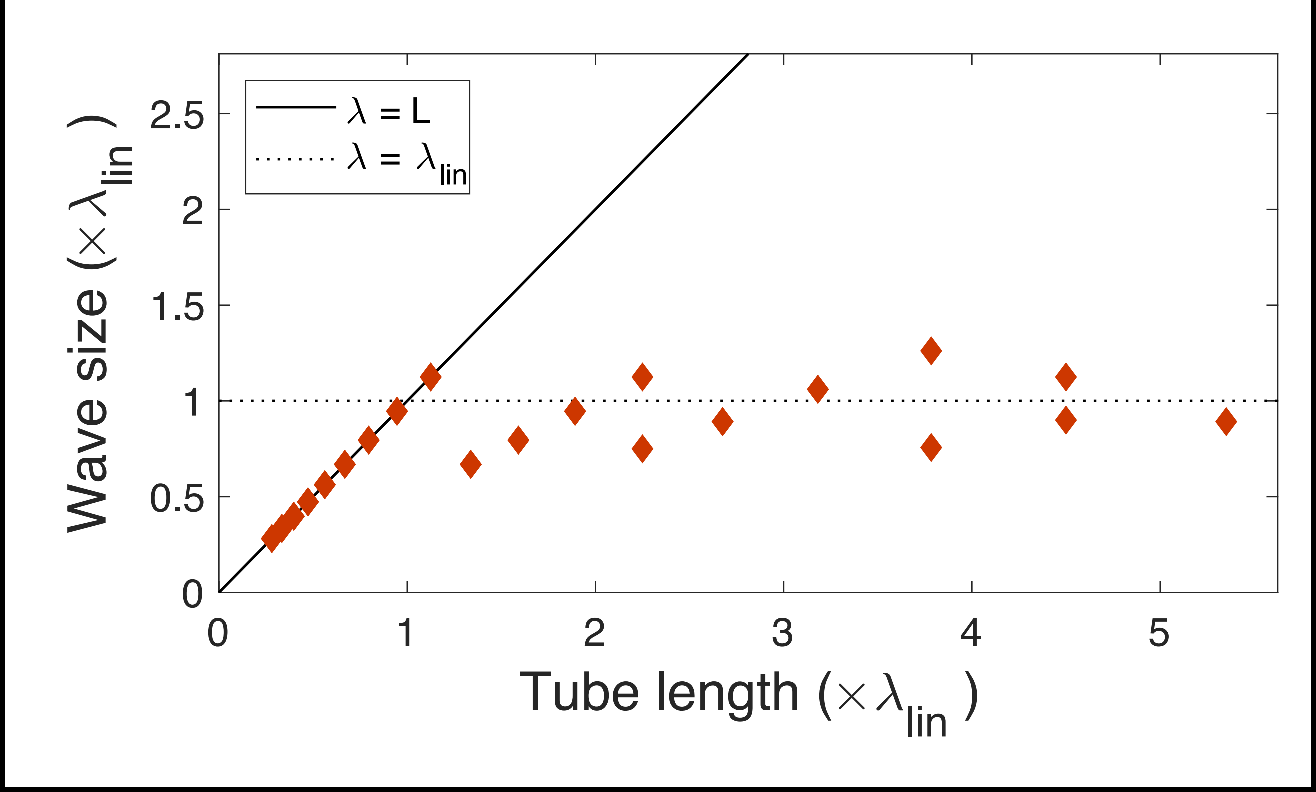
Traveling wave



Julien, **Alim**, PNAS (2018)

Traveling wave scales beyond intrinsic wavelength

Closed tube



Julien, **Alim**, PNAS (2018)

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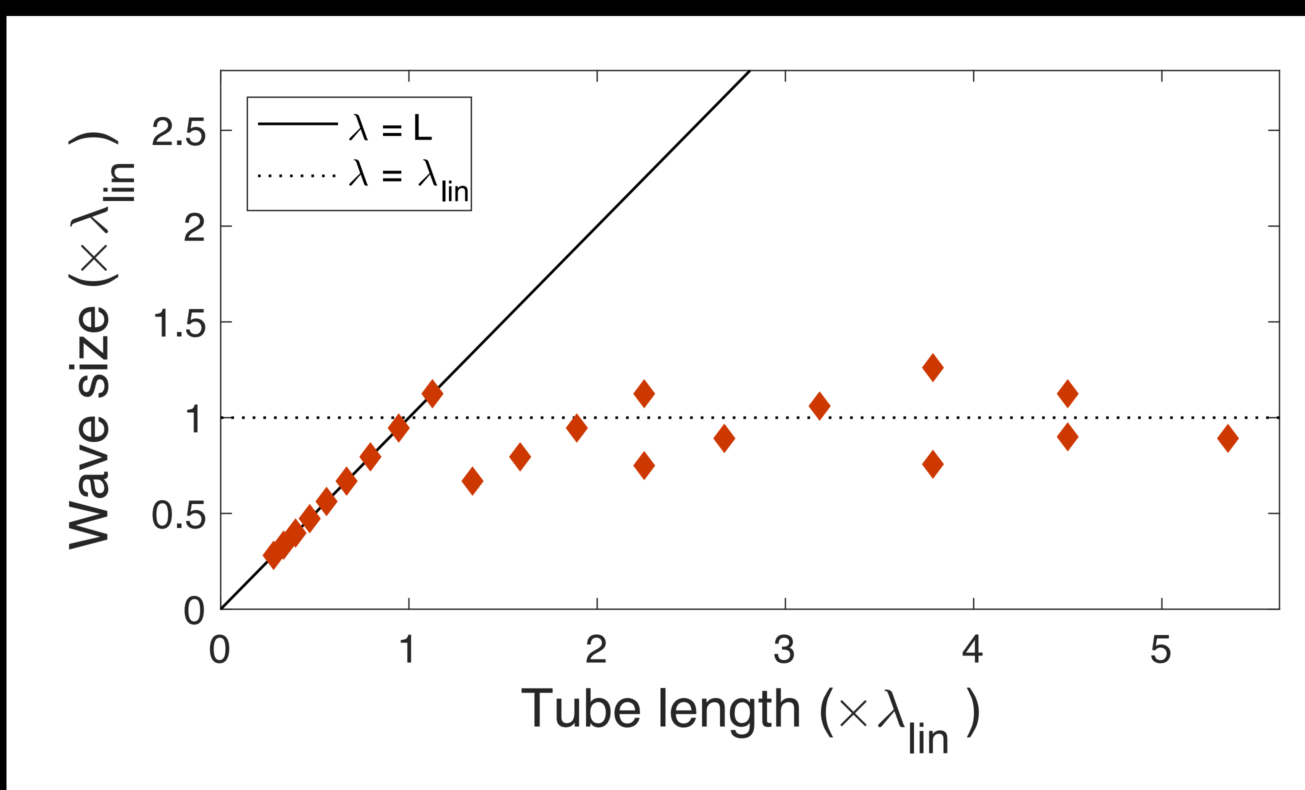
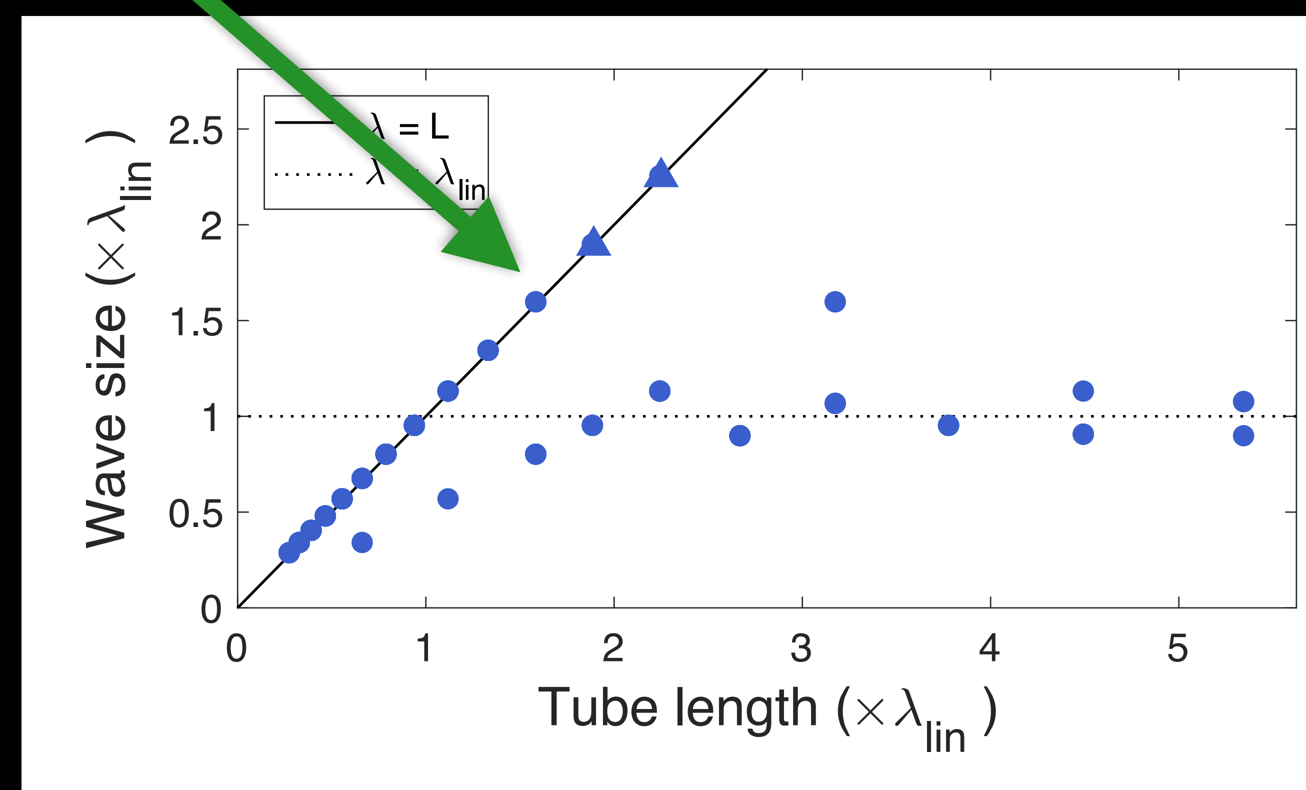


Scaling !

