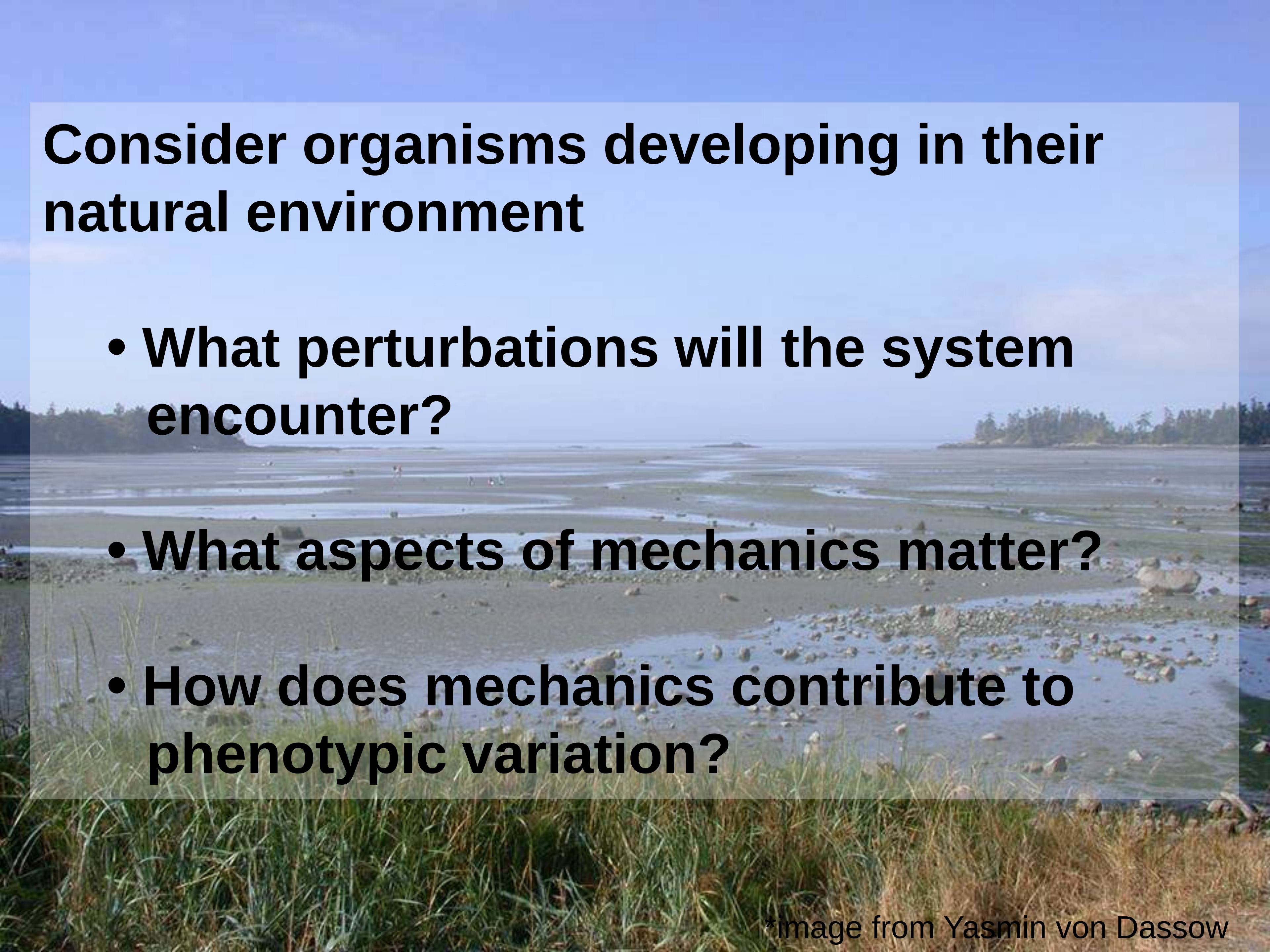
Biomechanics of development & organism-environment interactions

Michelangelo von Dassow

*image from Yasmin von Dassow



Consider organisms developing in their natural environment

- **What perturbations will the system encounter?**
- **What aspects of mechanics matter?**
- **How does mechanics contribute to phenotypic variation?**

*image from Yasmin von Dassow

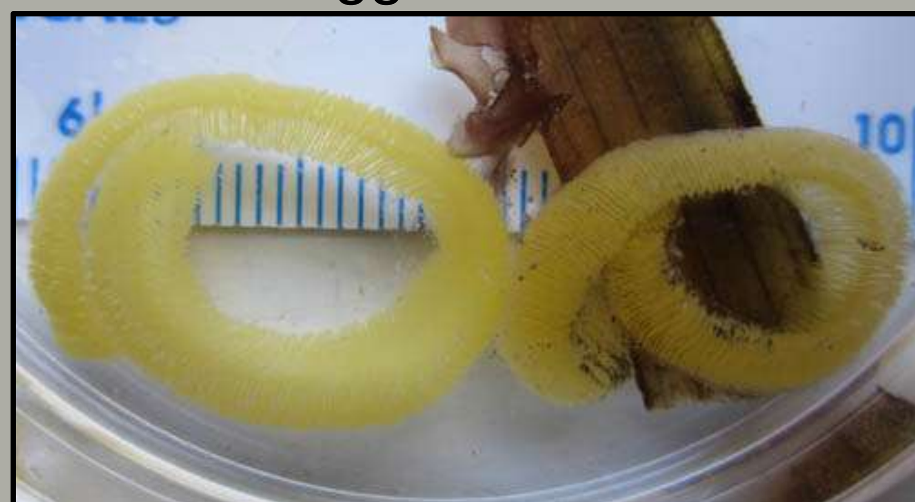
Embryos in False Bay

*image from Yasmin von Dassow

Embryos in False Bay

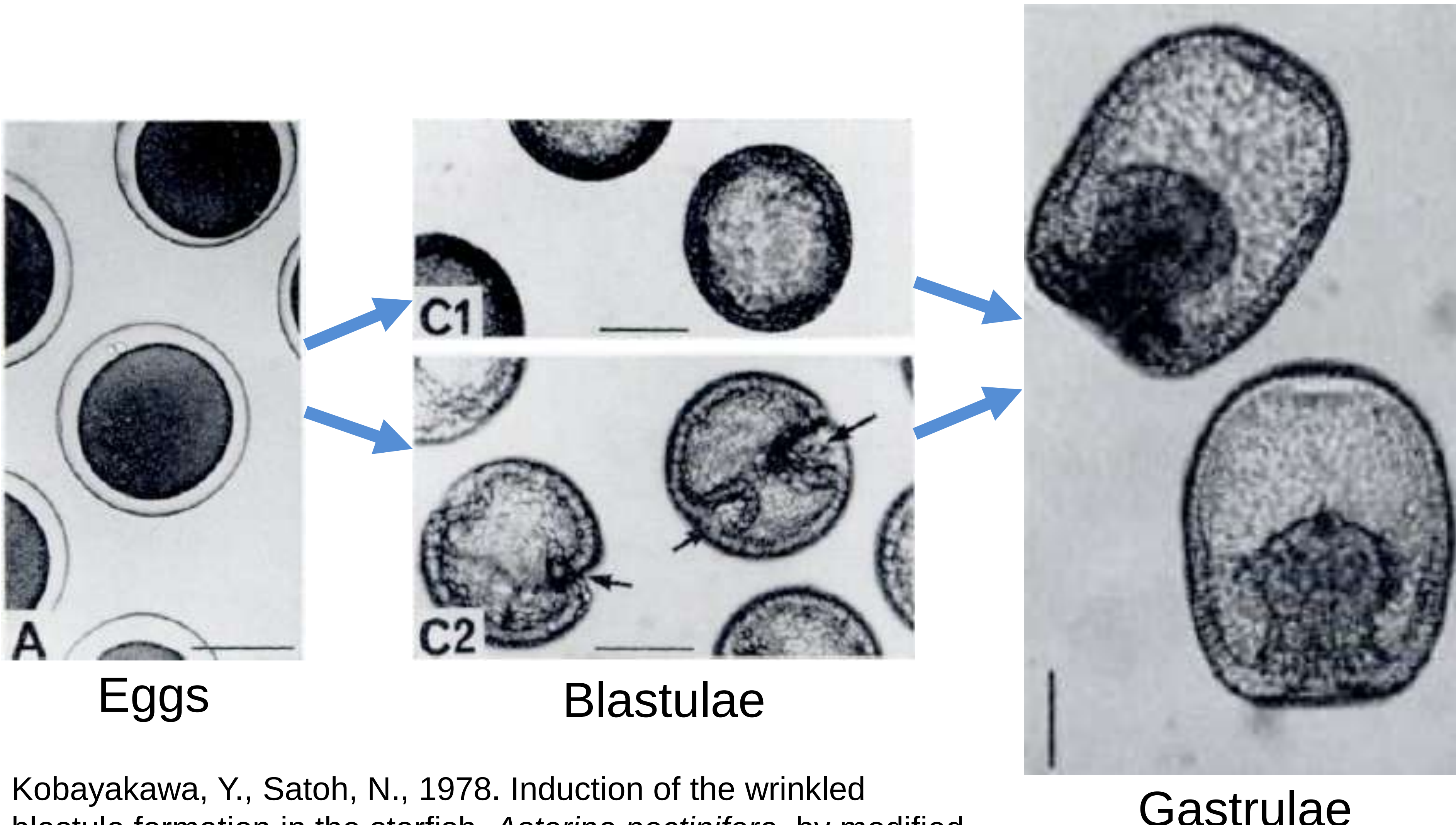
Snail

Egg masses



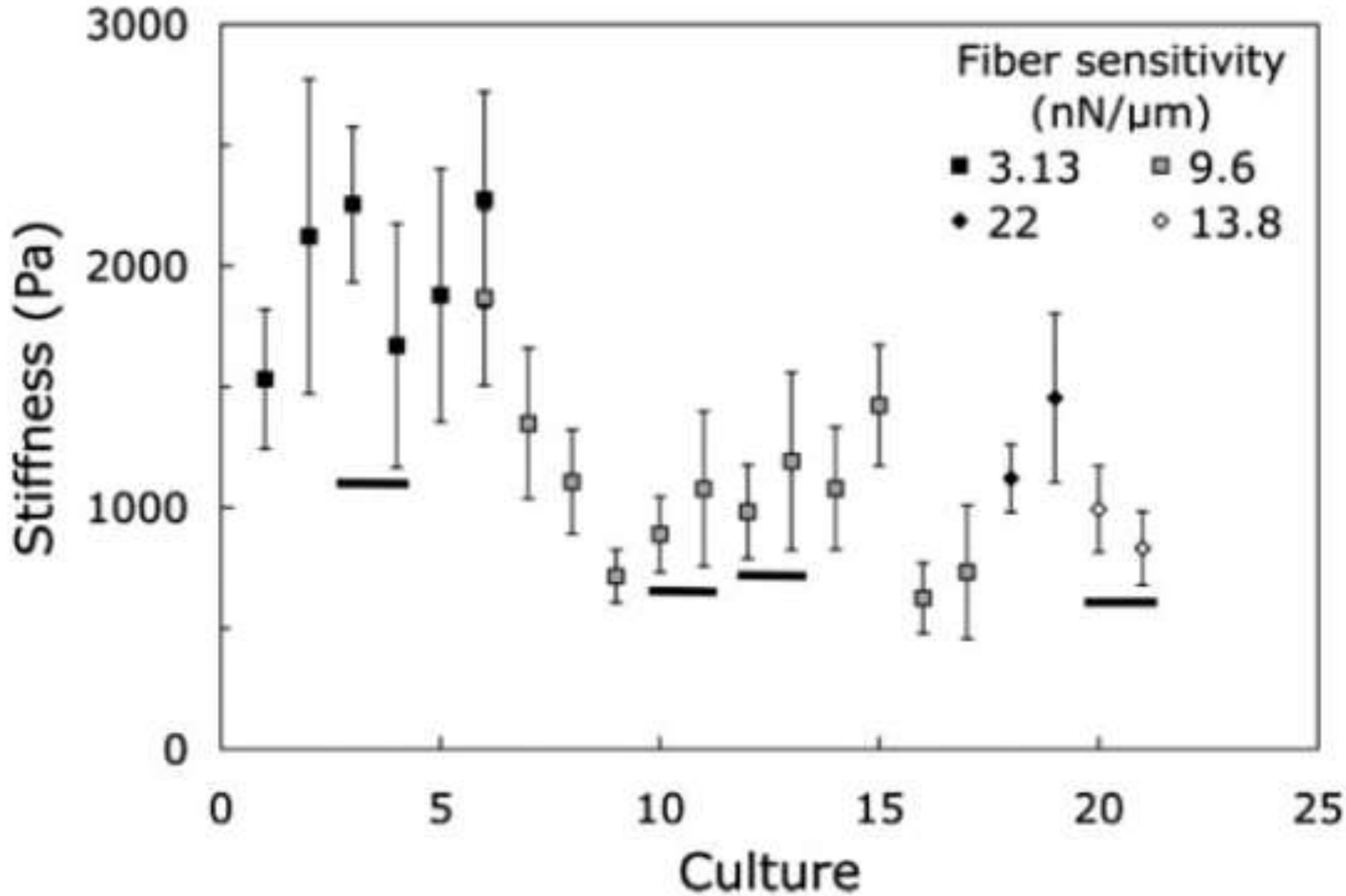
*images from Yasmin von Dassow

Starfish embryos
Salinity driven variation in embryo form



Kobayakawa, Y., Satoh, N., 1978. Induction of the wrinkled blastula formation in the starfish, *Asterina pectinifera*, by modified developmental conditions. Biological Bulletin 155, 150-160. Fig. 1

Sea urchin embryos
Variation in tissue stiffness



von Dassow, M., Davidson, L.A., 2007. Birth Defects Res C Embryo Today 81, 253-269 (**Based on data from Davidson, L.A., Oster, G.F., Keller, R.E., Koehl, M.A., 1999. Dev Biol 209, 221-238**.)

