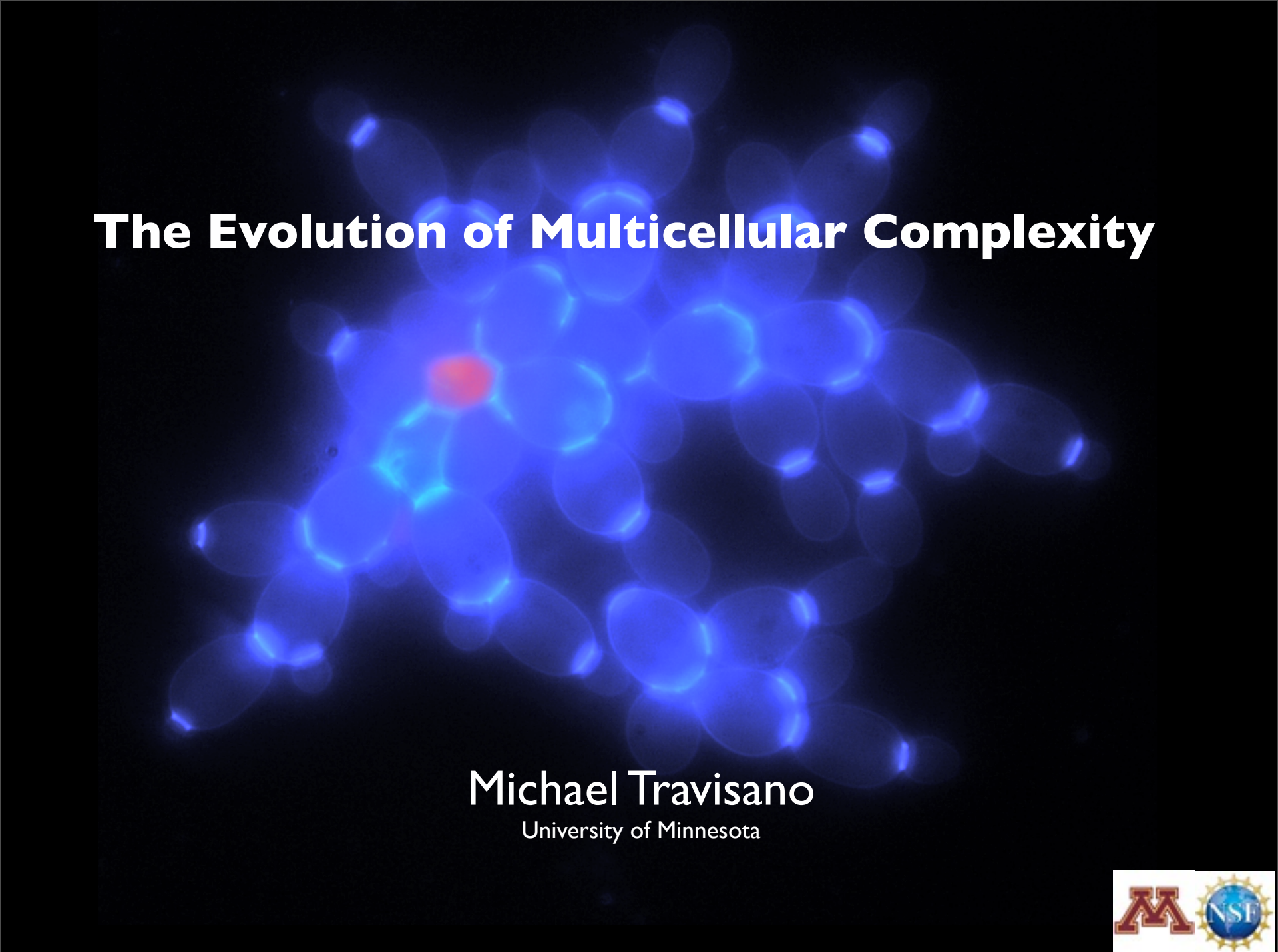
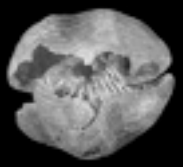
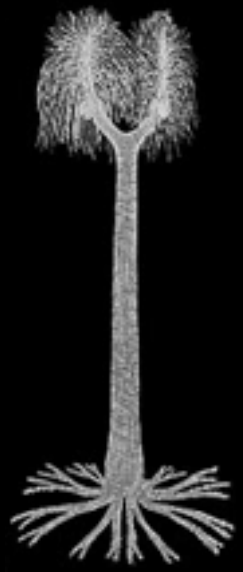
The Evolution of Multicellular Complexity