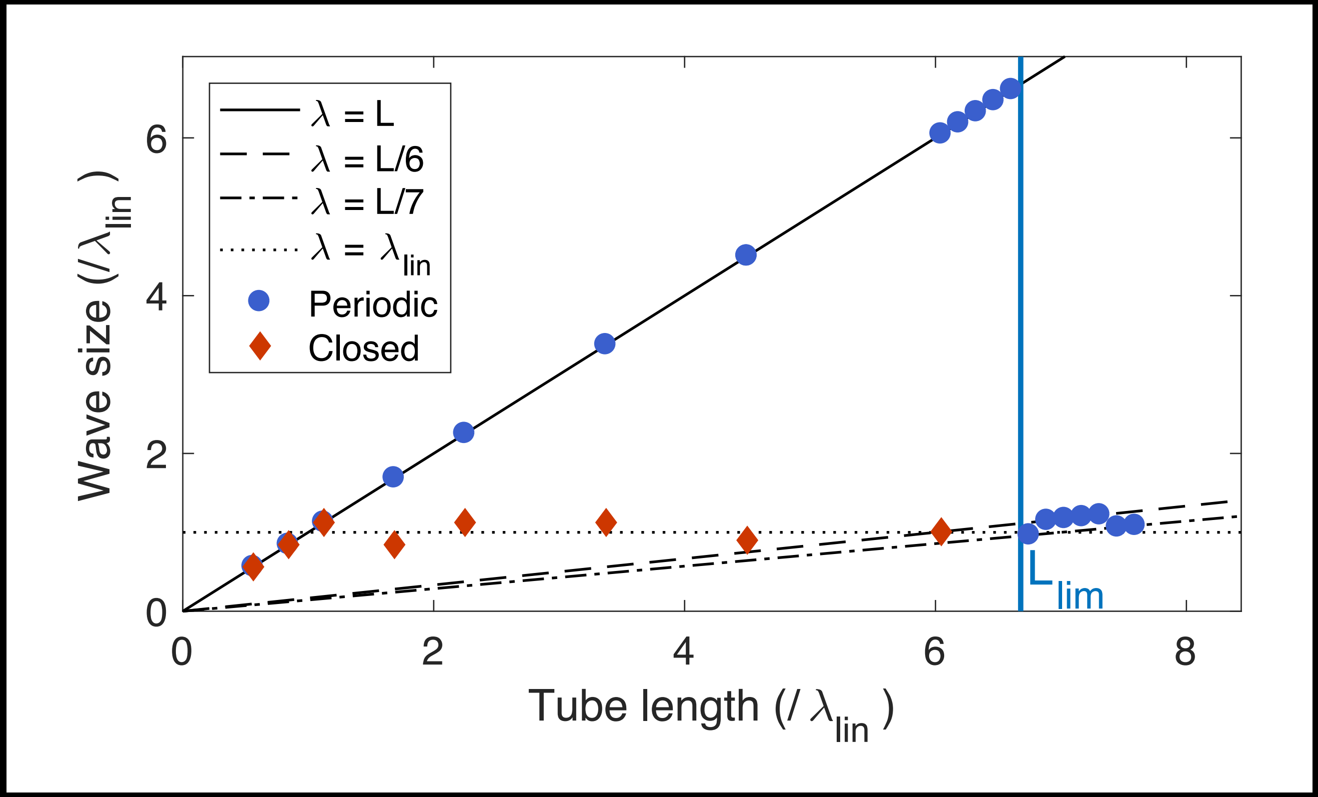
Looped tube



Julien, **Alim**, PNAS (2018)

Robust scaling in growing tubes

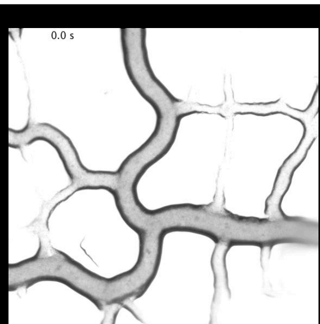
higher net flow - longer scaling



- Scaling up to 7x intrinsic wavelength
- Scaling limit now 4.7cm

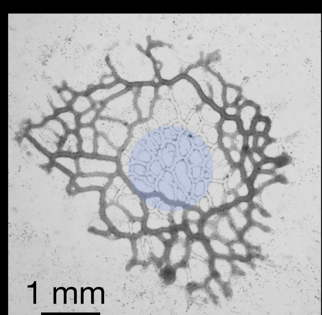
Julien, **Alim**, PNAS (2018)

Flow ⟲ Morphology

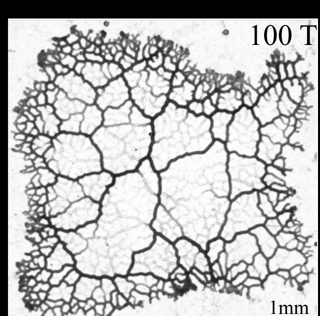


Flow control

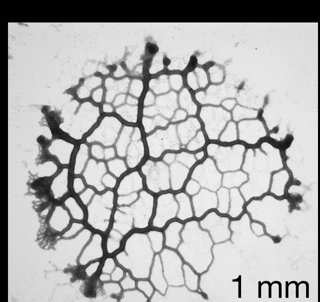
- Flows scale with network size
- Long-ranged coordination via transport



Adaptability

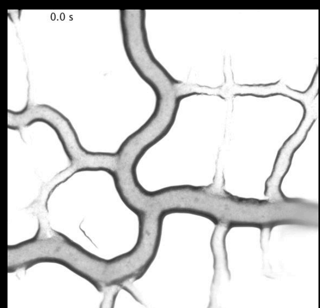


Topology



Hierarchy

Flow ⟲ Morphology



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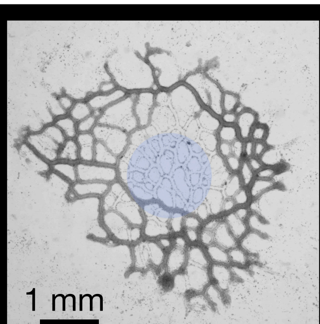

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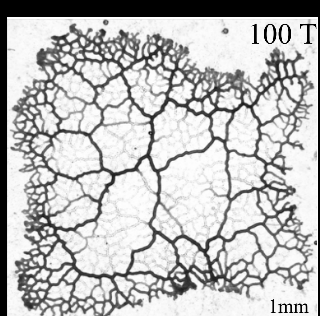

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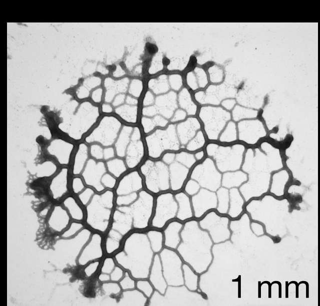
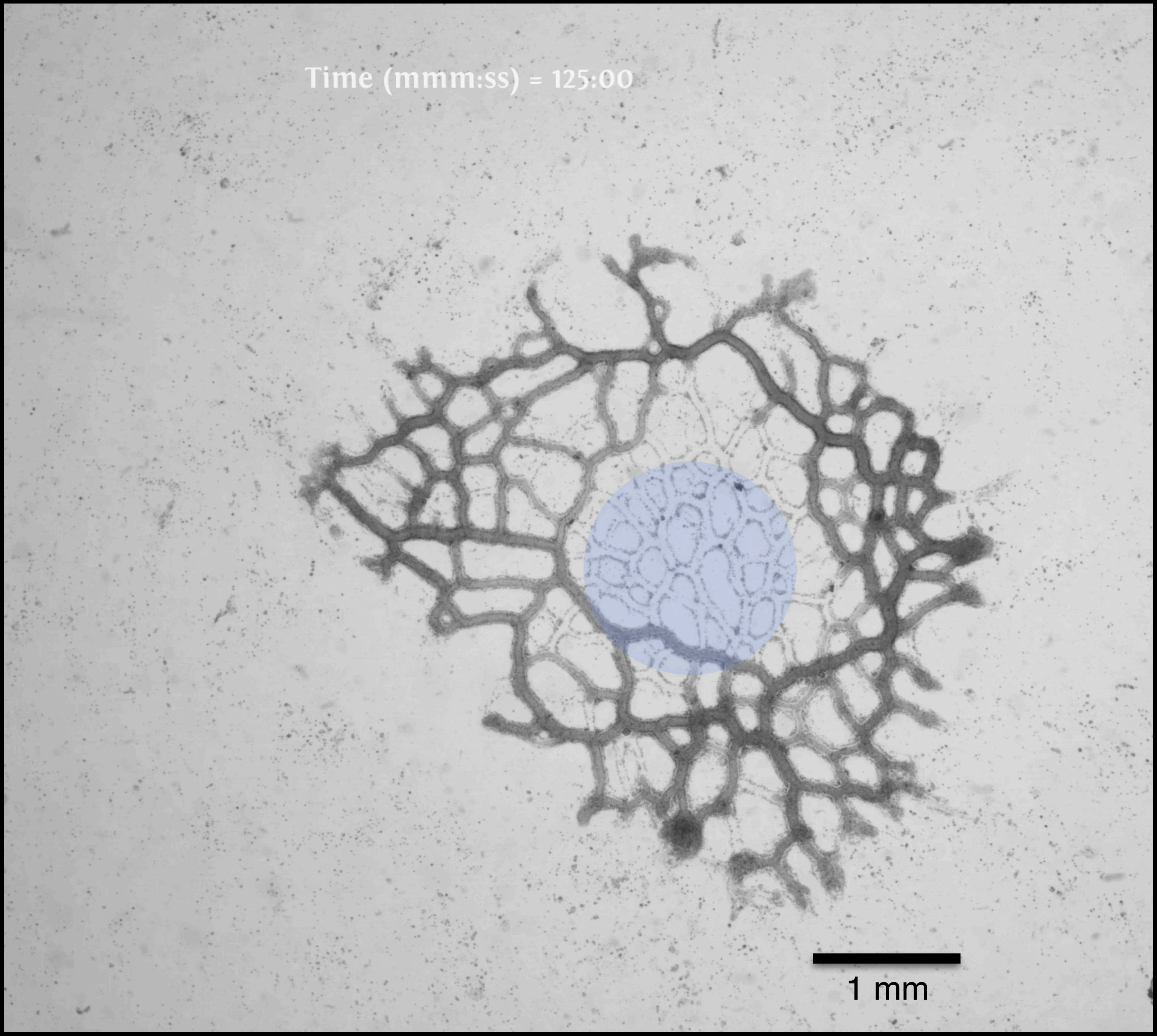