Is morphogenesis sensitive to tissue mechanics?

Natural variability sets lower bound on sensitivity

Thanks to:

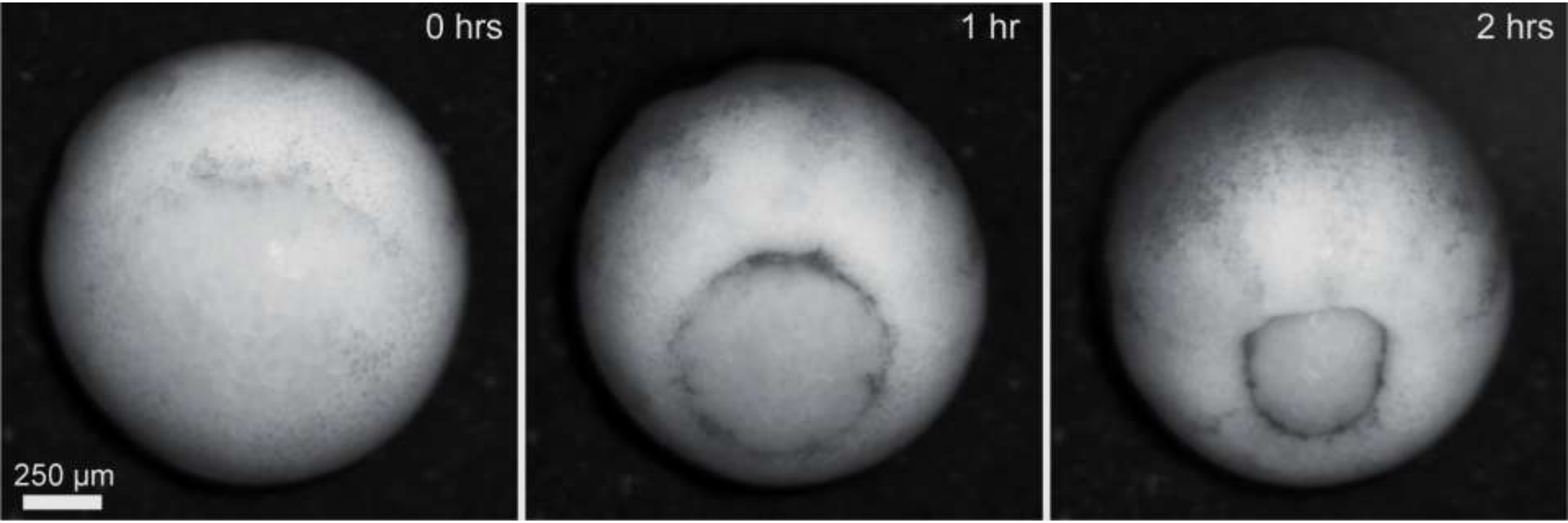
Lance Davidson

Jim Strother, Yasmin von Dassow, Lin Zhang, Jian Zhou, Hye-Young Kim, Sagar Joshi, N. Priest, R.R. Strathmann, B. Miner, and J. Zhang, D. Weber, T. Cui, J. Hokanson, J. Wagenaar, I. Albrecht

The Hartwell Foundation
NIH
NSF

Dept. of Bioengineering, U. of Pittsburgh

Frog gastrulation (blastopore closure)



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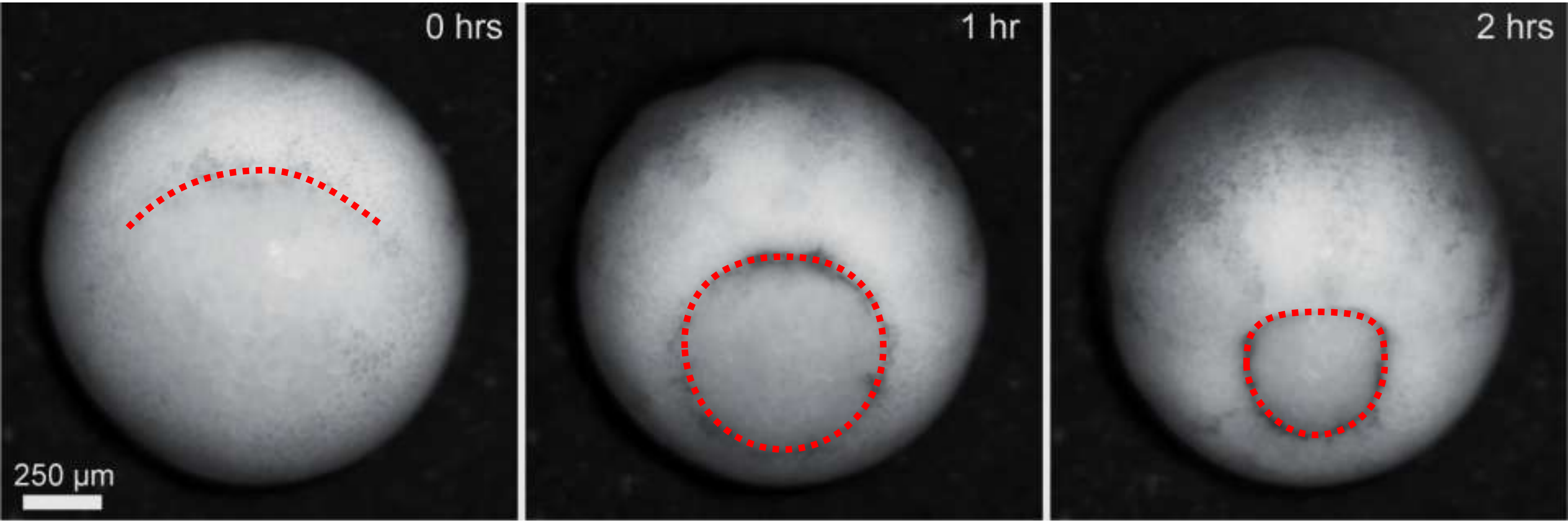
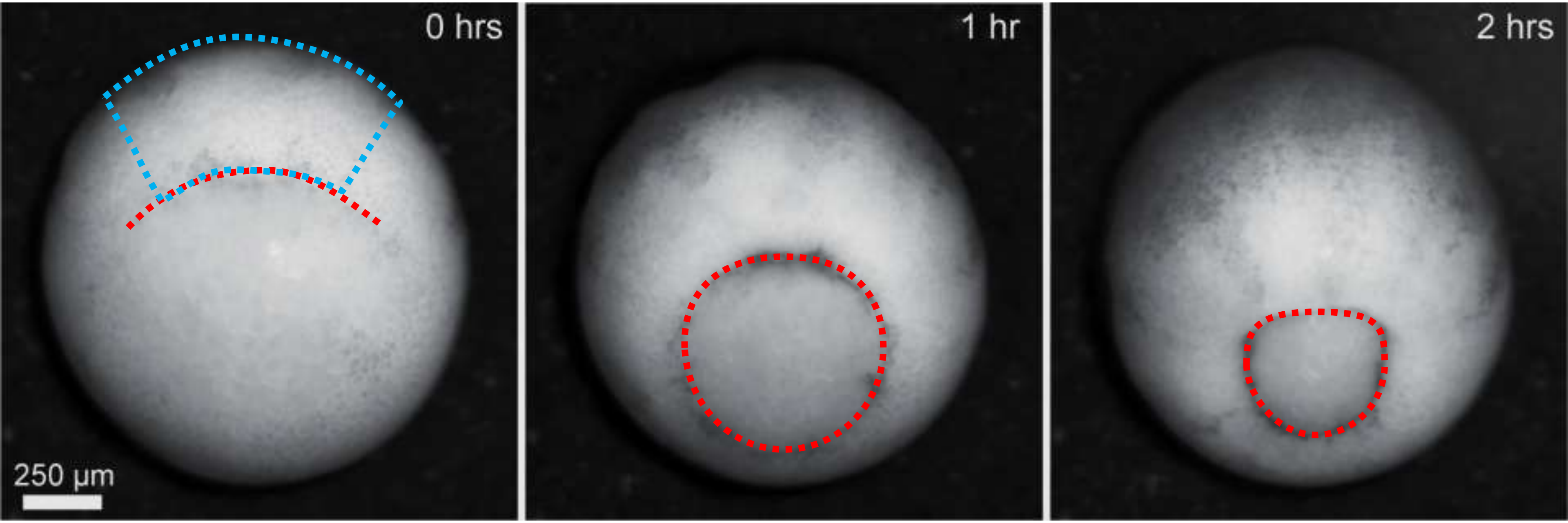
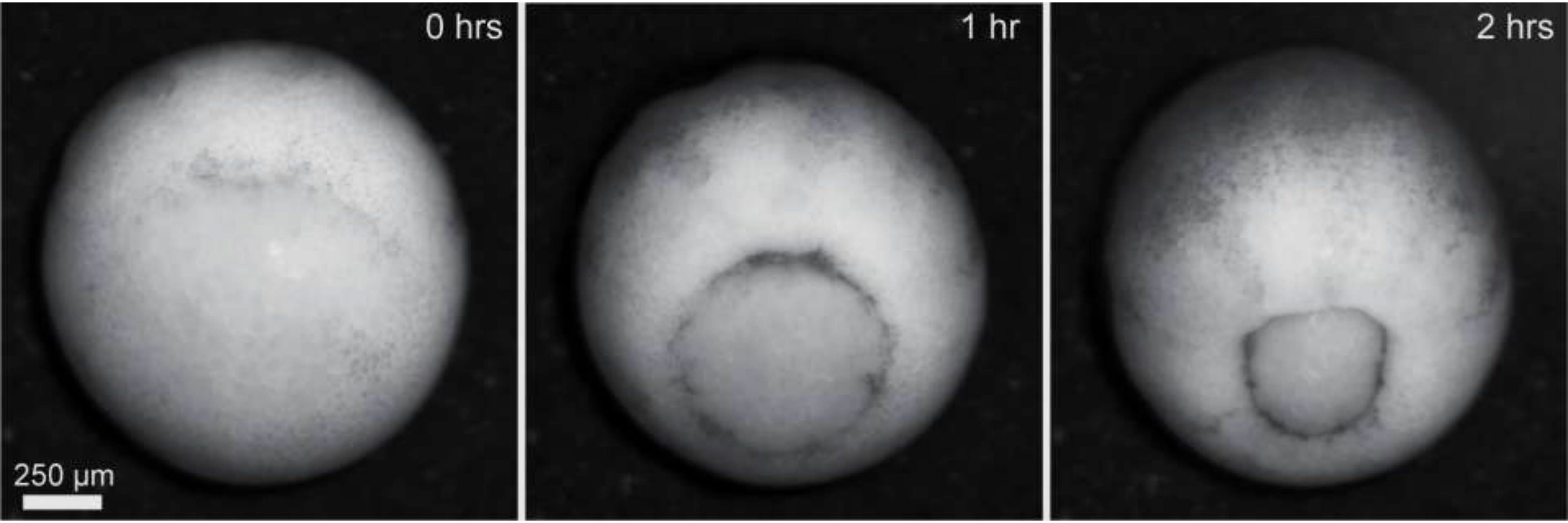