Michael Travisano
University of Minnesota

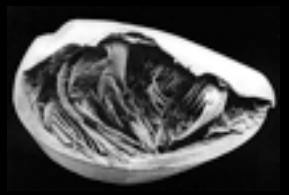


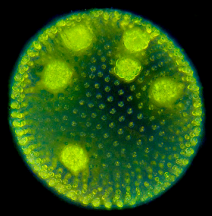




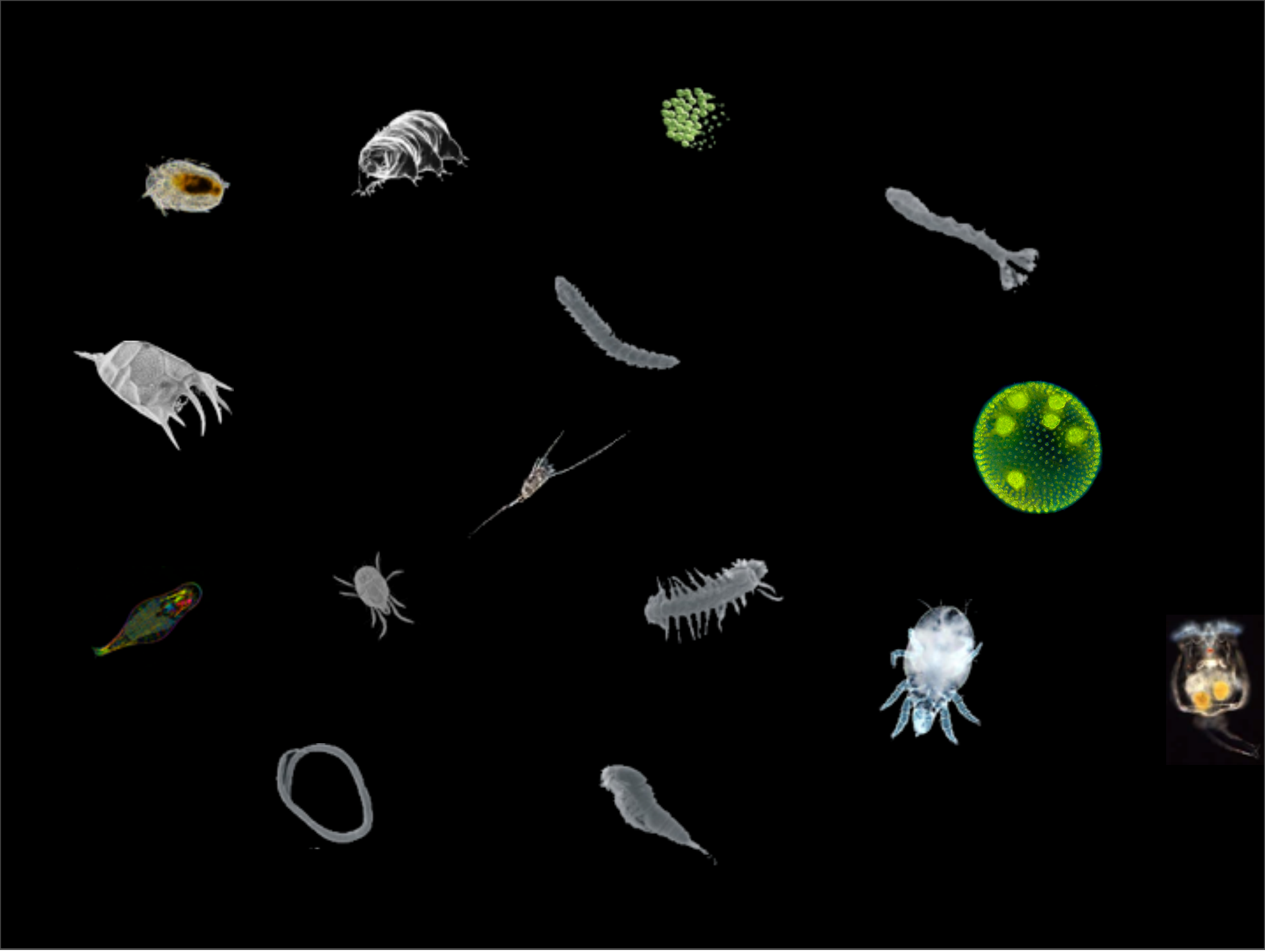




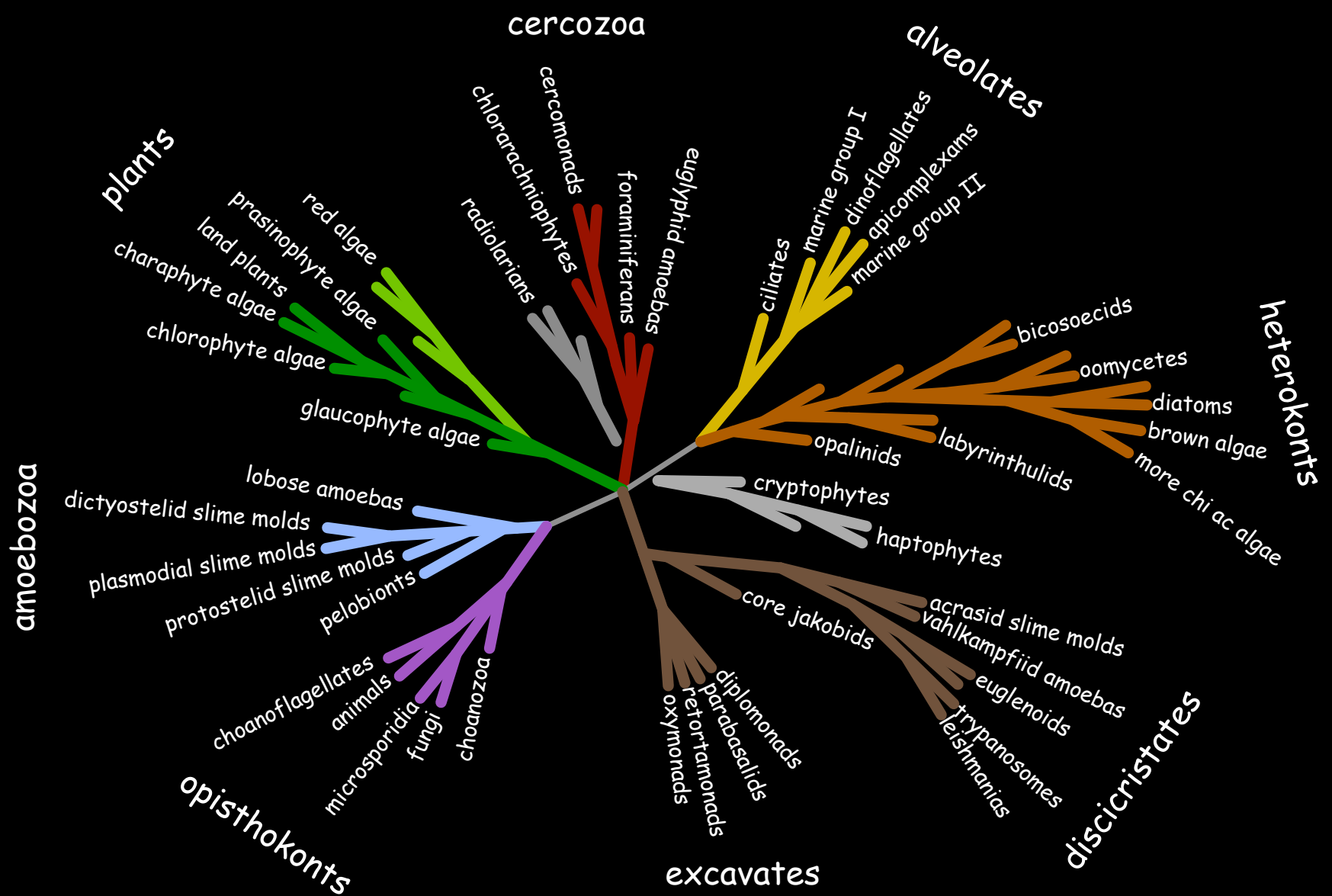






Eukaryotic Tree of Life



Baldauf 2003

Eukaryotic Tree of Life

Lineages with at least one multicellular species