Hierarchy

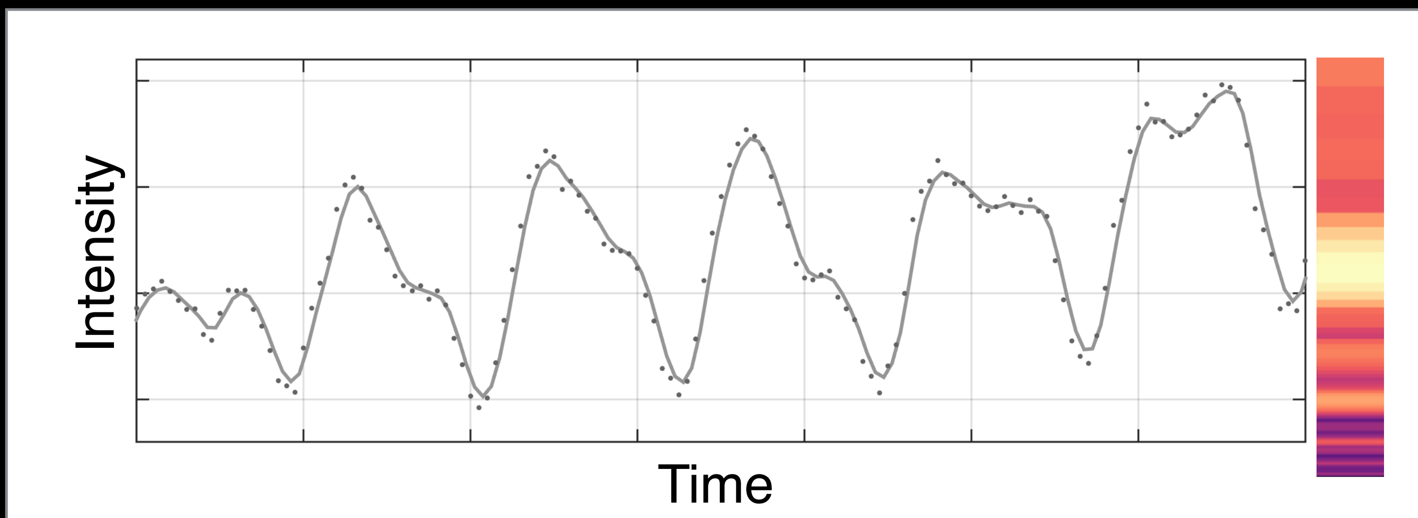
Light induces localized pruning

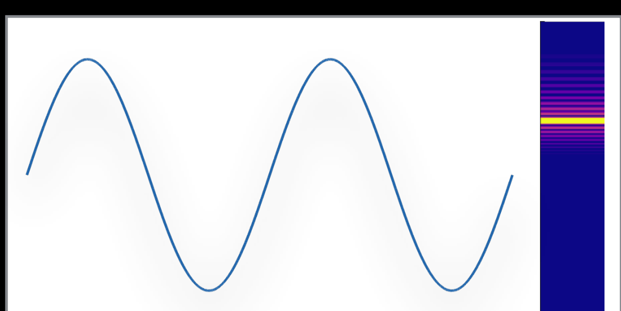
Felix Bäuerle

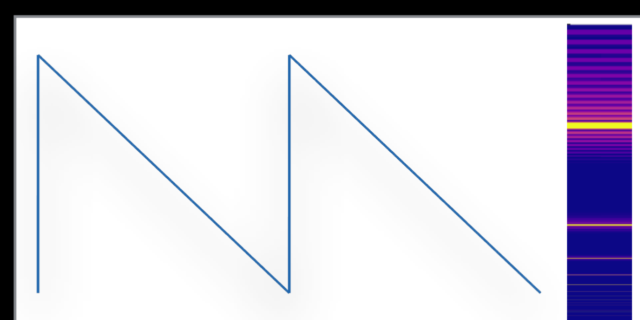


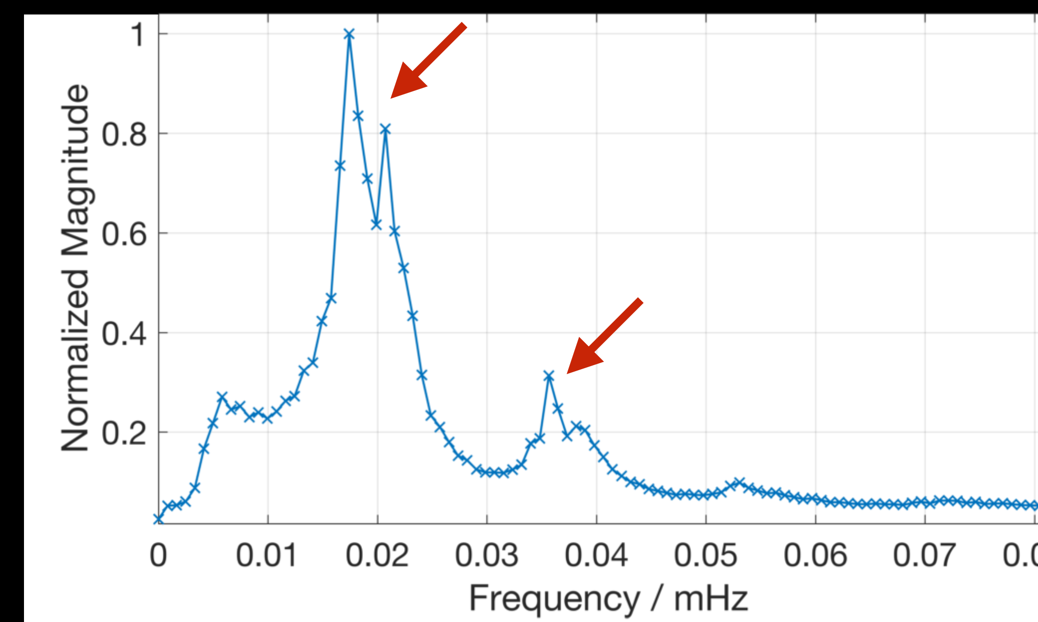
Bäuerle, **Alim**, submitted (2019)

Can overtone change transport?









- Waveform known to adapt under stimuli, but function is missing

Baranowski Z., et al. Cell Biol. Int. Repts.(1982)

Mori et al. Protoplasma (1986)

Dominant wave and one overtone at work

Bäuerle, **Alim**, submitted (2019)

Phase between modes changes tube occlusion

Assume two periodic contraction waves around a baseline

$$H_1(\xi) = H_0 + A_1 \cos(2\pi\xi)$$
$$H_{1+2}(\xi, \vartheta) = H_0 + A_1 \cos(2\pi\xi) + A_2 \cos(4\pi\xi + \vartheta)$$

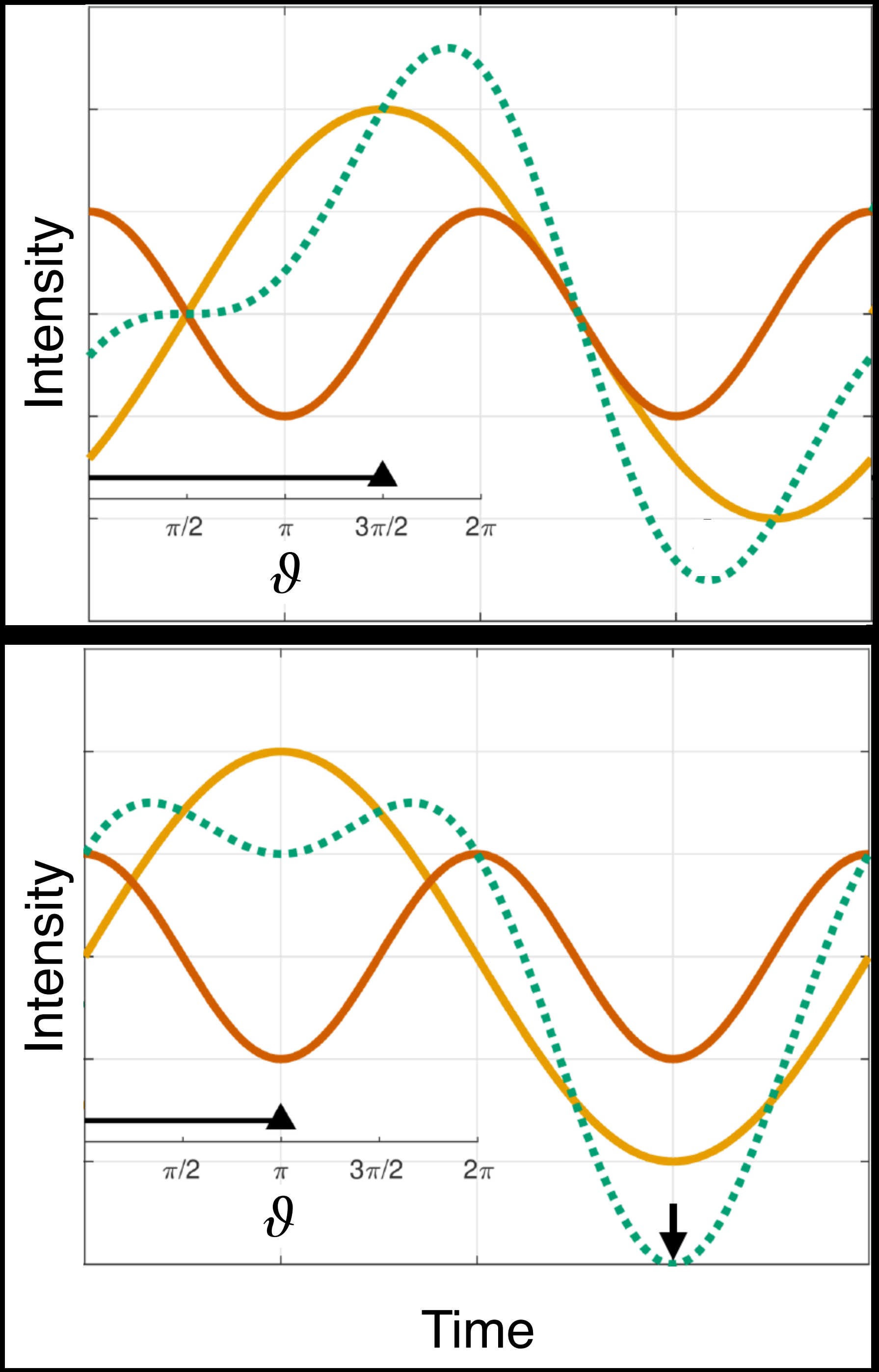
$$\xi = x/L - t/T$$

Deformation energy

$$U_{el}(H) = \frac{E}{2} \int \left(\frac{H - H_0}{H_0} \right)^2 dA$$

Assume equal energy for both waves

$$U_{el}(H_1) = U_{el}(H_{1+2}) \qquad \Rightarrow A_2 = -\frac{3}{2}\frac{A_1^2}{H_0}\cos(\vartheta)$$