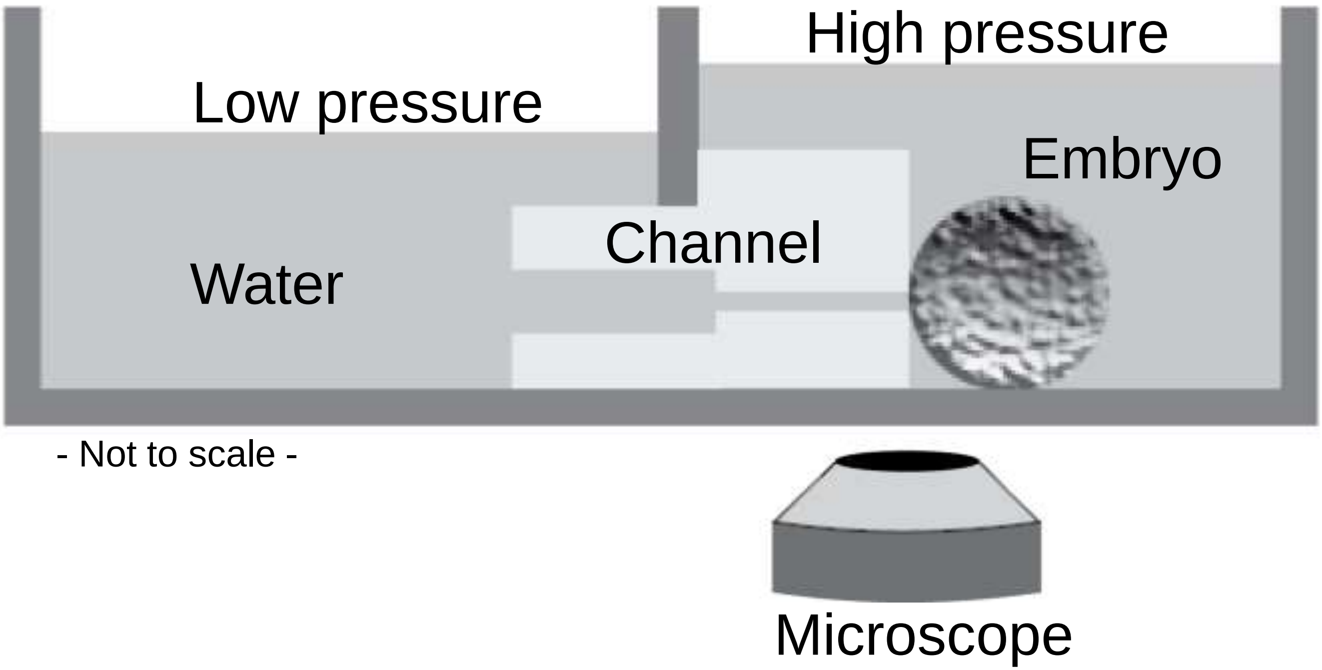
Frog gastrulation (blastopore closure)



Frog gastrulation

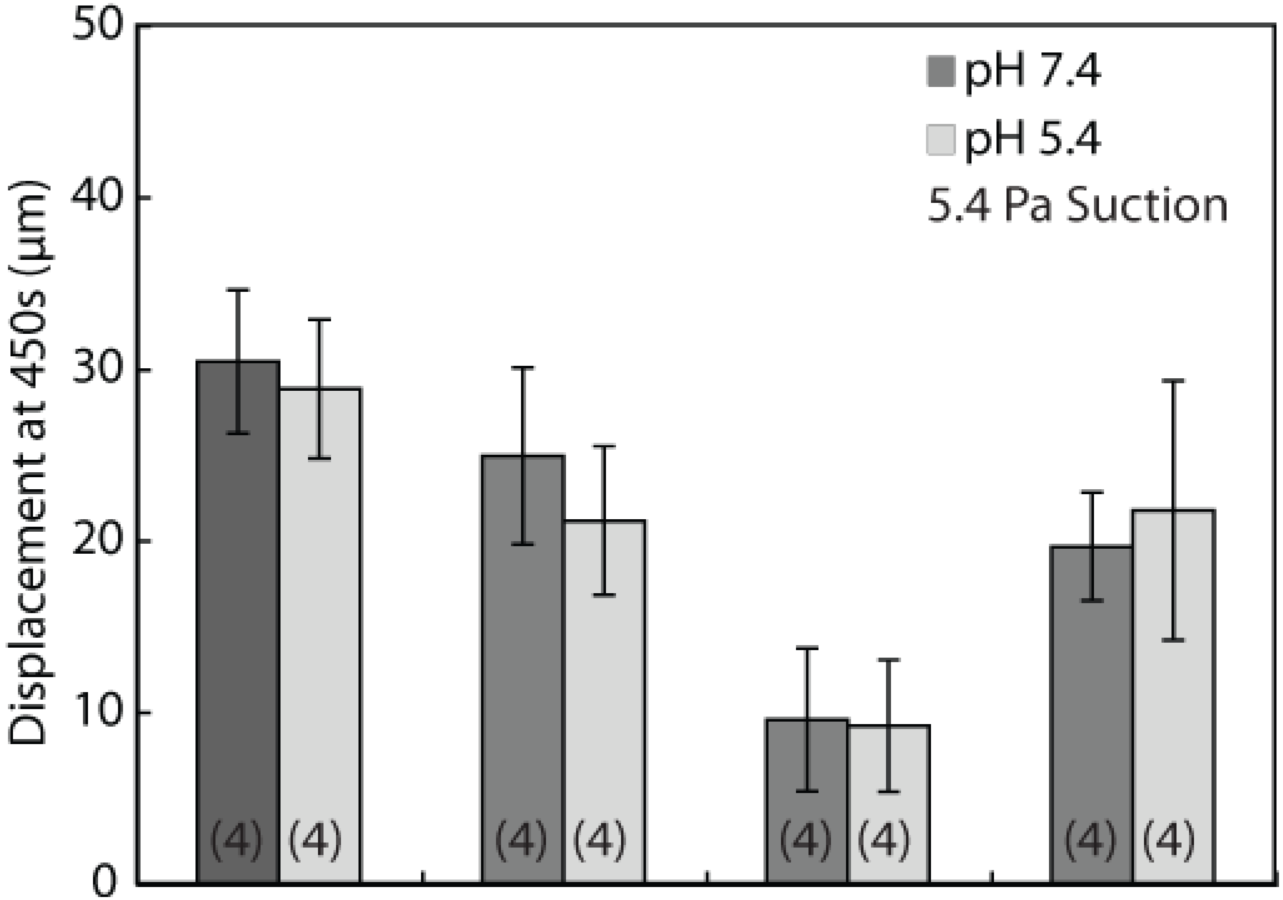


Micro-aspiration:
Measure mechanics with intact embryos



Displacement is inversely proportional to tissue stiffness

How much do environmental factors contribute to mechanical variation?



- Neither pH nor salt concentration affected stiffness
- 0.3 µM Latrunculin B reduced stiffness*
- **High clutch to clutch variation***

*$P \leq 0.05$, 2-way ANOVA

von Dassow, M., Davidson, L.A., 2009. Developmental Dynamics 238, 2-18

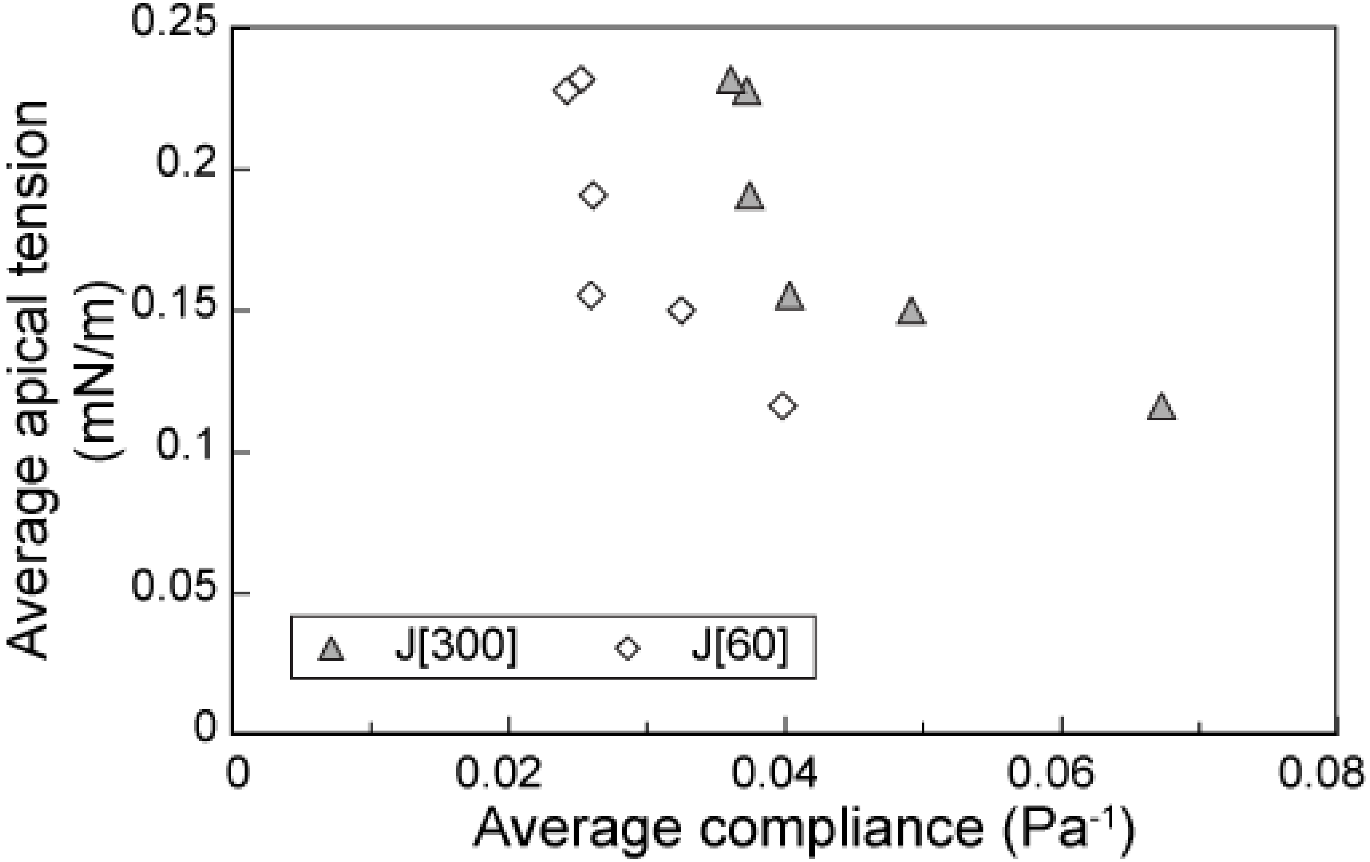
Conclusions (part 1):

- Natural variation in mechanics is substantial.
- Morphogenesis is surprisingly insensitive to mechanical variation.

What properties allow morphogenesis to be so robust?

- **Coupling between stiffness and force production?**

Softer clutches may produce lower forces



J(60): $P = 0.04$; J(300): $P \leq 0.01$; Kendall's Tau

von Dassow, M., Strother, J.A., Davidson, L.A., 2010. PLoS One 5, e15359

Do changes in morphogenetic rates require fine control of tissue mechanics?

Morphogenesis is faster at high temperatures.

Therefore, we expect warm embryos to:

- Be softer

  and/or

- Exert more force

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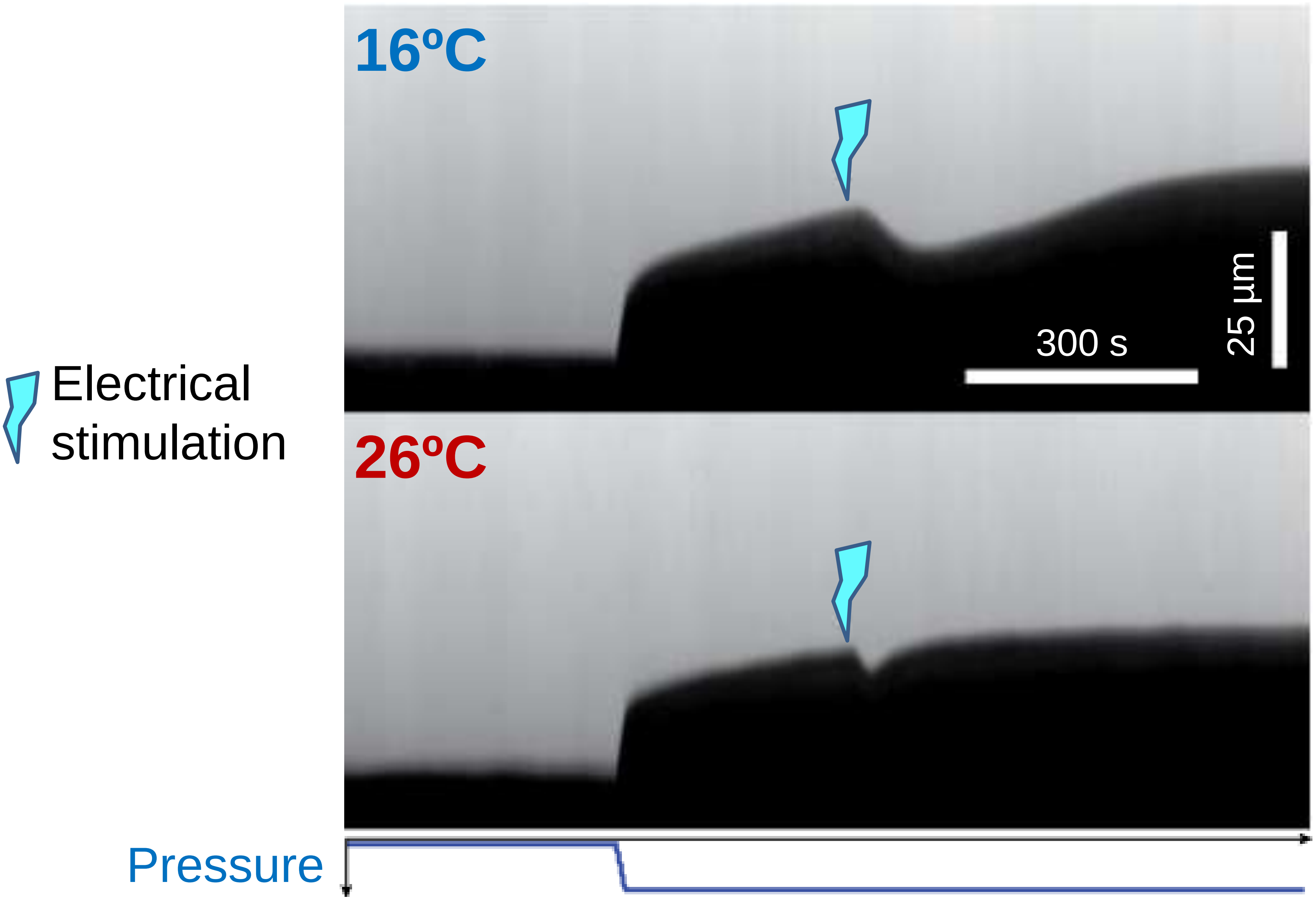
- Be softer

  and/or

- Exert more force

- Compared embryos at 16º to 26ºC
- Used micro-aspiration to determine viscoelastic properties
- Used induced contractions as proxy for force generation