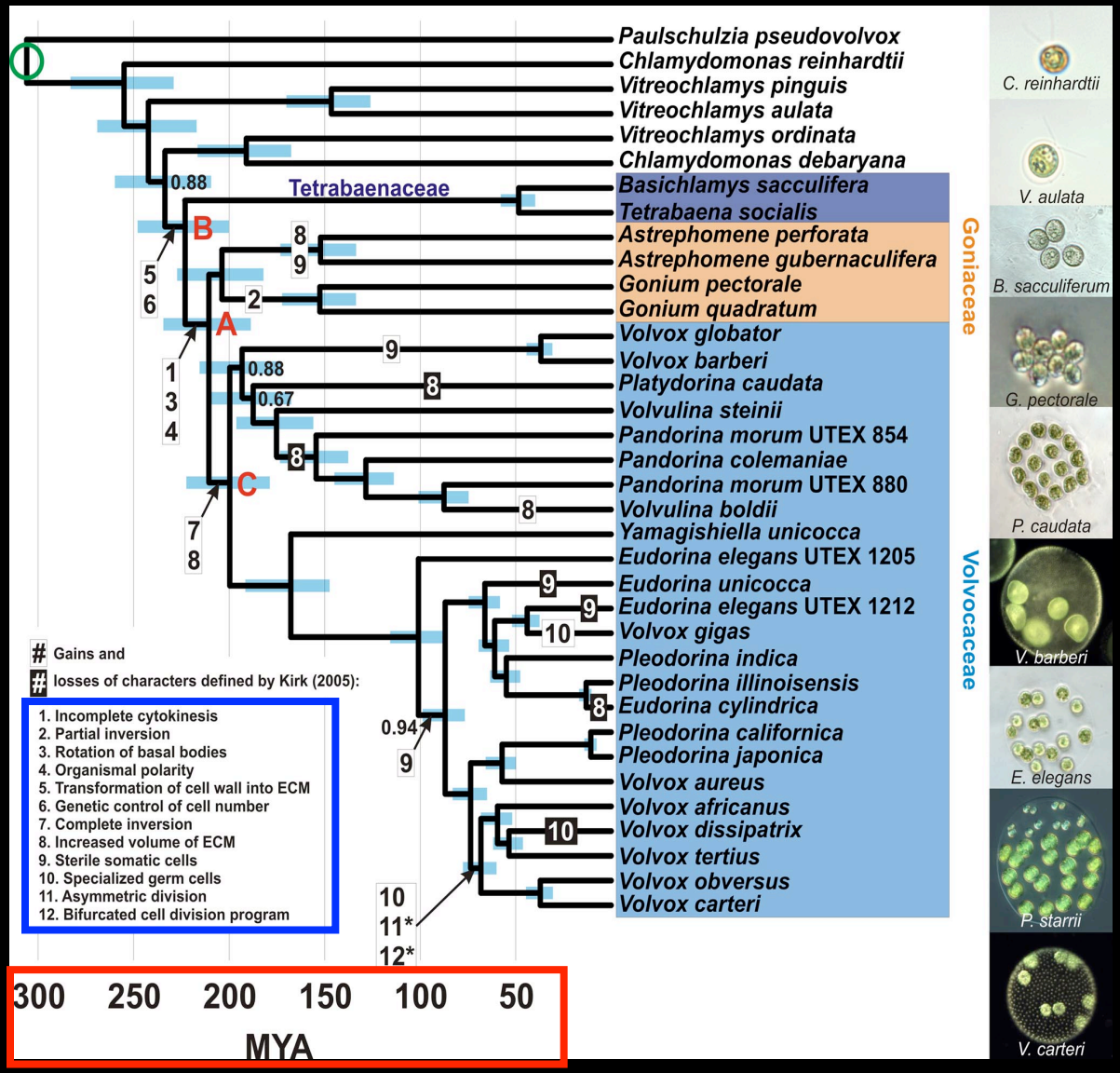
Baldauf 2003, King 2004
Grosberg & Strathmann 2007

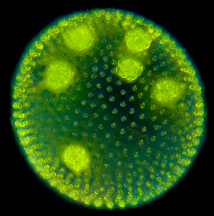
There were at least 25 transitions to multicellularity

There were at least 25 transitions to multicellularity

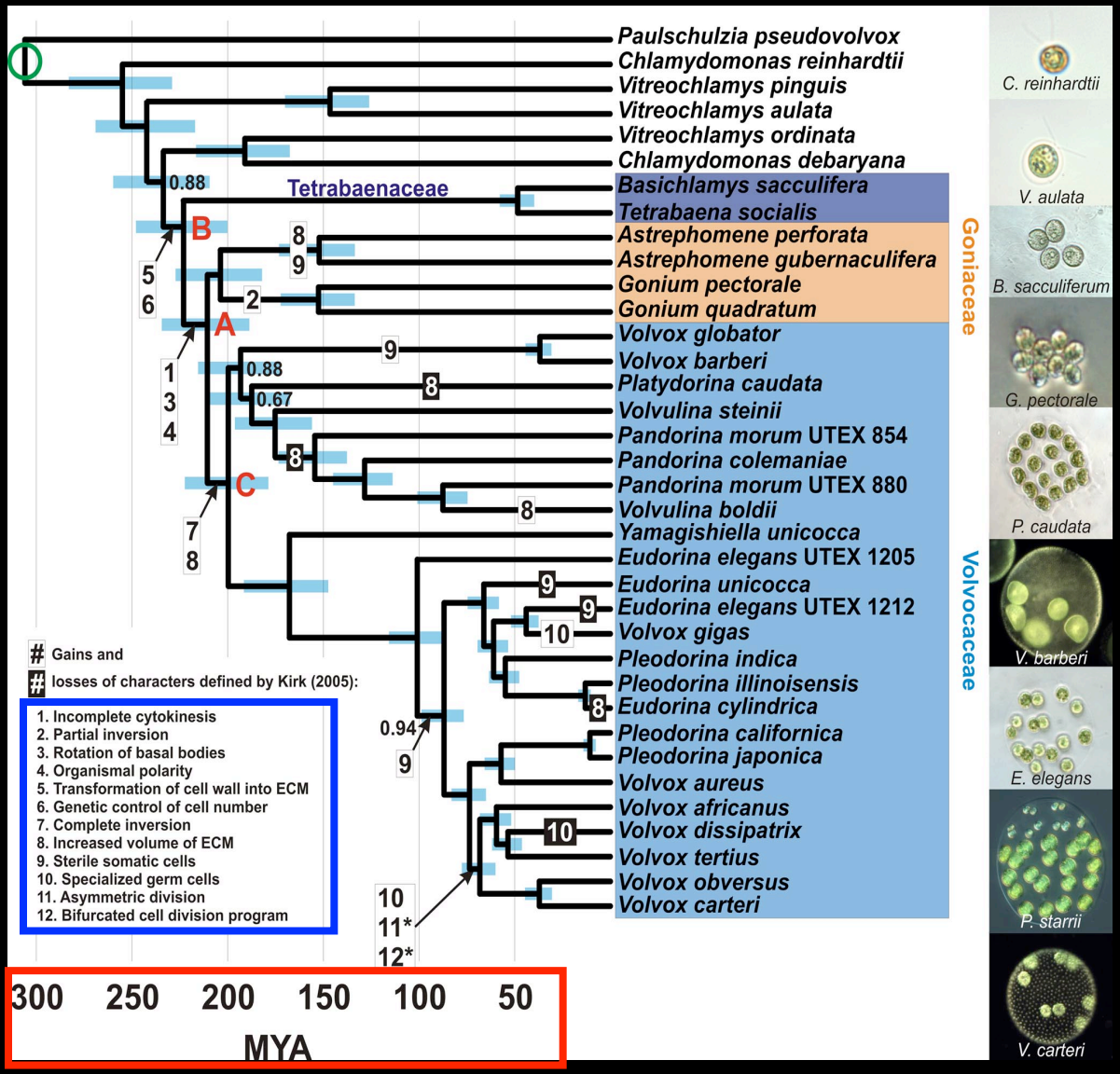
Why?