Bäuerle, **Alim**, submitted (2019)

Phase between modes changes increases flow 25% at no cost

Assume two periodic contraction waves around a baseline

$$H_1(\xi) = H_0 + A_1\cos(2\pi\xi)$$
$$H_{1+2}(\xi,\vartheta) = H_0 + A_1\cos(2\pi\xi) + A_2\cos(4\pi\xi+\vartheta)$$

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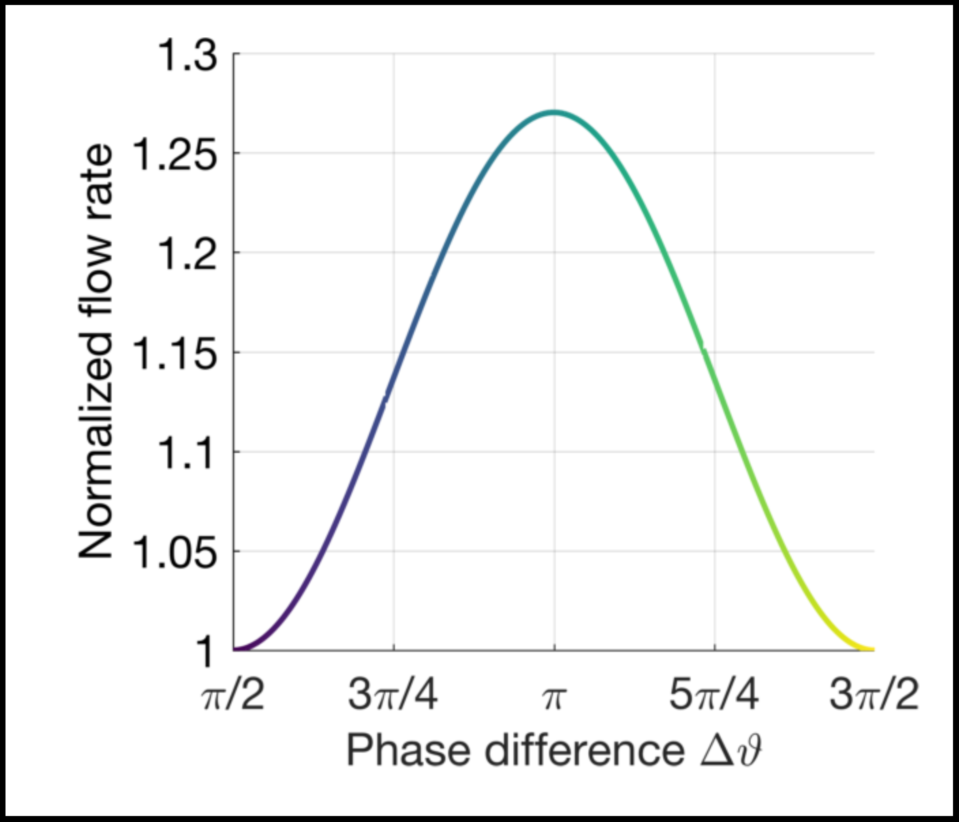
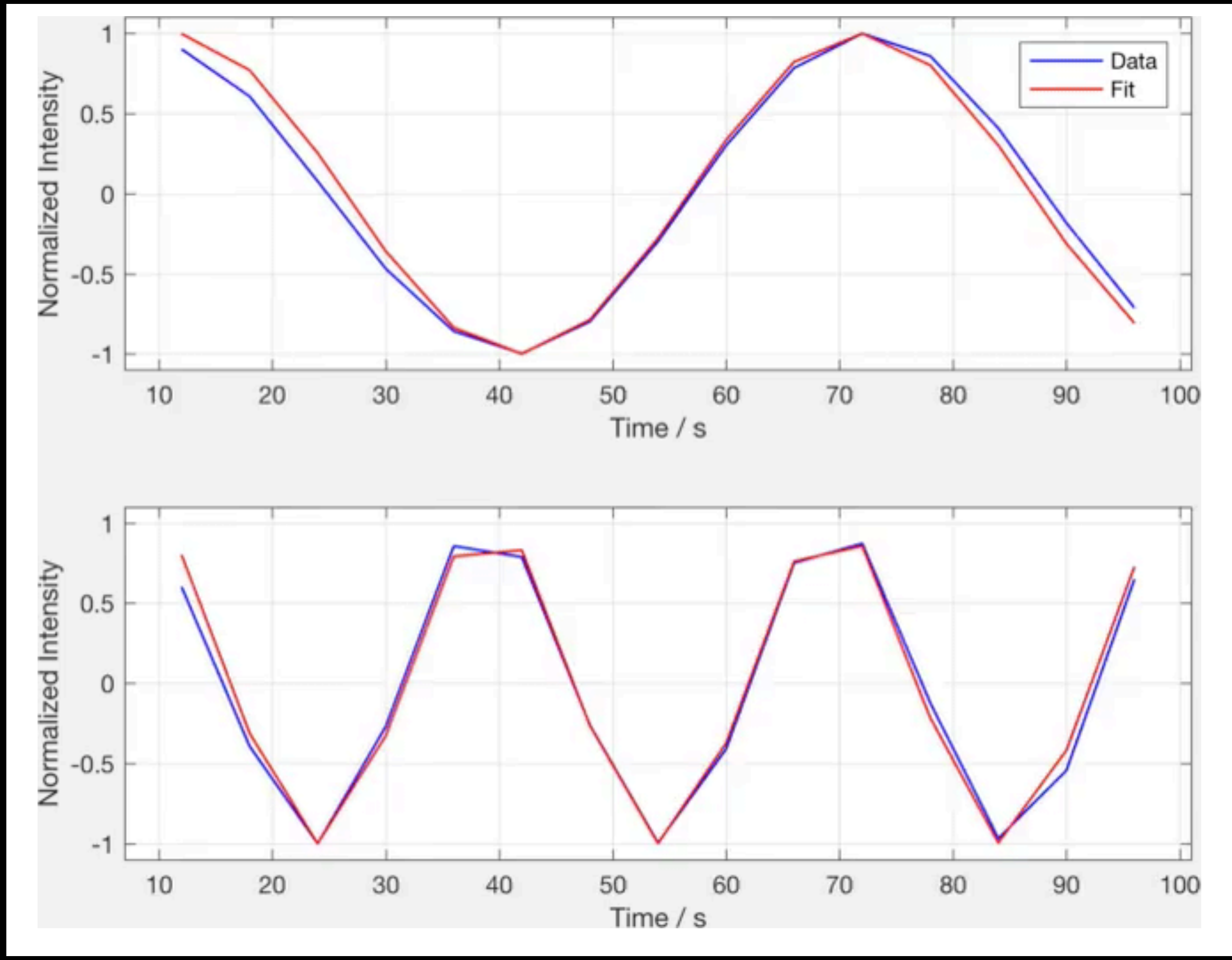


25% increase in flow at constant cost

Bäuerle, **Alim**, submitted (2019)

Quantifying phase shift in data

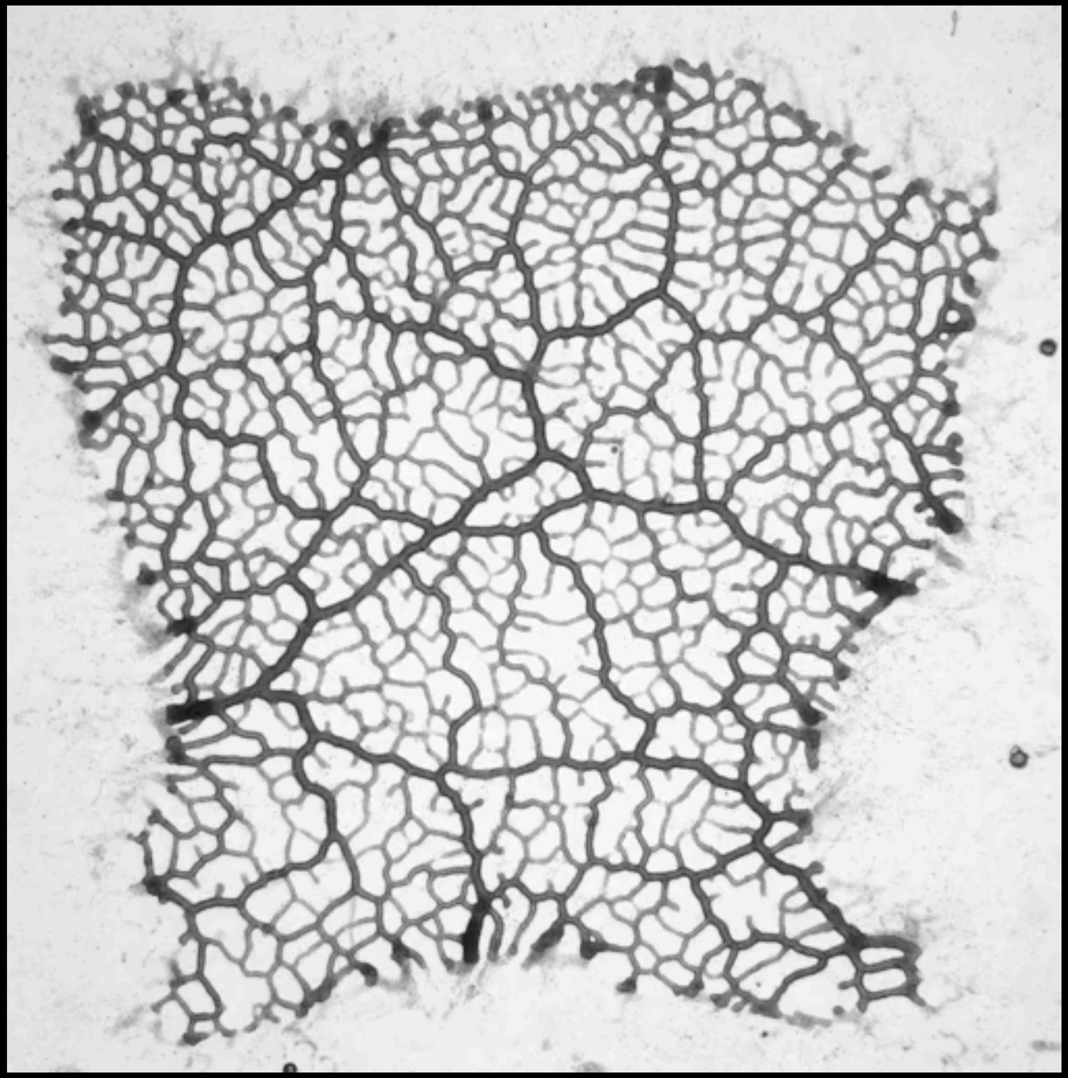
- Contraction wave as a discrete sample
- Filtering out the corresponding frequency bands
- Stepwise fitting of phase to the given waveform