16ºC
26ºC
300 s
25 µm
Electrical stimulation
Pressure

We expected warm embryos to:

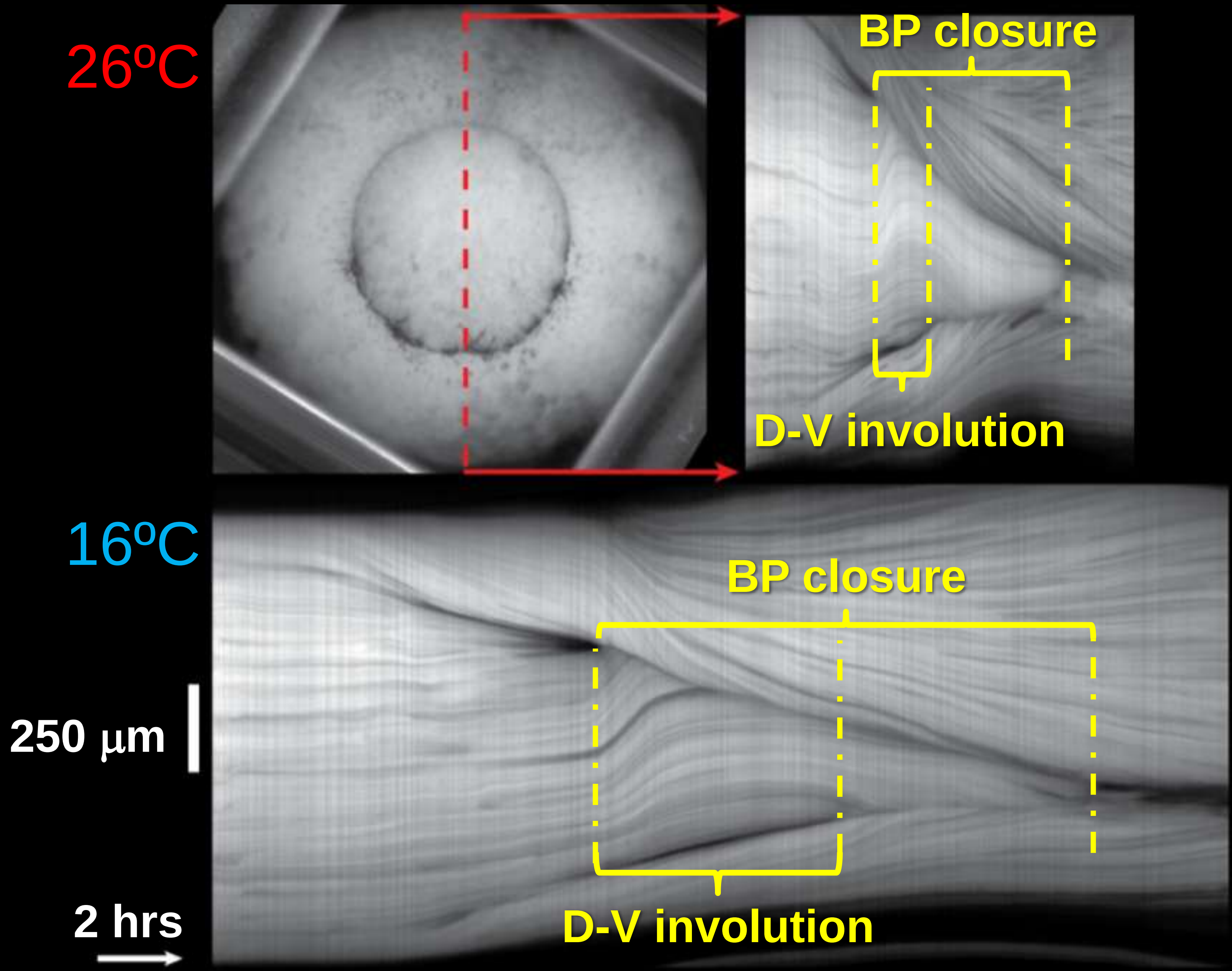
~~Be softer~~

and/or

~~Exert more force~~

Does morphogenesis change?

- Compared embryos at 16º to 26ºC
- Measured relative timing of two processes


26ºC
BP closure
D-V involution
16ºC
BP closure
250 µm
D-V involution
2 hrs

We expected warm embryos to:

~~Be softer~~

and/or

~~Exert more force~~

Does morphogenesis change?

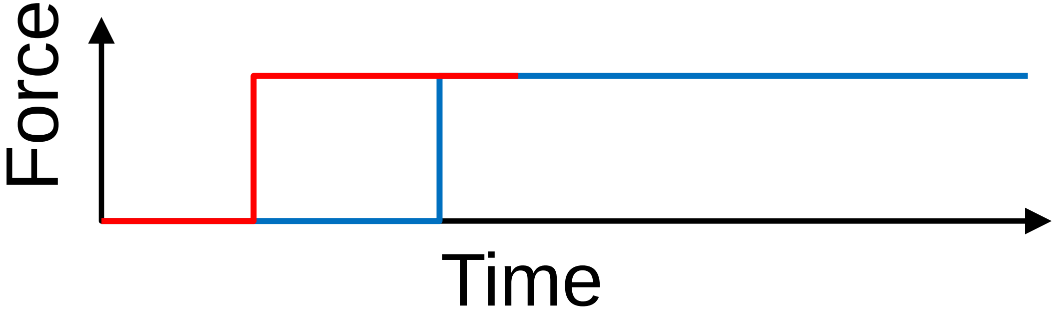
Yes

Could mechanics drive the temperature-dependent differences in morphogenesis?

Could mechanics drive the temperature-dependent differences in morphogenesis?

Assumptions

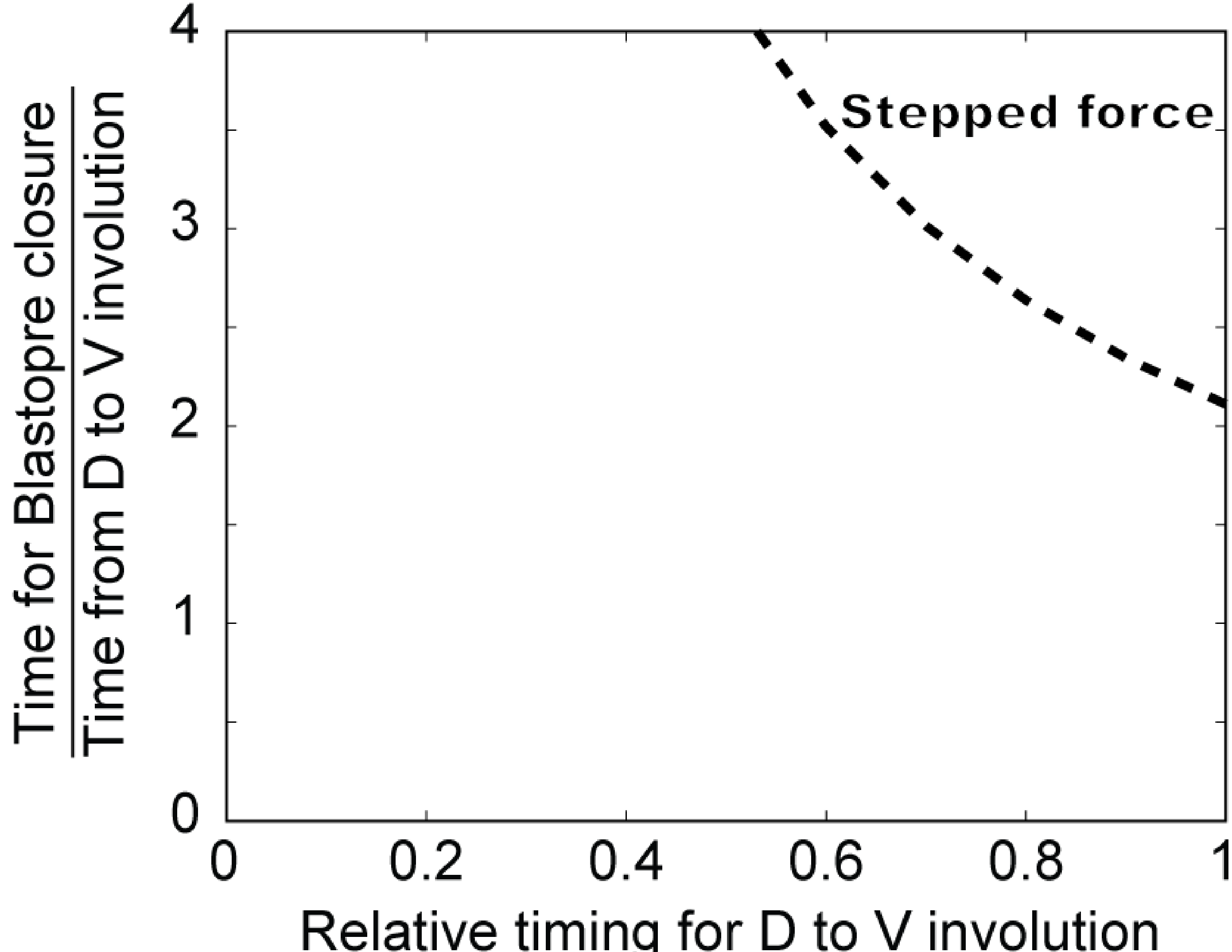
Forces:



Viscoelasticity: $J(t) = J(1)*t^{\beta} = J(1)*t^{\beta}$

Geometry: 1D, small deformation

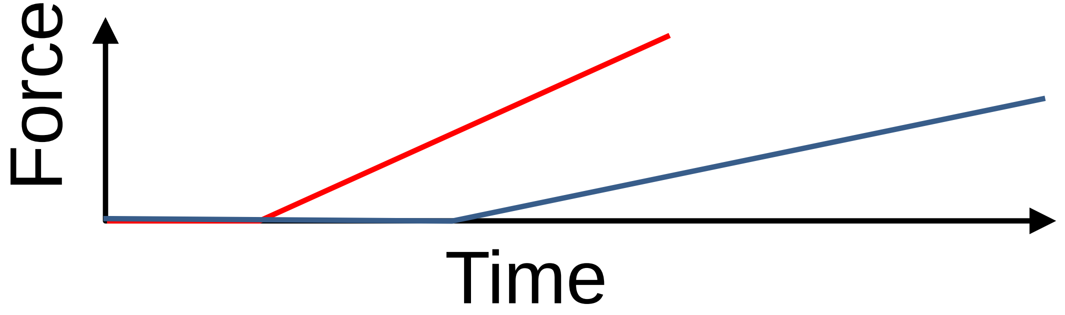
Viscoelasticity and timing of forces could alter temperature-dependence of morphogenesis



Could mechanics drive the temperature-dependent differences in morphogenesis?