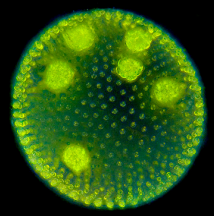
If multicellularity is a key innovation,
then wouldn't selection had lead to an ecological selective sweep?





Herron et al 2009





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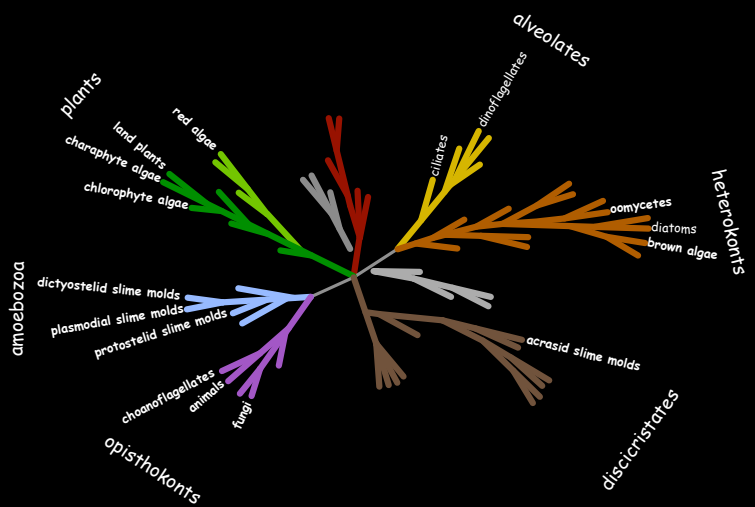
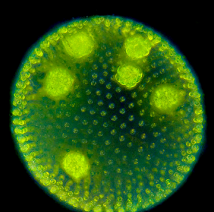
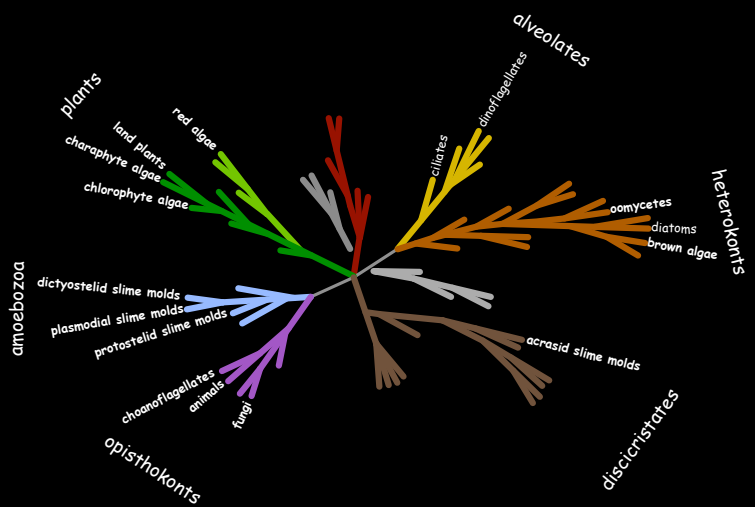




1. Multiple origins of multicellularity



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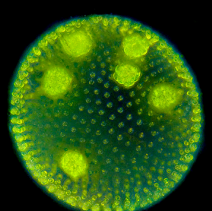

2. An ongoing process?

3

Evolution by Natural Selection

Evolution by Natural Selection

1. Individuals within populations are variable.

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2. The variation among individuals is, at least in part, heritable from parents to offspring.

3. Some individuals are more successful at surviving and reproducing than others.

4. The survival and reproduction of individuals is tied to the variation among individuals. The individuals with the most favorable variations are naturally selected.

The theory of natural selection does not predict increases in complexity

It predicts that fitness will increase in the short-term

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It predicts that fitness will increase in the short-term

cyanobacteria

little change in
3,500 million years

crinoids

little change in
450 million years

horsetails

little change in
375 million years

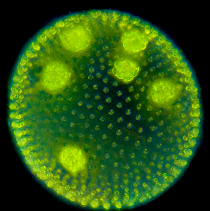
Yet some Lineages have become more Complex

Yet some Lineages have become more Complex

Is complexity adaptive?

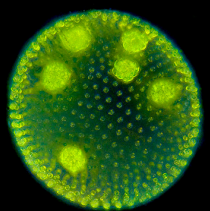
Questions about multicellularity

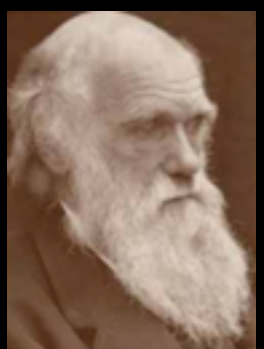
1. Why were there multiple origins?



2. Why is it ongoing process?

Questions about multicellularity





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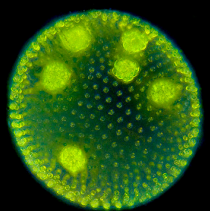

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NATURAL ENGINEERING

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Dynamics of adaptation and diversification: A 10,000-generation experiment with bacterial populations

(experimental evolution/macroevolution/natural selection/cell size/*Escherichia coli*)

RICHARD E. LENSKI AND MICHAEL TRAVISANO*

Proc. Natl. Acad. Sci. USA
Vol. 91, pp. 6808–6814, July 1994

Experimental Tests of the Roles of Adaptation, Chance, and History in Evolution

Michael Travisano, Judith A. Mongold, Albert F. Bennett, Richard E. Lenski* SCIENCE • VOL. 267 • 6 JANUARY 1995