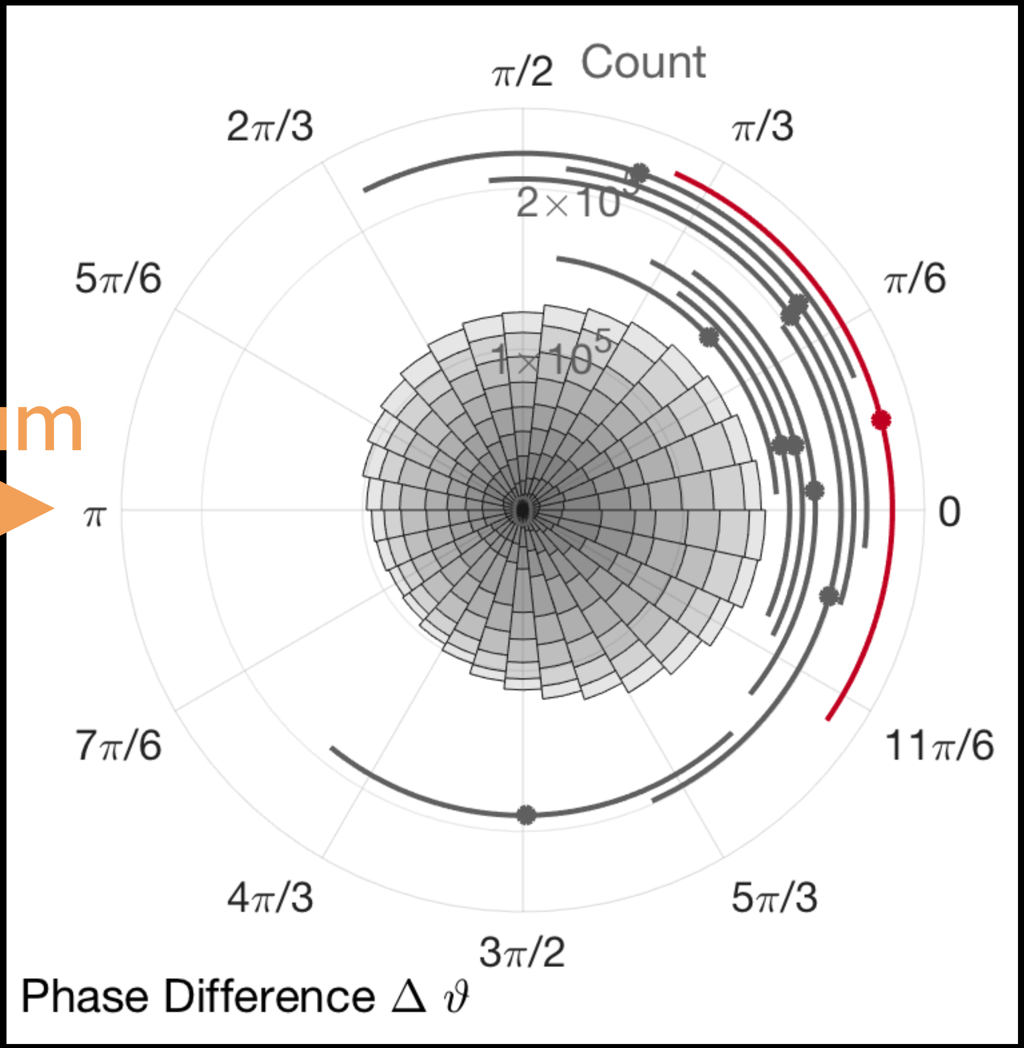
$\Rightarrow \Delta\vartheta$ in Physarum

Bäuerle, **Alim**, submitted (2019)

Non-optimal pumping without light stimulus



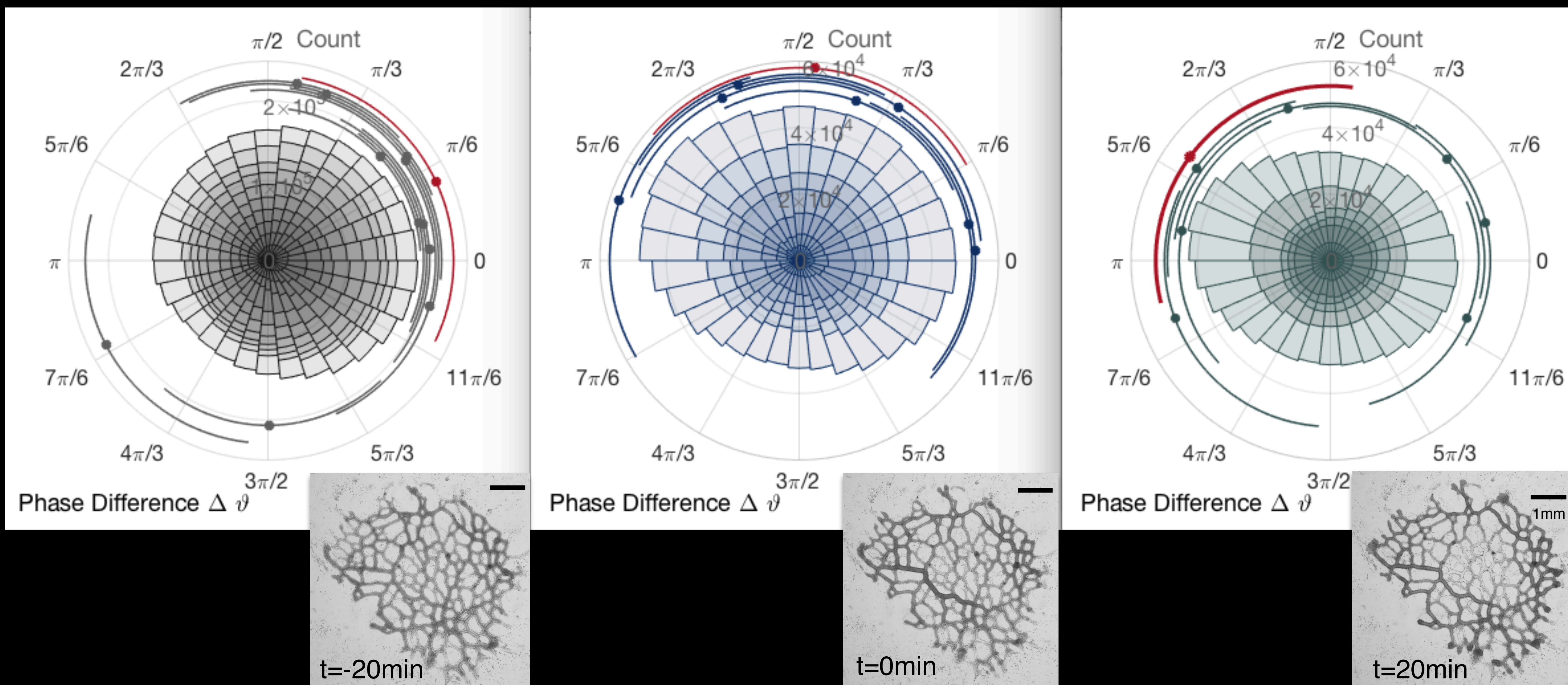
optimum



- non-optimal phase difference in line with forced elastic tube

Bäuerle, **Alim**, submitted (2019)

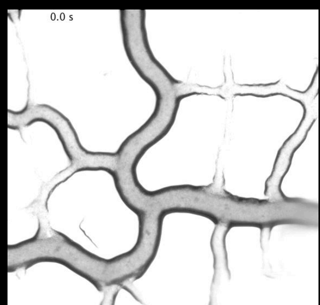
Phase-shift between modes drives optimal pumping



- Light might allow mechanically for stress-stiffening

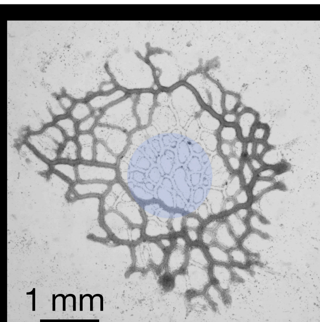
Bäuerle, **Alim**, submitted (2019)