Assumptions

Forces:



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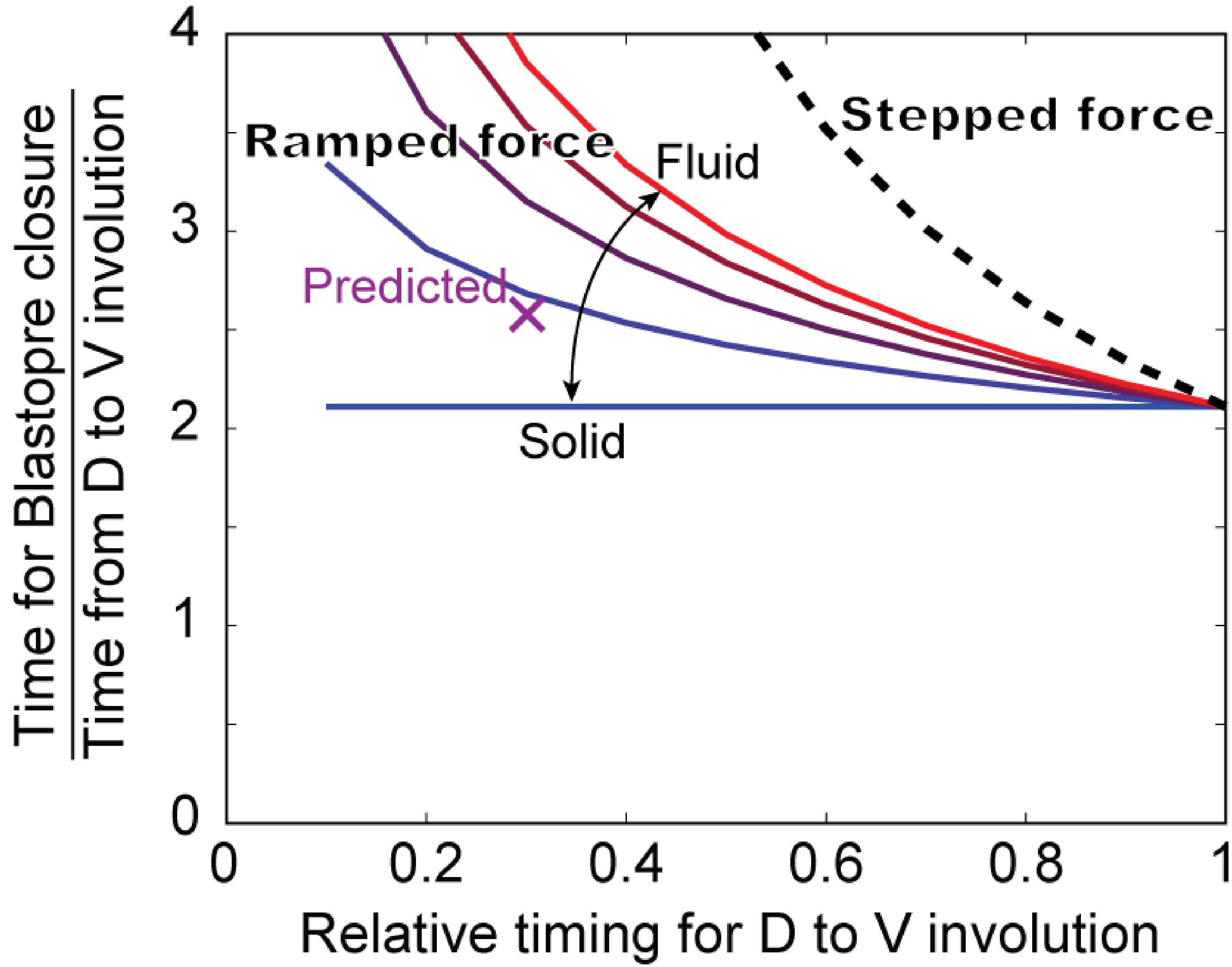
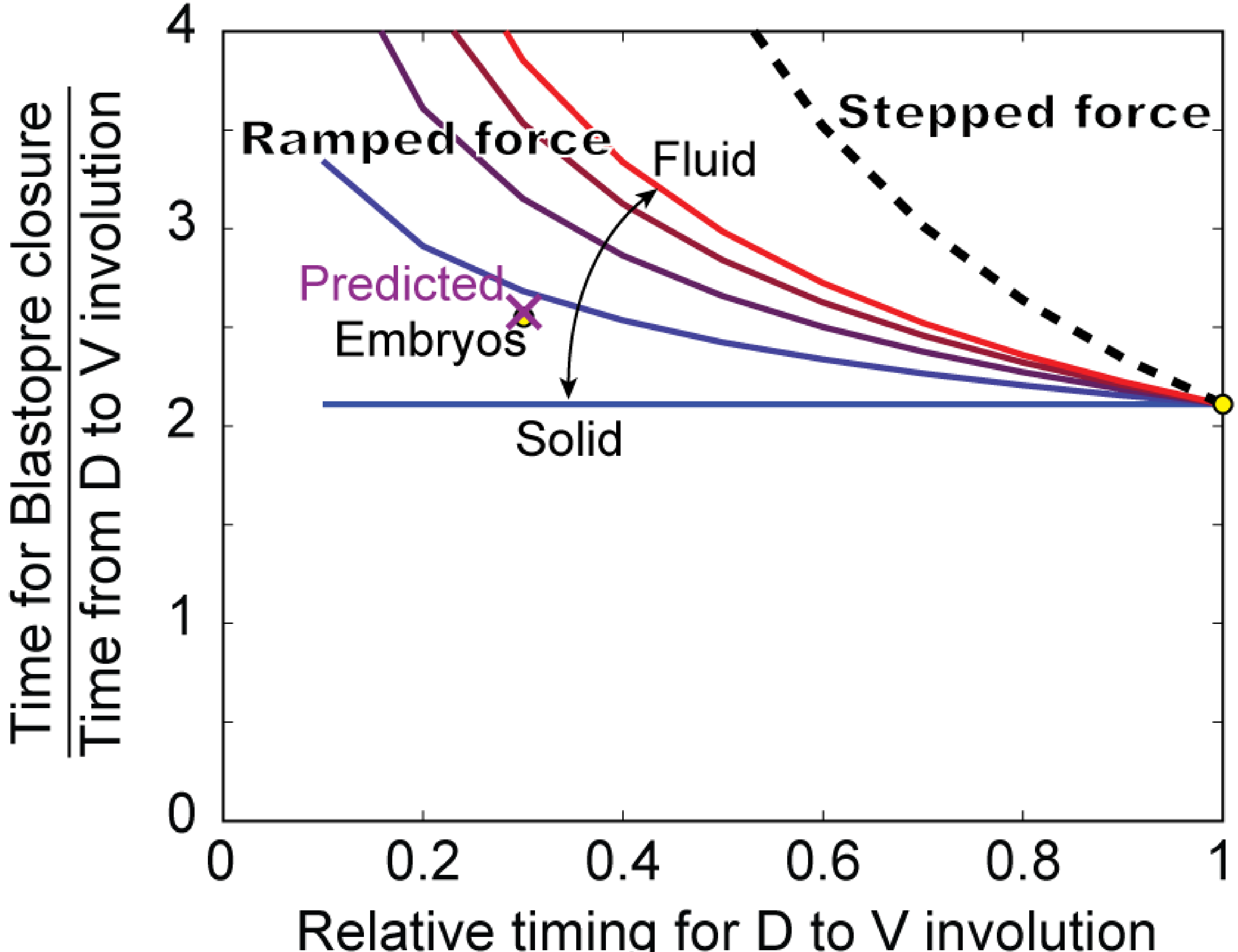
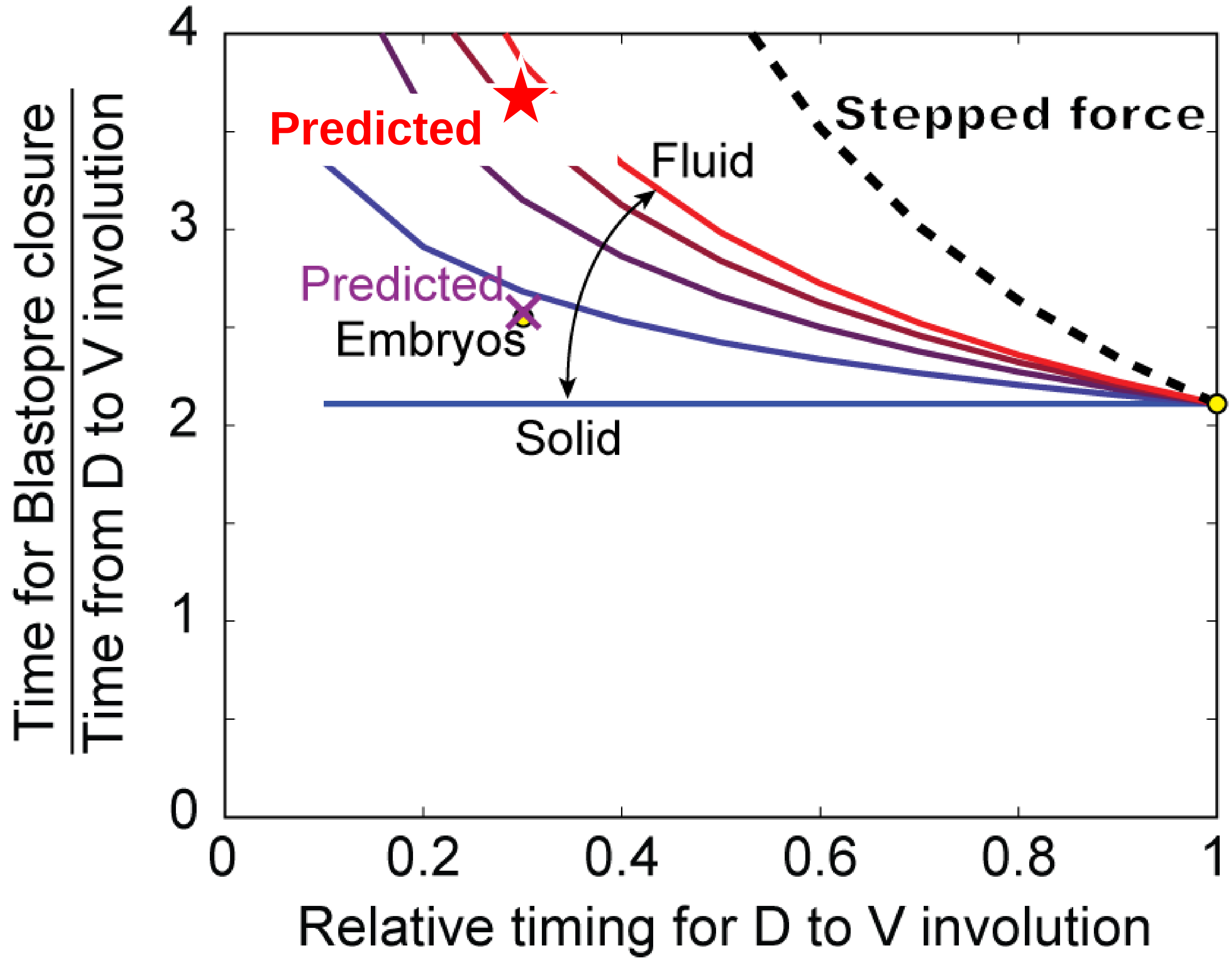


Viscoelasticity and timing of forces could alter temperature-dependence of morphogenesis



Viscoelasticity and timing of forces could alter temperature-dependence of morphogenesis



Conclusions (part 2)

- Organism-environment interactions suggest new ways to think about mechanics.
- *Xenopus* tolerates 2x range in tissue stiffness
- *Xenopus* tolerates >3x range in developmental rate due to:
  - Tolerance of morphogenetic variation
  - *Not* modifying tissue mechanics
- Mechanics affects *variation* in morphogenesis

Membranipora membranacea

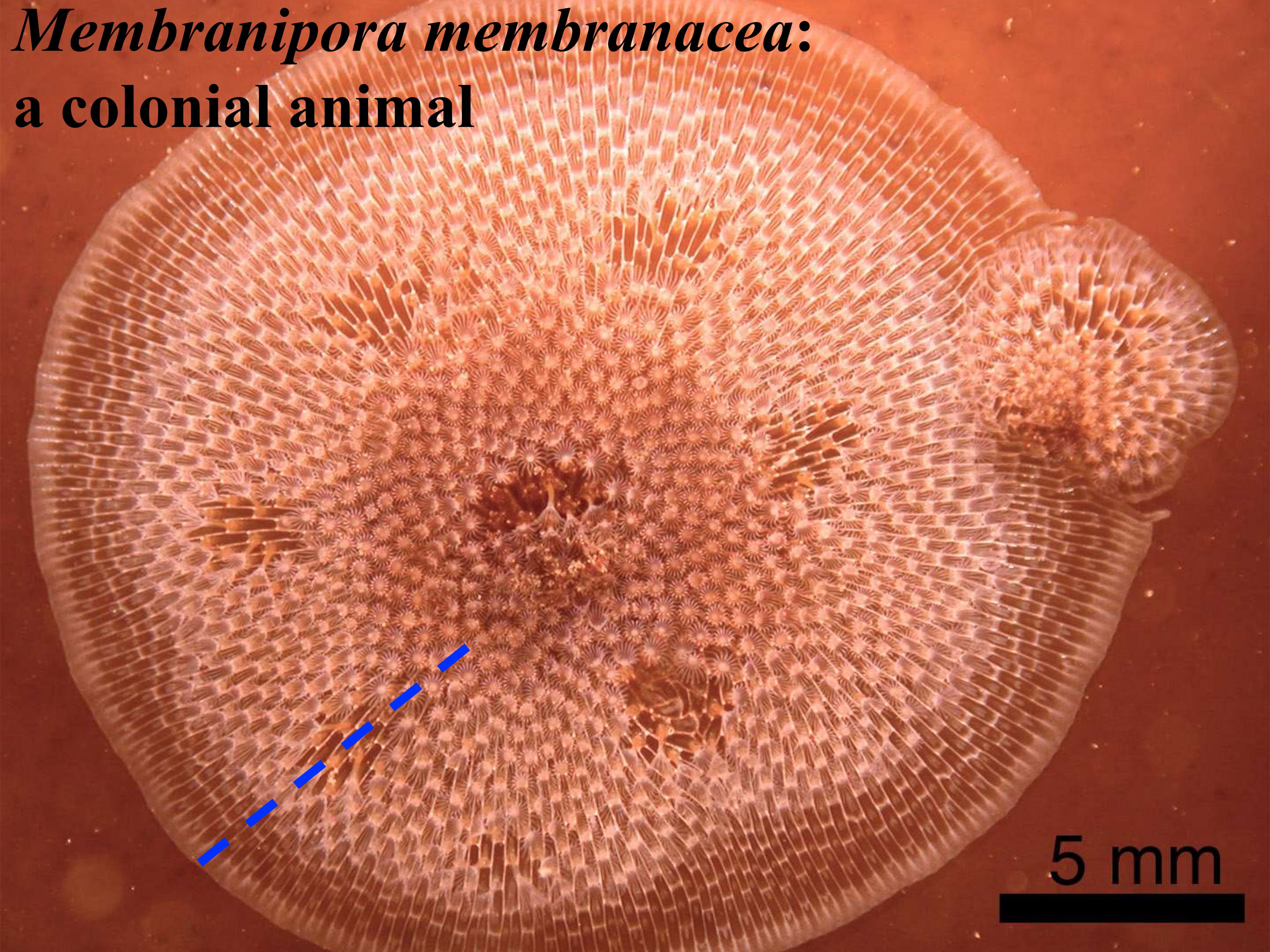
Thanks to:

Mimi Koehl

Yasmin von Dassow, George von Dassow, Scott Jackson, Jim Strother, Matt McHenry, Hannah Stewart, Richard Strathmann, Scott Schwinge, Blanche Bybee, Sean Cain, and Bruno Pernet.

Friday Harbor Labs
HHMI Predoctoral Fellowship
UC Berkeley Dept. of Integrative Biology

Membranipora membranacea: a colonial animal



A colony with a chimney, side view

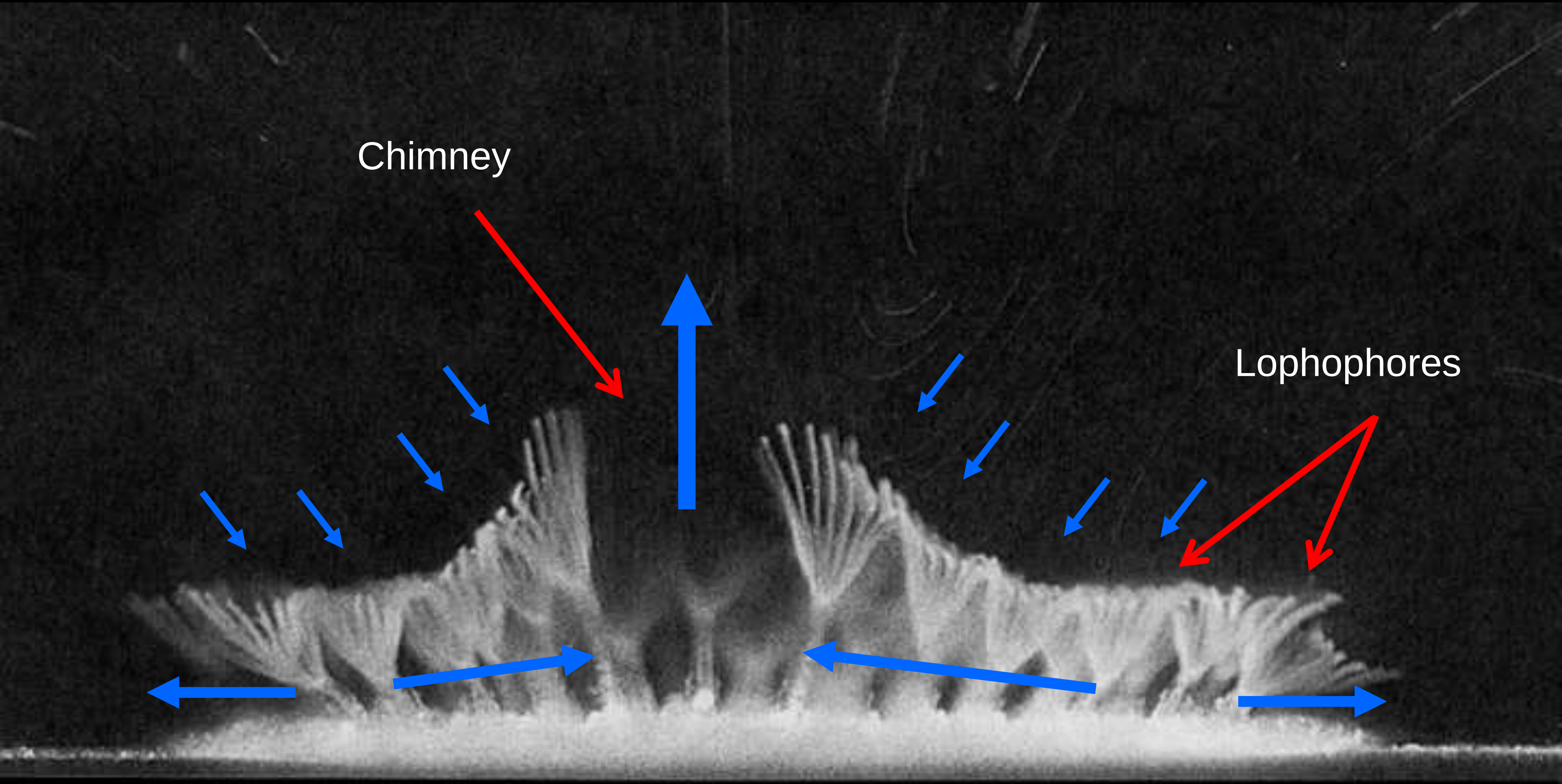
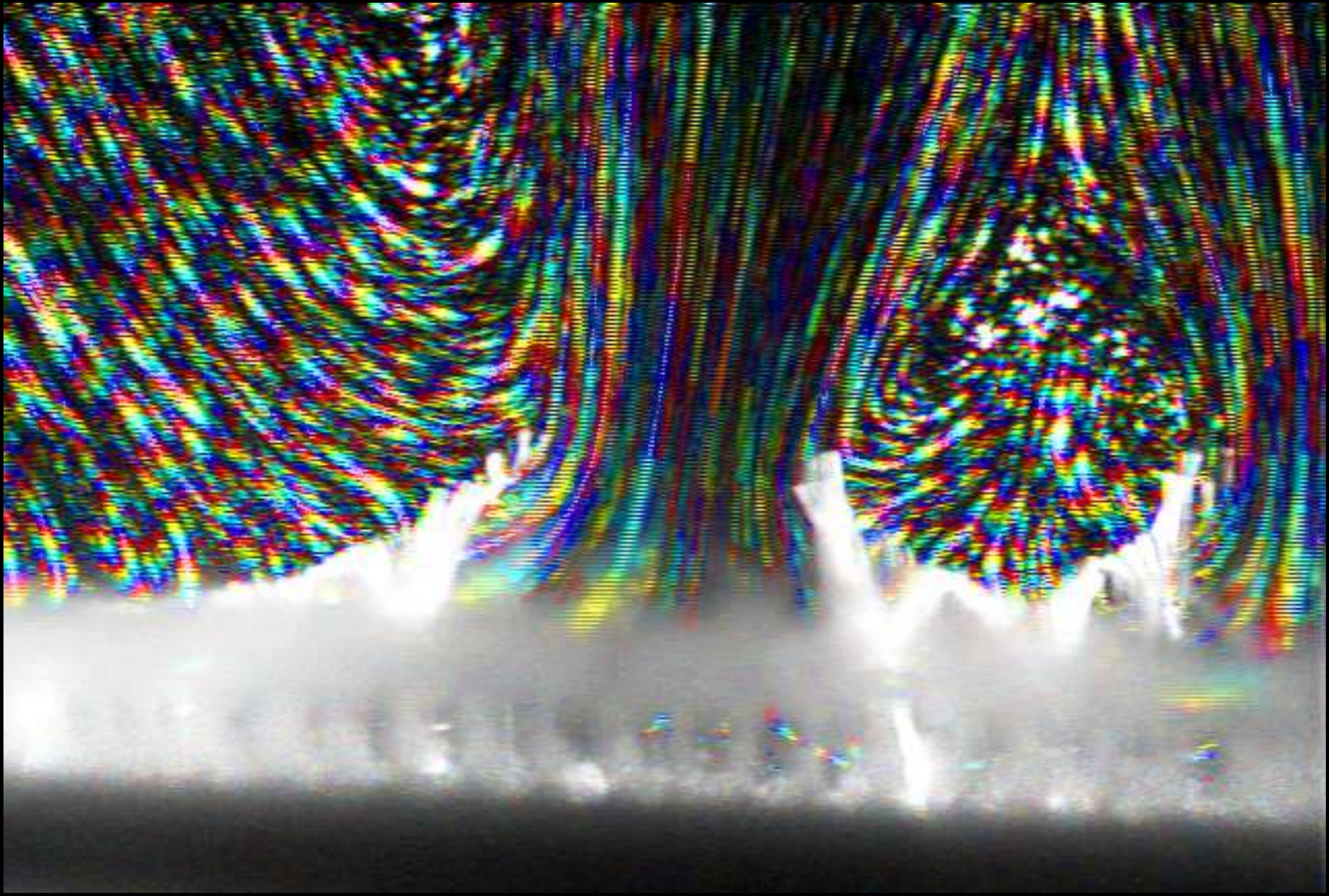


Photo from Grunbaum, D., 1997. Limnology and Oceanography 42, 741-752.