Adaptive radiation in a heterogeneous environment

Paul B. Rainey & Michael Travisano

NATURE | VOL 394 | 2 JULY 1998

THE ROYAL SOCIETY biology letters

The Prisoner's Dilemma and polymorphism in yeast *SUC* genes

Duncan Greig* and Michael Travisano

Hybrid Speciation in Experimental Populations of Yeast

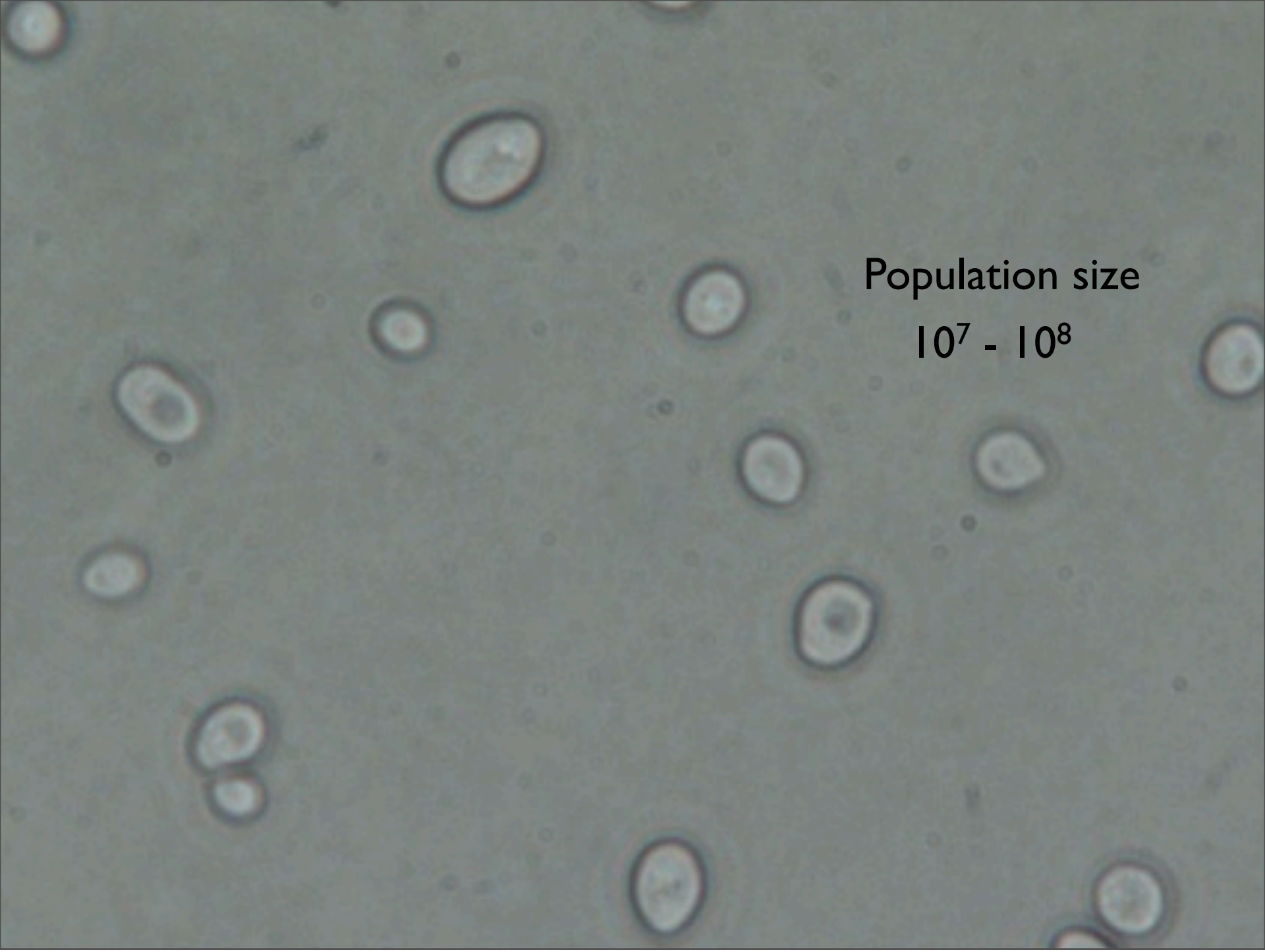
Duncan Greig,[1,2] Edward J. Louis,[3] Rhona H. Borts,[3] Michael Travisano[2]*

PROCEEDINGS OF THE ROYAL SOCIETY B

Proc. R. Soc. B (2009) **276**, 2065–2070
doi:10.1098/rspb.2008.1827
Published online 4 March 2009

Spatial structure leads to ecological breakdown and loss of diversity

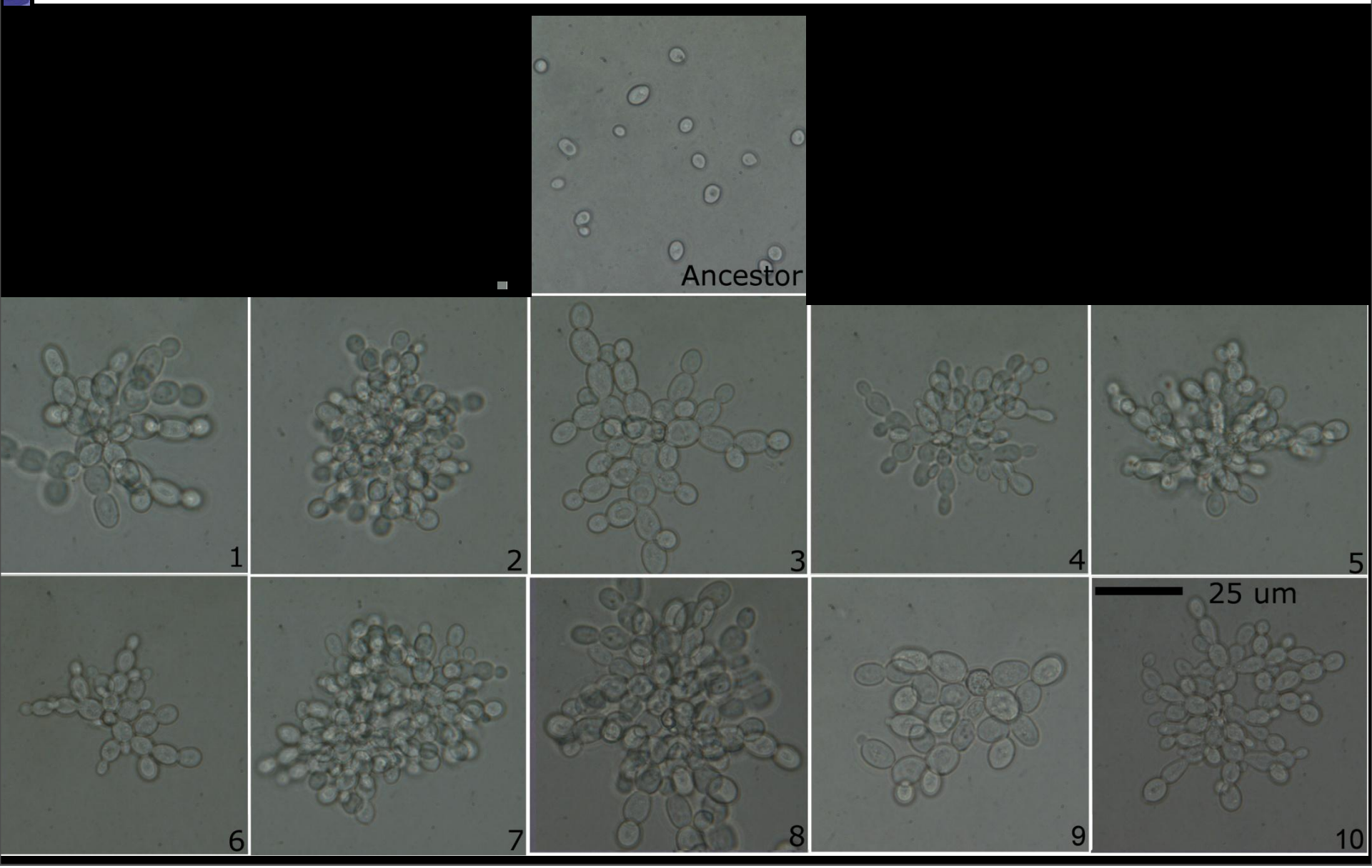
Gerda Saxer[1,2,3,*], Michael Doebeli[1,4] and Michael Travisano[2,5]