Flow ⟲ Morphology



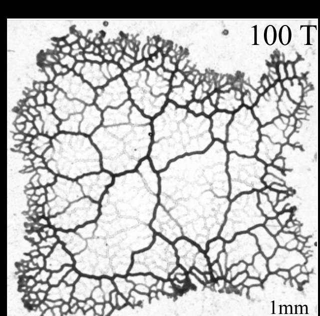
Flow control

- Flows scale with network size
- Long-ranged coordination via transport

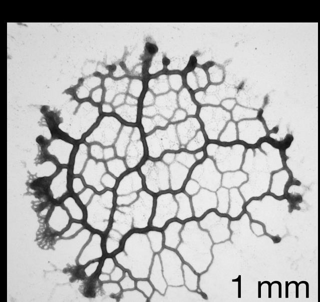


Adaptability

- Increase transport/flux/absorption

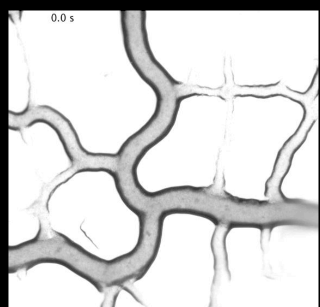


Topology



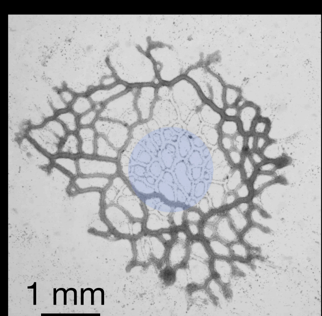
Hierarchy

Flow ⟲ Morphology



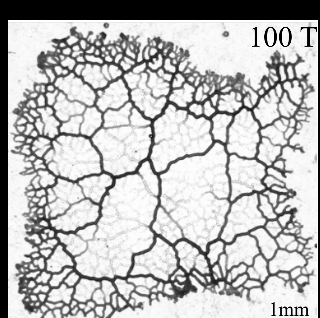
Flow control

- Flows scale with network size
- Long-ranged coordination via transport

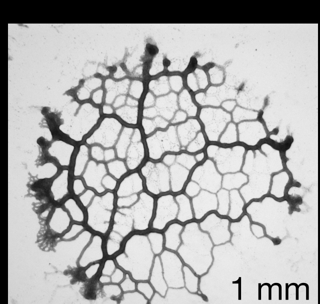


Adaptability

- Increase transport/flux/absorption
- Self-organised optimization

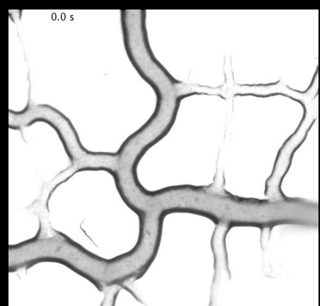


Topology



Hierarchy

Flow ⟲ Morphology



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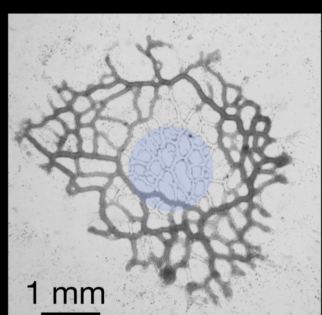

Adaptability

- Increase transport/flux/absorption
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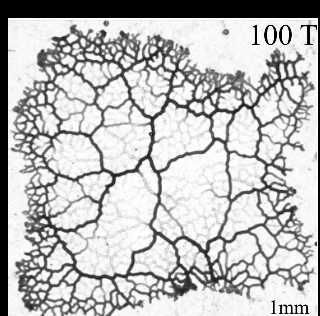
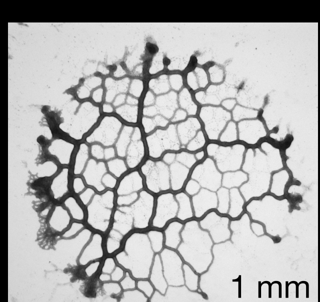


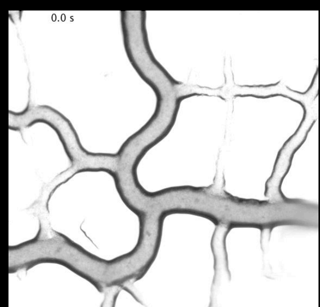
Topology

- Stabilize flow patterns
- Loops increase overall flow



Hierarchy

Flow ⟲ Morphology



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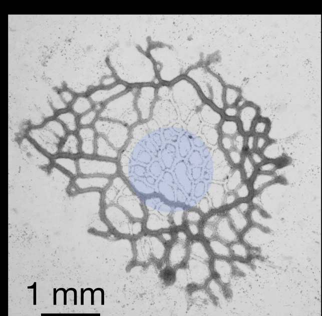

Adaptability

- Increase transport/flux/absorption
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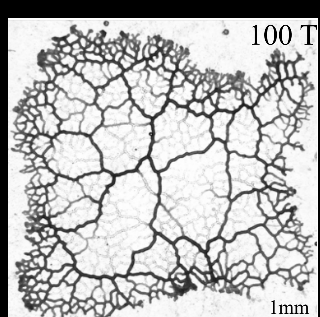

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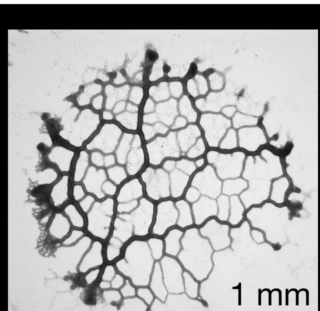
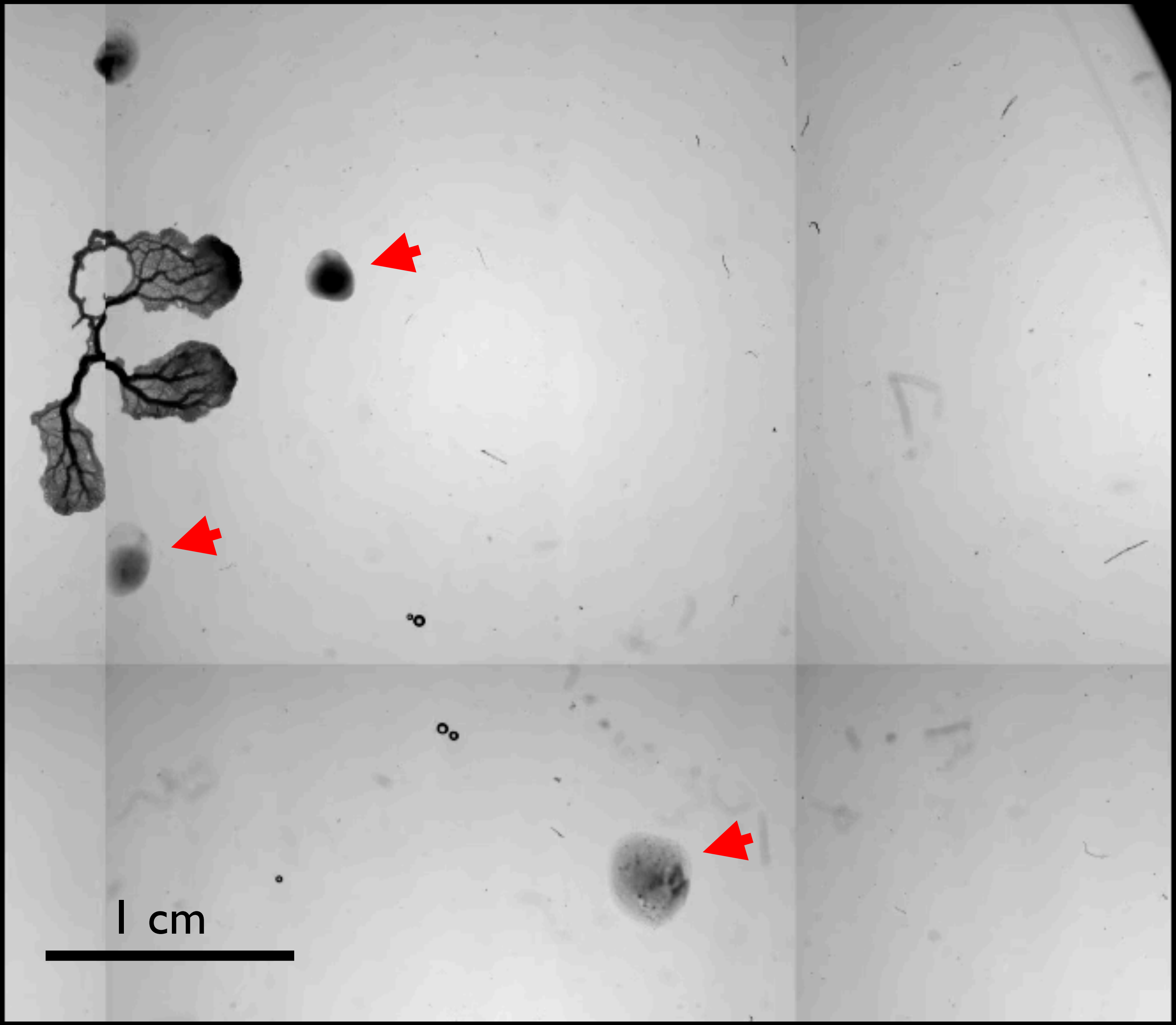