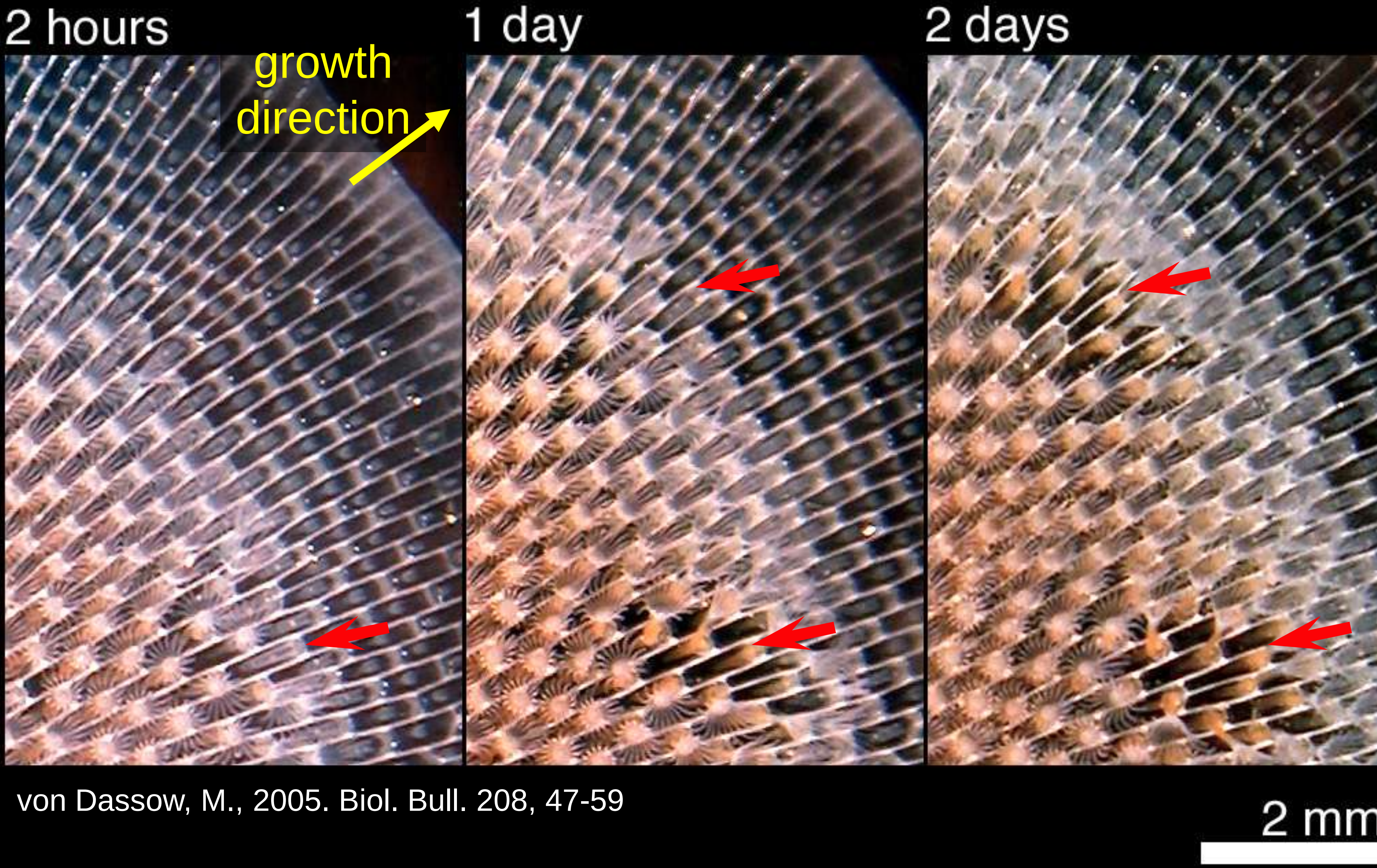
Flow generated by colony



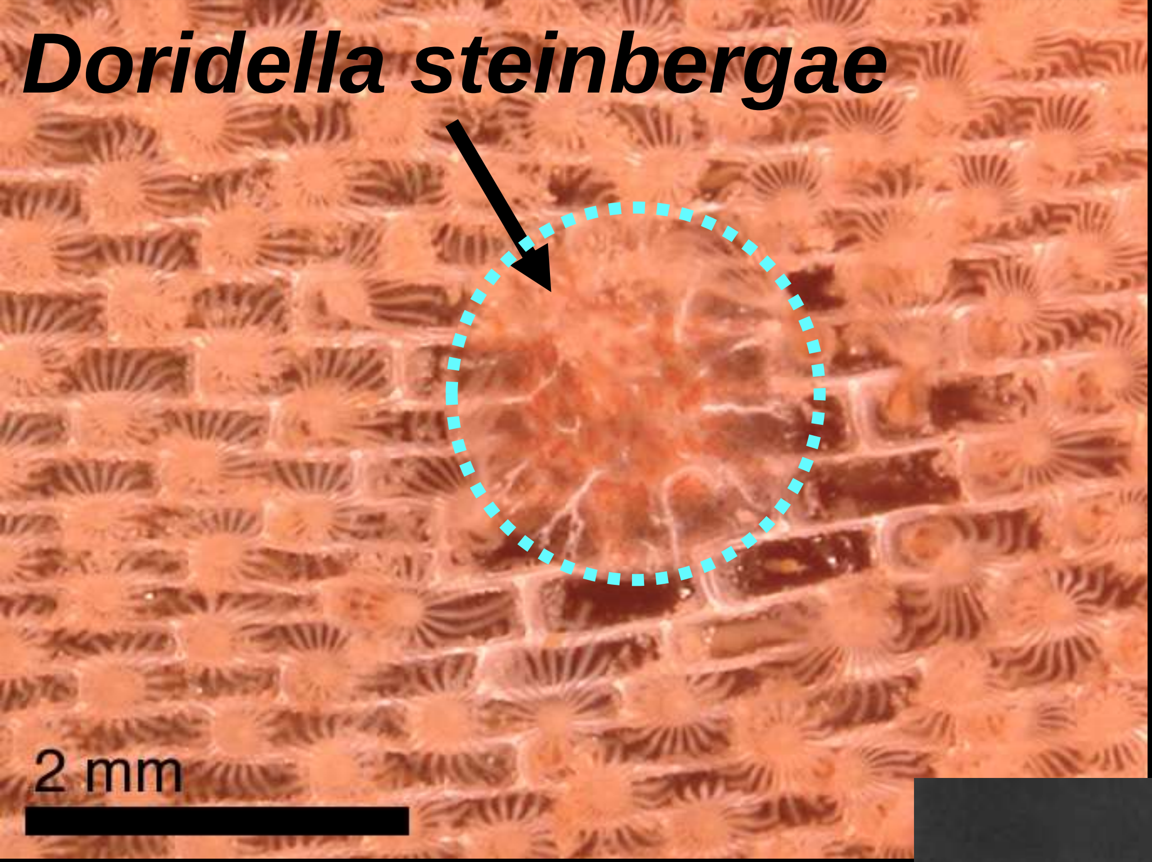
von Dassow, M., 2005. J Exp Biol 208, 2931-2938

1 mm

Chimneys form at the canopy edge



von Dassow, M., 2005. Biol. Bull. 208, 47-59



Defensive spines

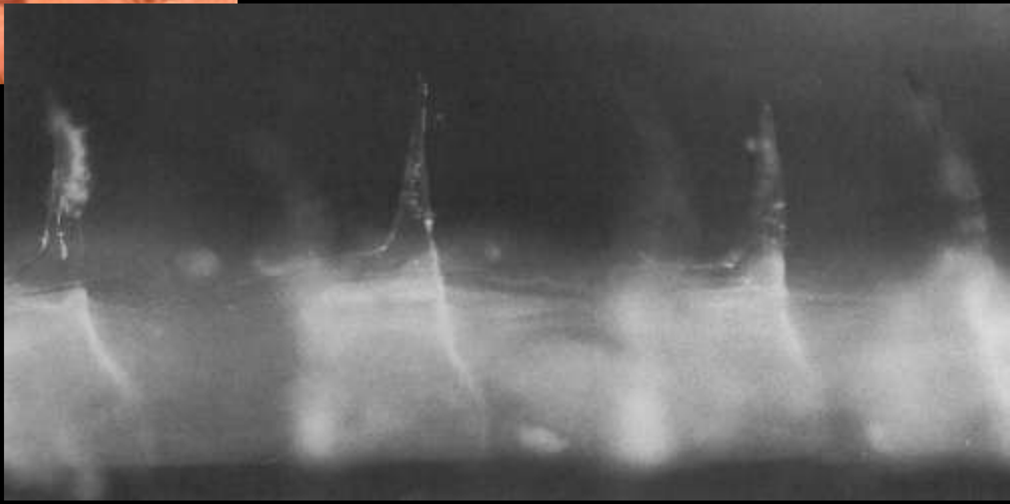


Photo from Grunbaum, D., 1997. Limnology and Oceanography 42, 741-752.

Phenotypic plasticity

➔ Flow-regulated patterning?

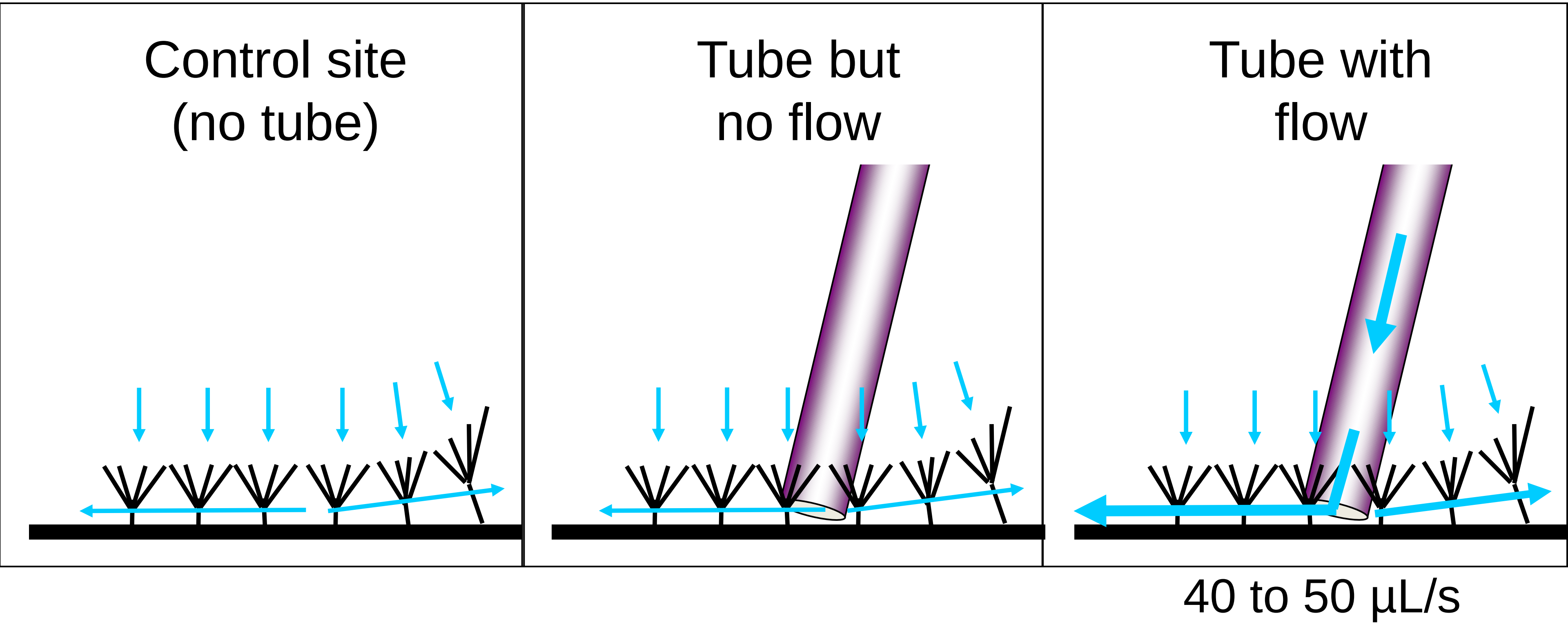
- Predatory nudibranchs
  - → Defensive spines form
    - → Raise resistance to flow
      - → Reduce chimney spacing

- Chimney formation & { zoooid size / injuries / substrate shape }

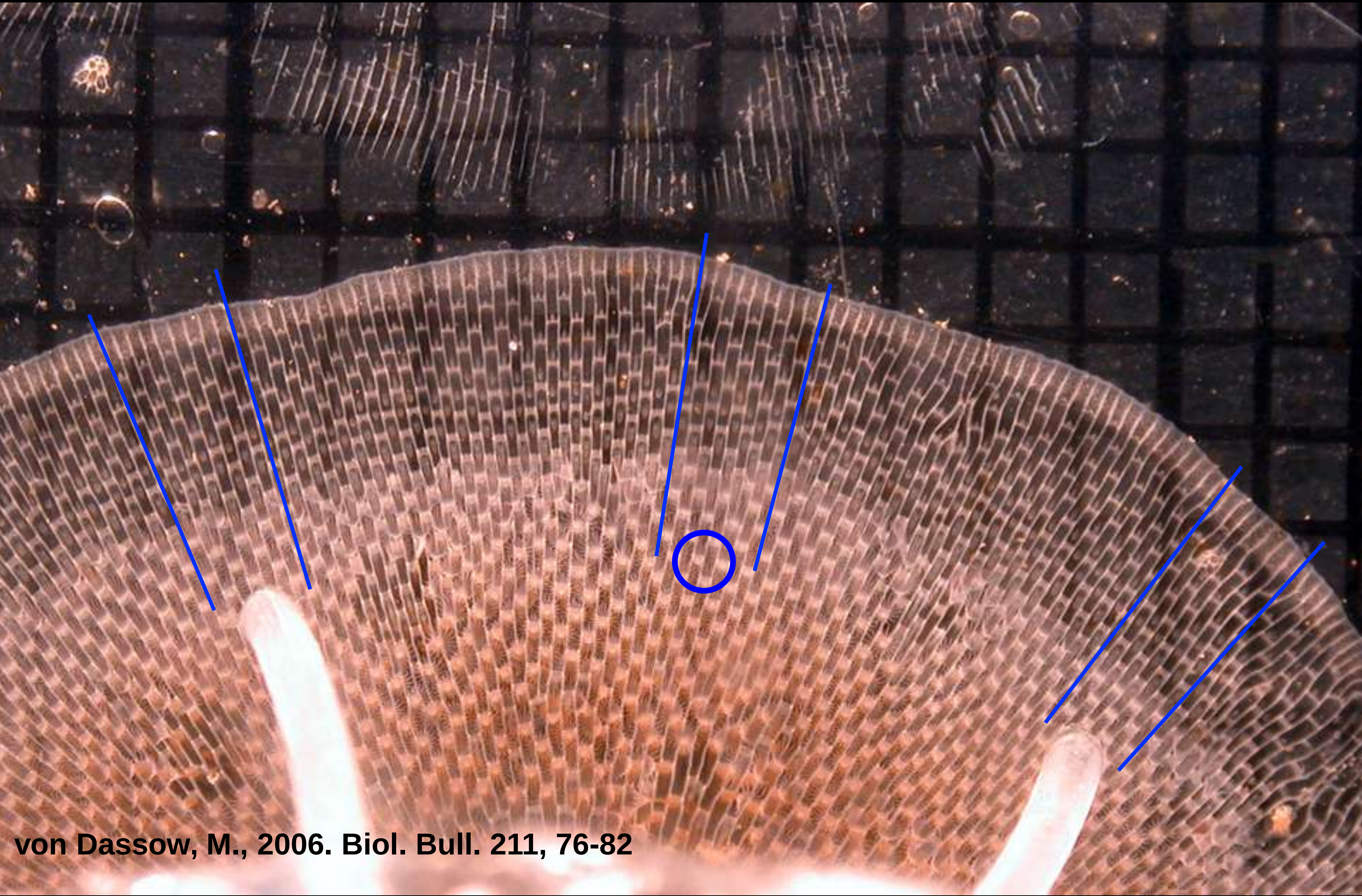
Does flow control where chimneys form?