Population size
10^7 - 10^8

Experimental evolution of multicellularity

William C. Ratcliff[a,1], R. Ford Denison[a], Mark Borrello[a], and Michael Travisano[a,b]

www.pnas.org/cgi/doi/10.1073/pnas.1115323109 2012



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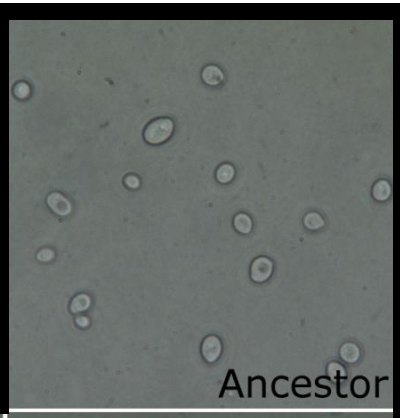

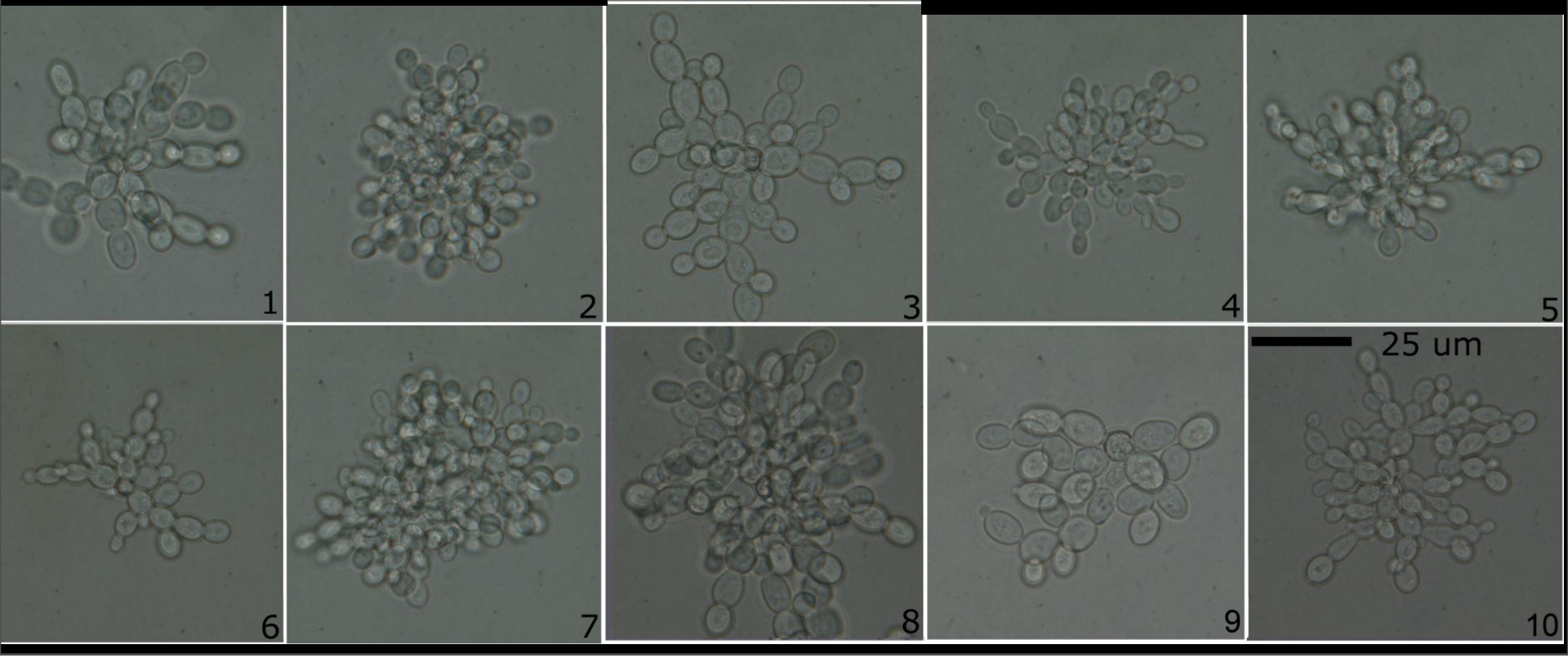

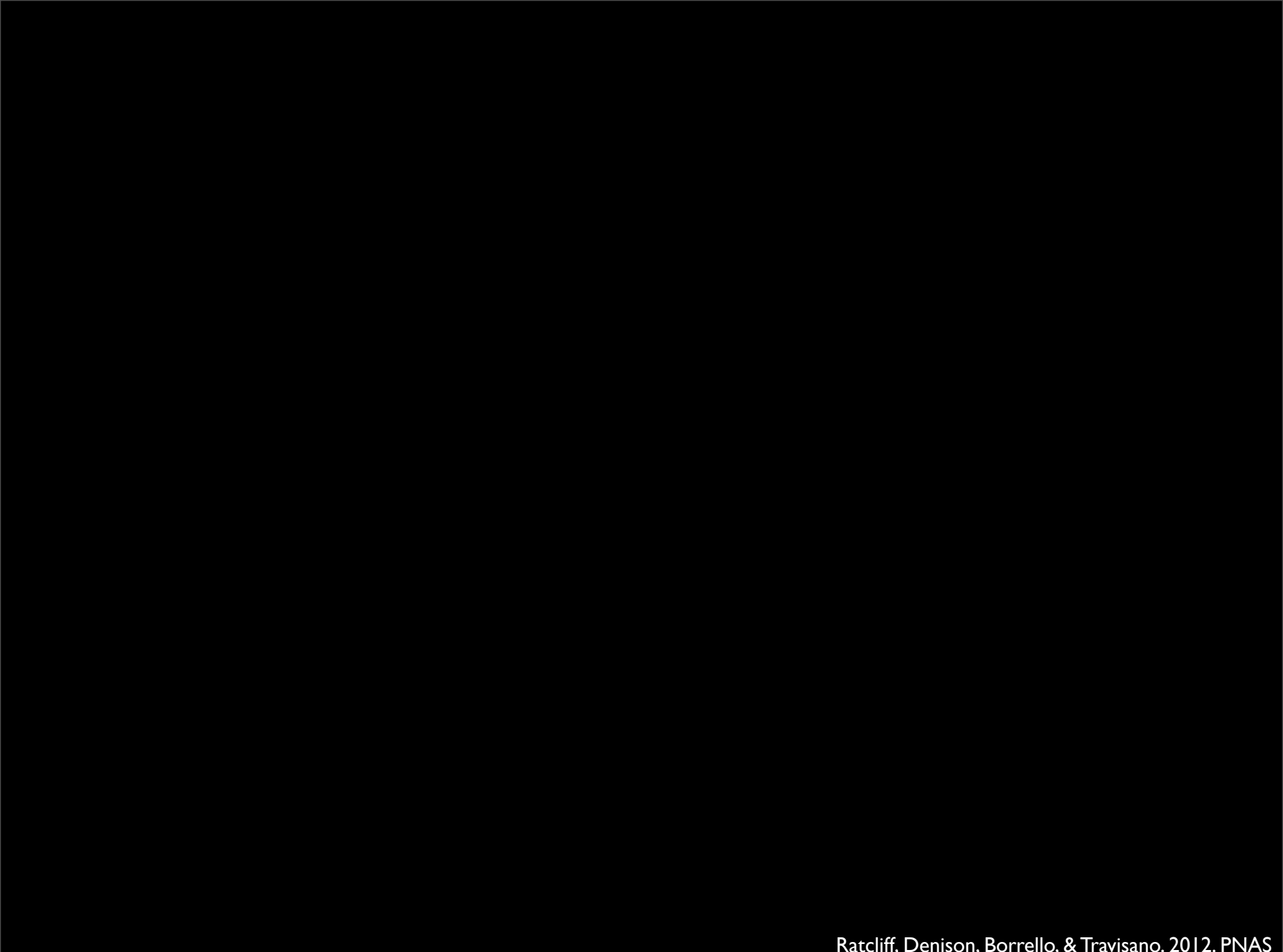

Ratcliff, Denison, Borrello, & Travisano. 2012. PNAS

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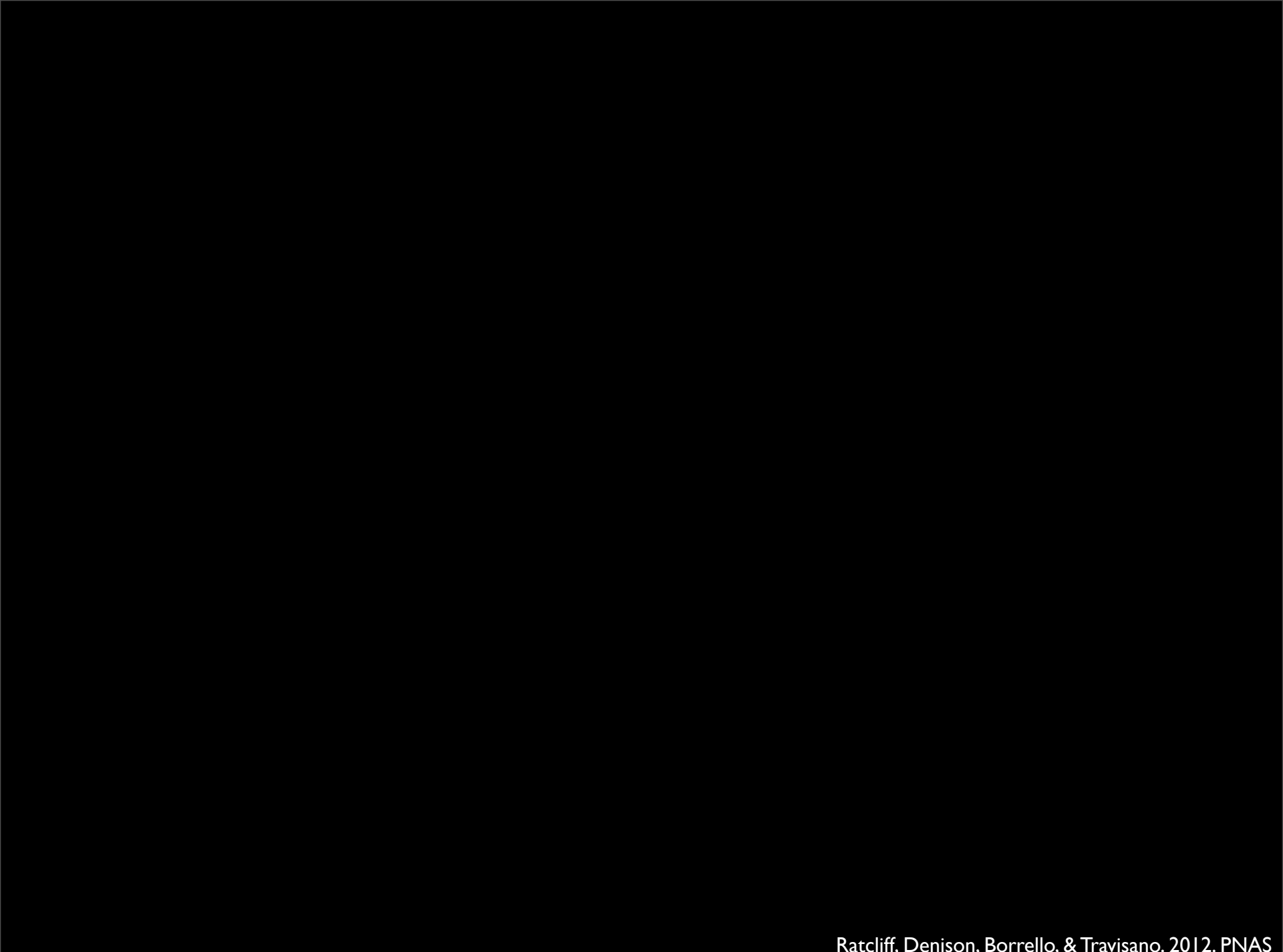
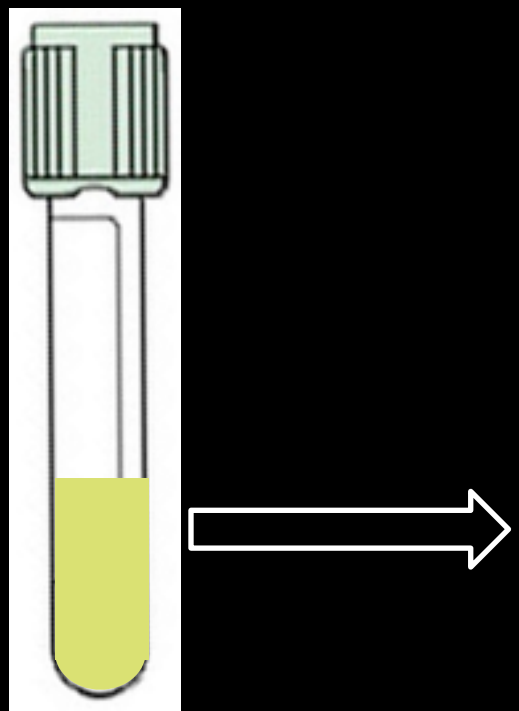