Hierarchy

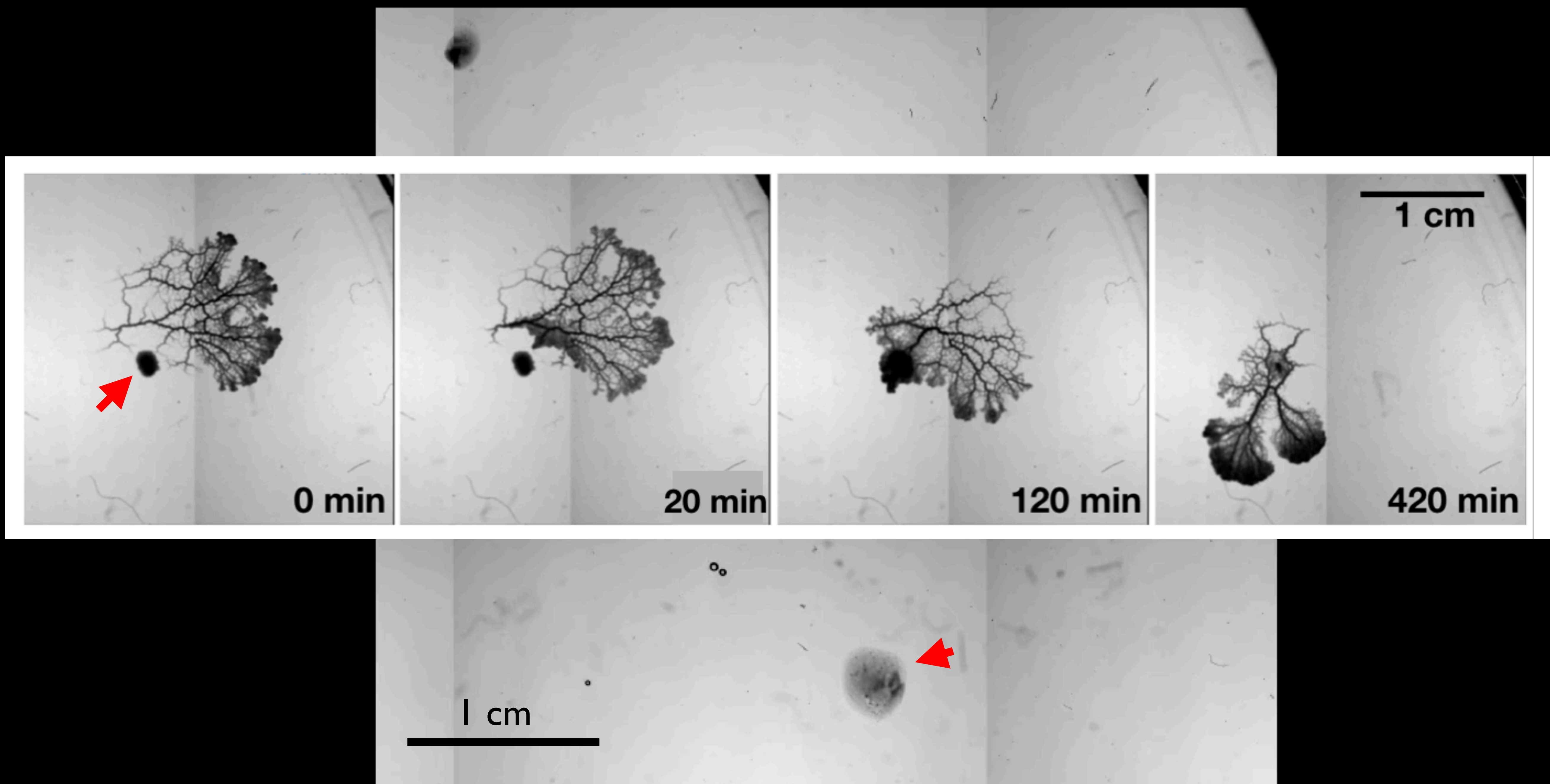
Encoding memory in morphology

Mirna Kramar

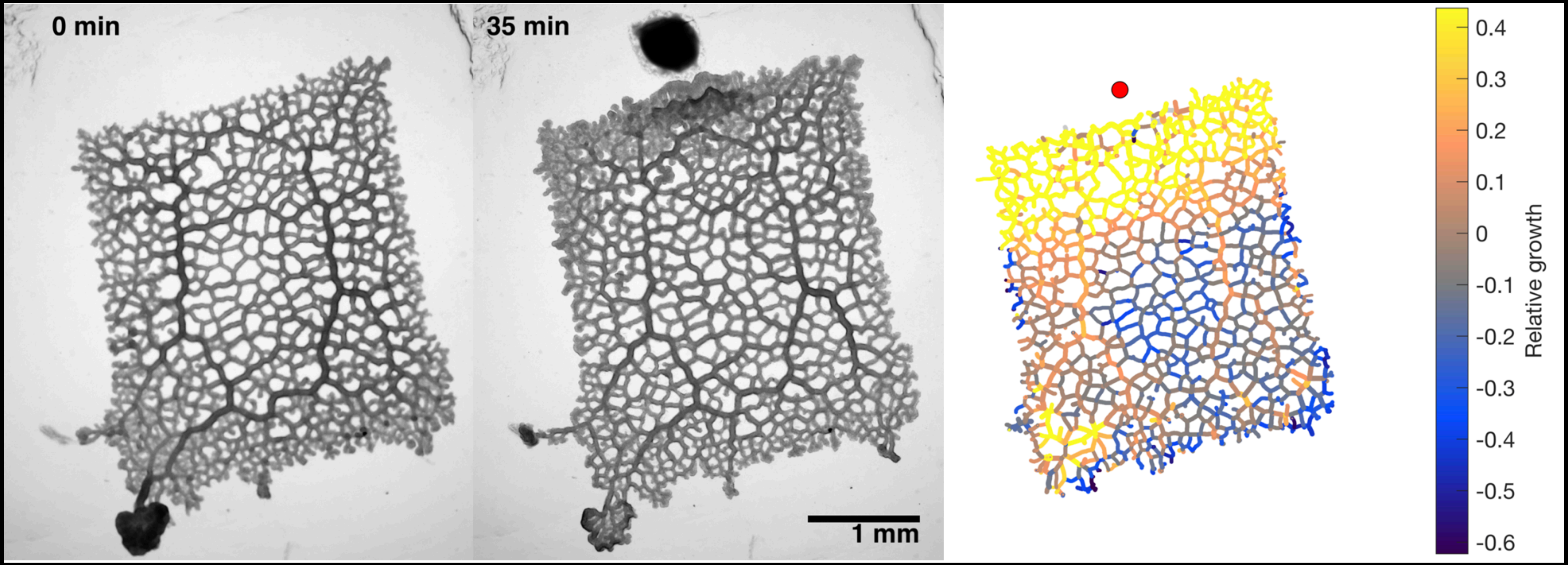


Encoding memory in morphology

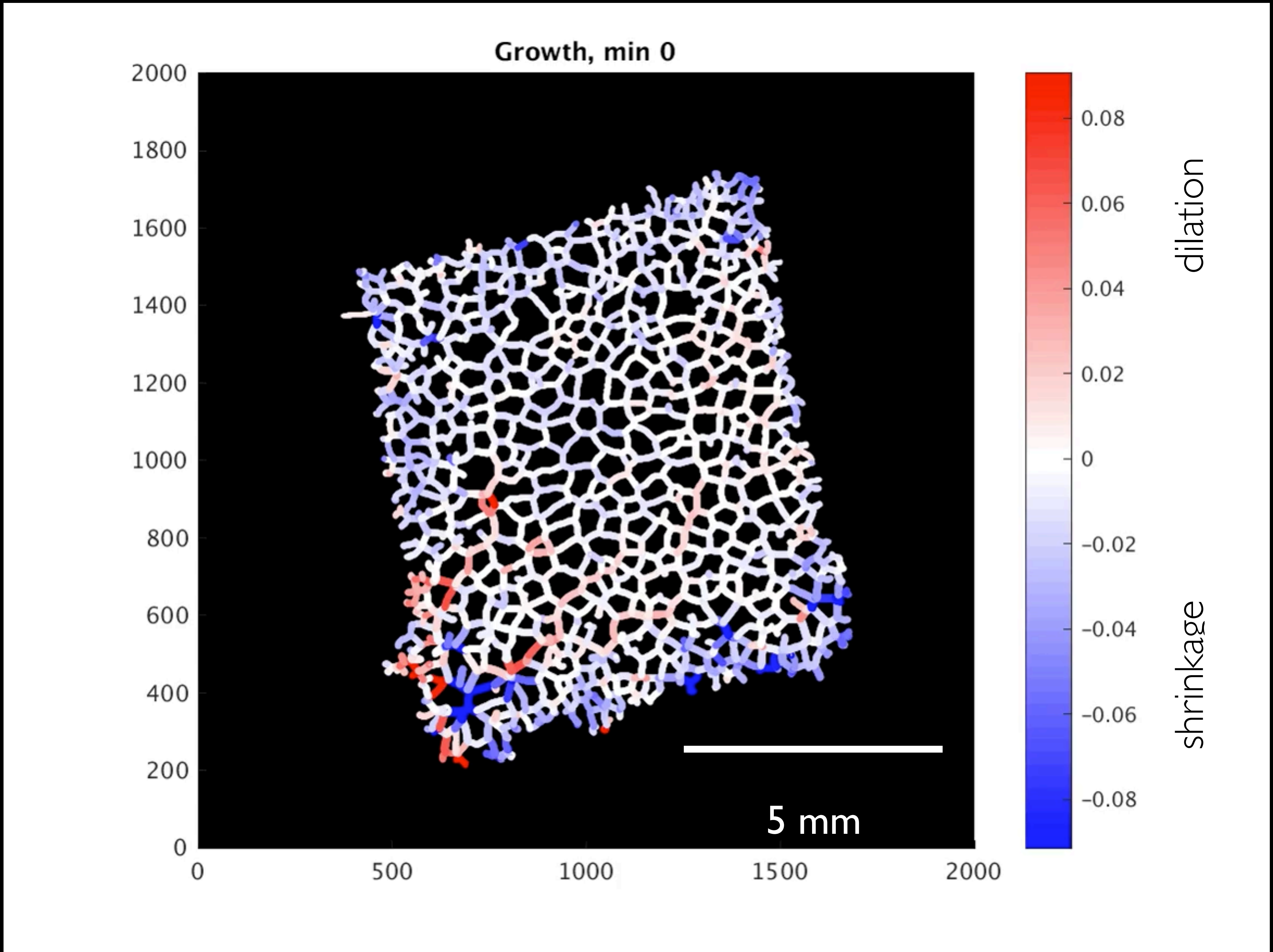
Mirna Kramar



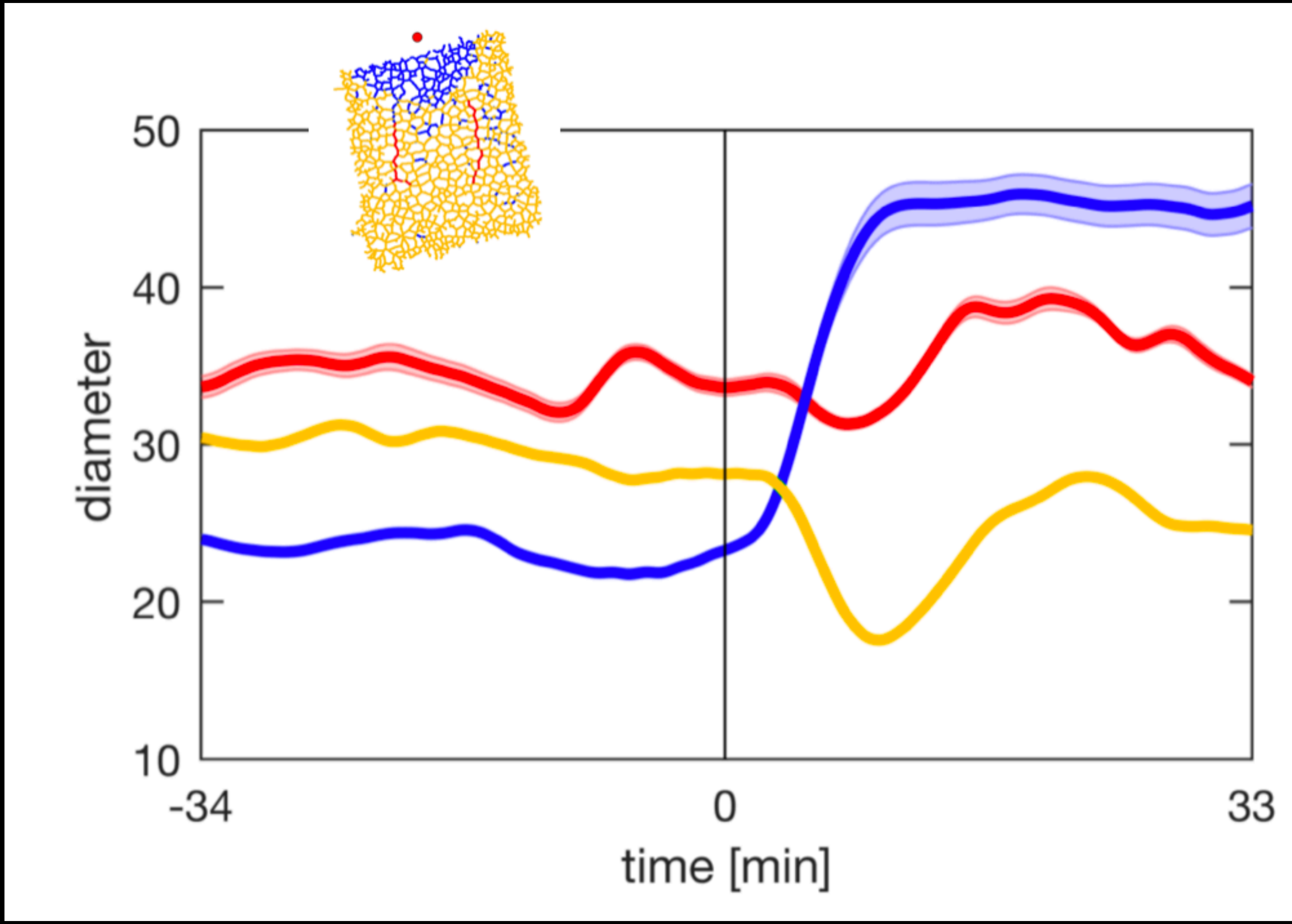
Stimulus encodes hierarchy



Dilation spreads by flow from stimulus site



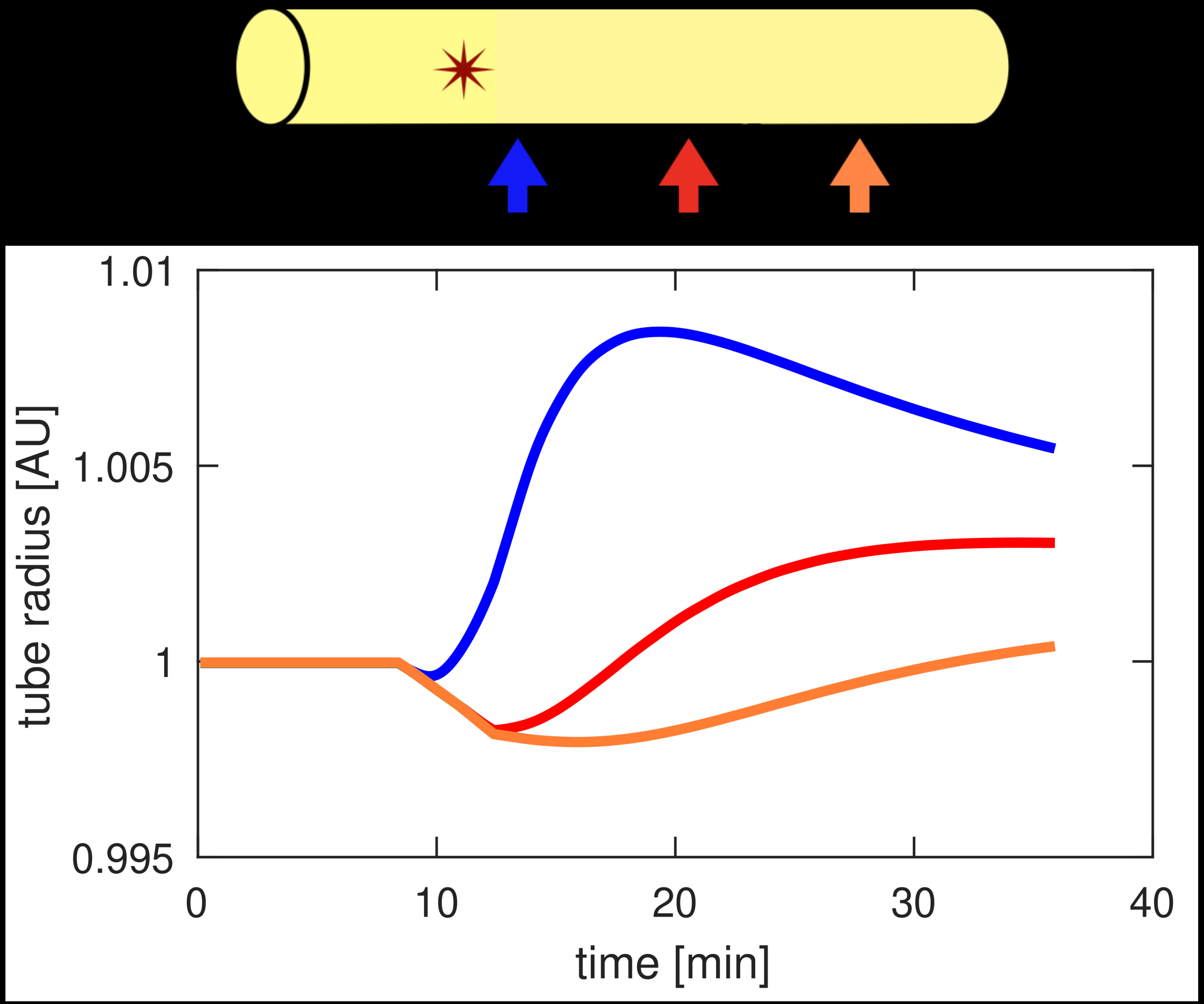
Characteristic dynamics suggest tube softening



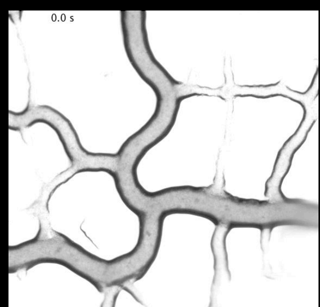
Model of tube softening by advected agent works!

- Stimulus releases softening agent
- Softening agent advected and degraded over time

$$E = E_0 - \delta E \frac{\langle c \rangle}{\langle c_0 \rangle + \langle c \rangle}$$



Flow Morphology



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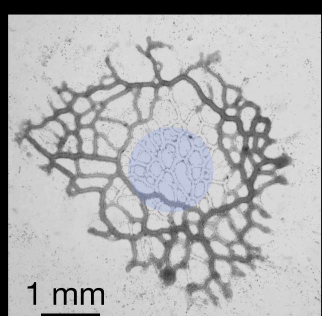
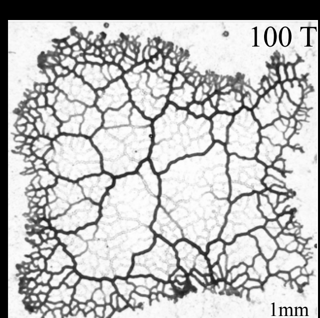


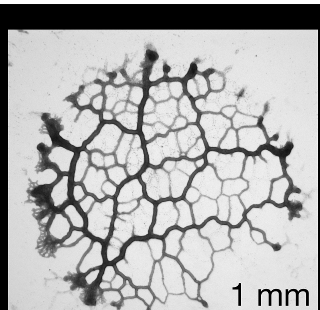
Adaptability

- Increase transport/flux/absorption
- Self-organised optimization



Topology