Does high excurrent flow speed induce chimney formation?

Injected seawater under the canopy
to increase the flow out the canopy edge



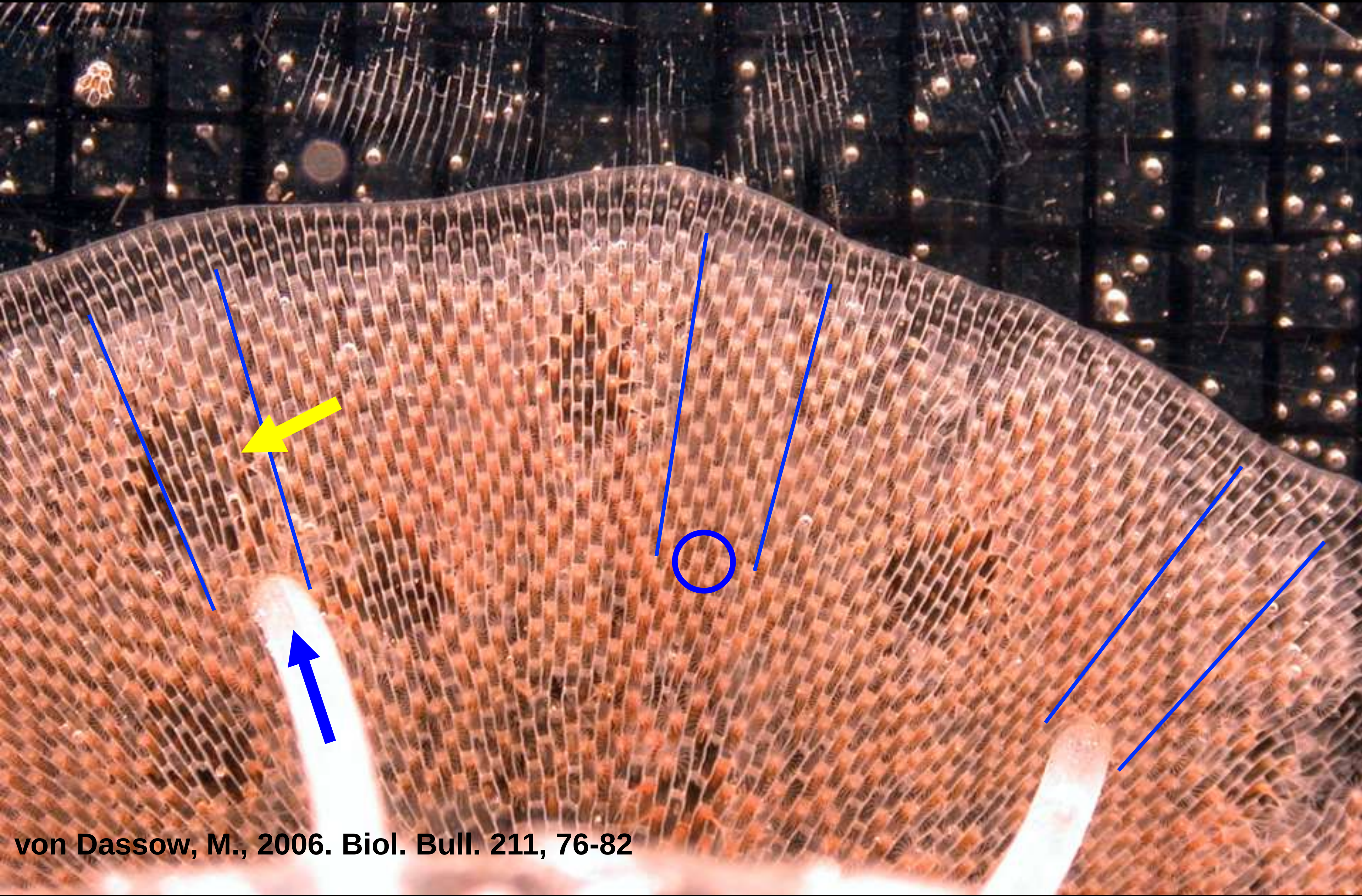
Prior to starting flow



von Dassow, M., 2006. Biol. Bull. 211, 76-82

5 days after starting flow

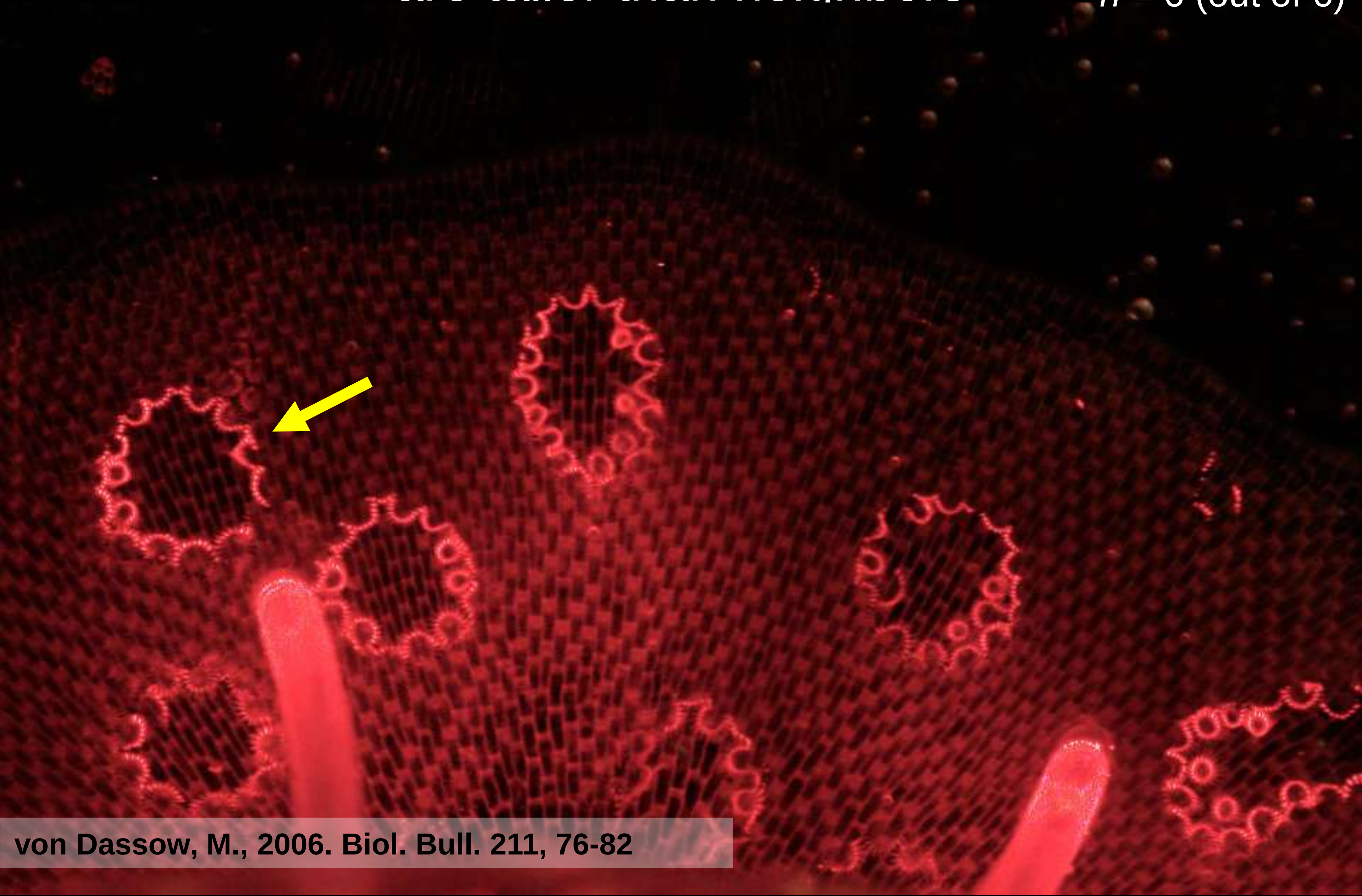
n = 9



von Dassow, M., 2006. Biol. Bull. 211, 76-82

Lophophores surrounding the opening are taller than neighbors

n = 6 (out of 6)



von Dassow, M., 2006. Biol. Bull. 211, 76-82

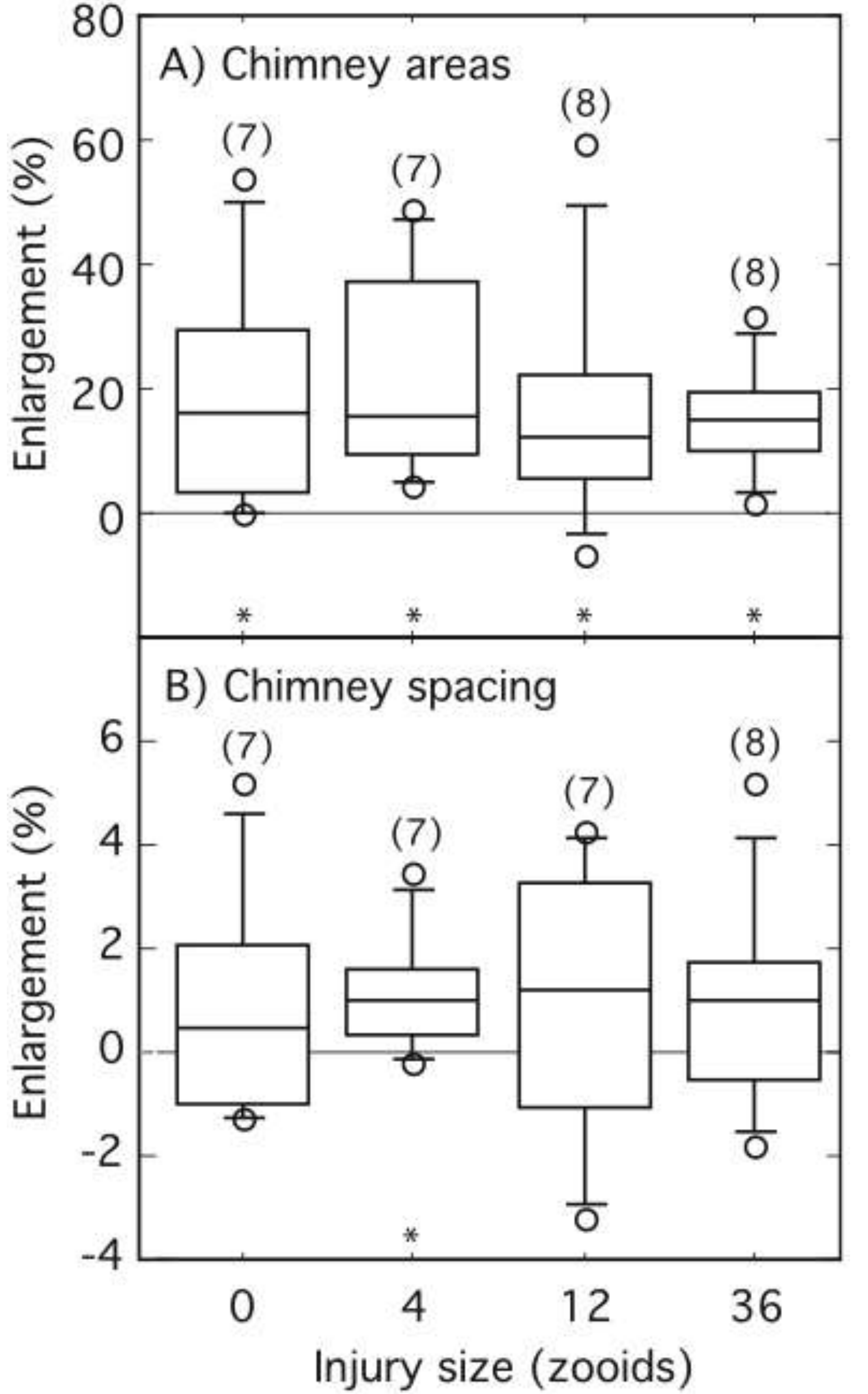
- High flow ➔ Chimney formation

- Flow affects conduit formation in both internal and external fluid transport systems

How might this affect responses to the environment?

Injuries did not affect nearby chimneys

Perturbations do not spread to existing chimneys



von Dassow, M., 2005.
Biol. Bull. 208, 47-59

Conclusions (part 3)

- Flow affects patterning in an external fluid transport system

  ➔ Drives responses to environment?

- But, changes in flow may not affect existing chimneys

  ➔ Limits responses to environment?

Consider organisms in their environment

- **What perturbations does the system normally face?**
- **What aspects of mechanics matter?**
- **How does mechanics contribute to phenotypic variation?**

*image from Yasmin von Dassow

*image from Yasmin von Dassow