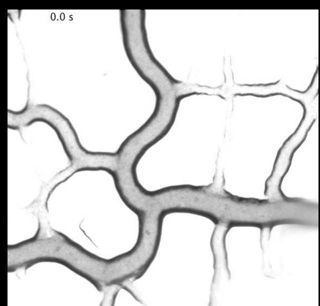
- Stabilize flow patterns
- Loops increase overall flow



Hierarchy

- Store information about history of events

Flow ⇄ Morphology



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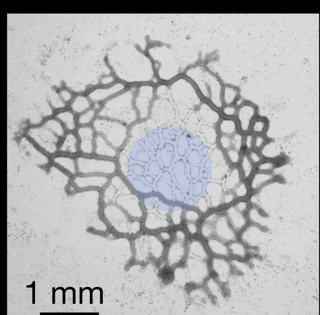
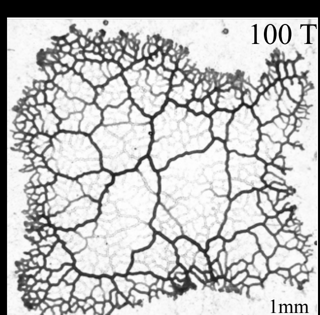


Adaptability

- Increase transport/flux/absorption
- Self-organised optimization



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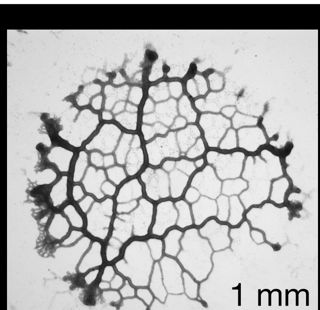

Hierarchy

- Store information about history of events
- Memory to function, problem solving

Experiment ⟳ Theory

Post-docs

Natalie Andrew
Jean-Daniel Julien
Philipp Fleig
Agnese Codutti

PhD students

Jason Khadka
Felix Bäuerle
Mirna Kramar
João Ramos
Komal Bhattacharyya

Master students

Franz Kaiser
Felix Meigel
Noah Ziethen
Lisa Schick
Björn Kscheschinski

Bachelor students

Nico Schramma
Leonie Bastin
Carl Becker
Leonie Kemeter

Interns

Sophie Marbach
Suzanne Lafon
Stephan Mohr

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