Ratcliff, Denison, Borrello, & Travisano. 2012. PNAS

selection scheme



24 hour, shaking incubation

Ratcliff, Denison, Borrello, & Travisano. 2012. PNAS

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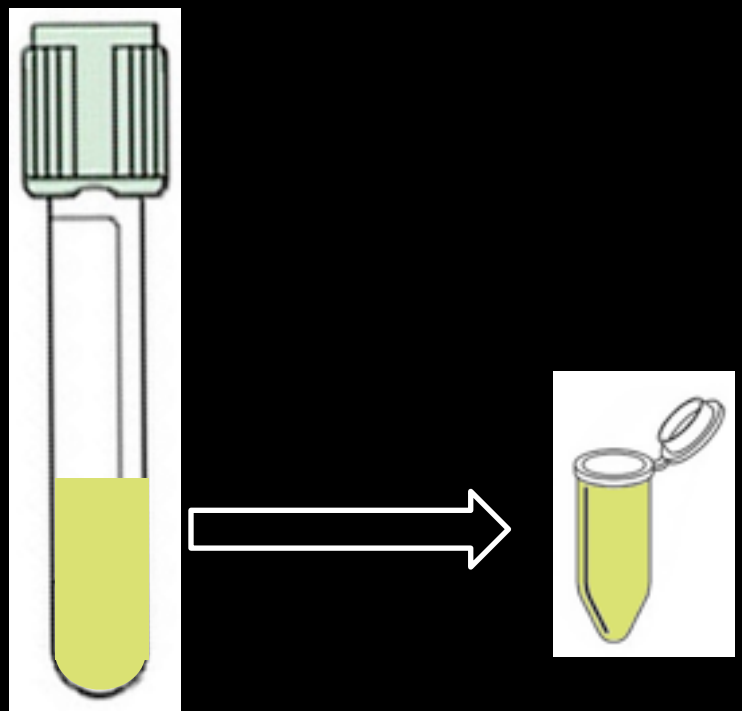

24 hour, shaking incubation

centrifuge 100g for 10 seconds

Ratcliff, Denison, Borrello, & Travisano. 2012. PNAS

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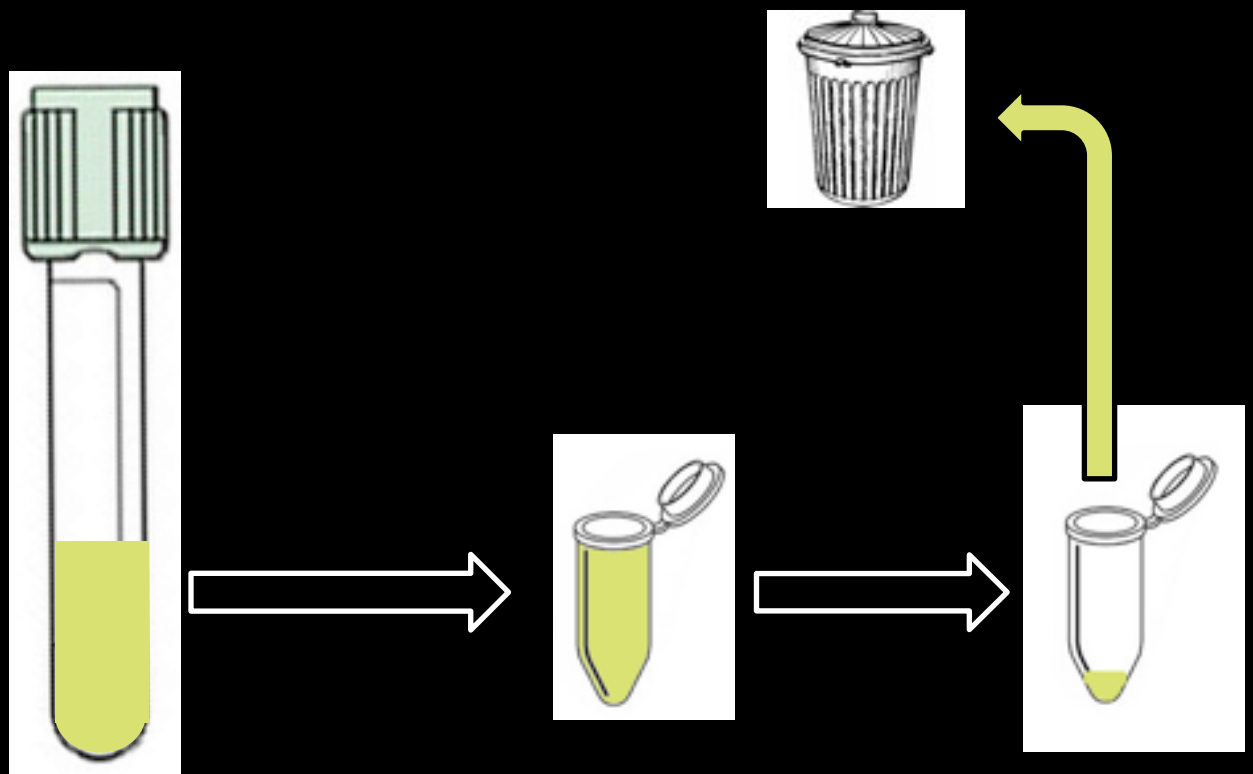


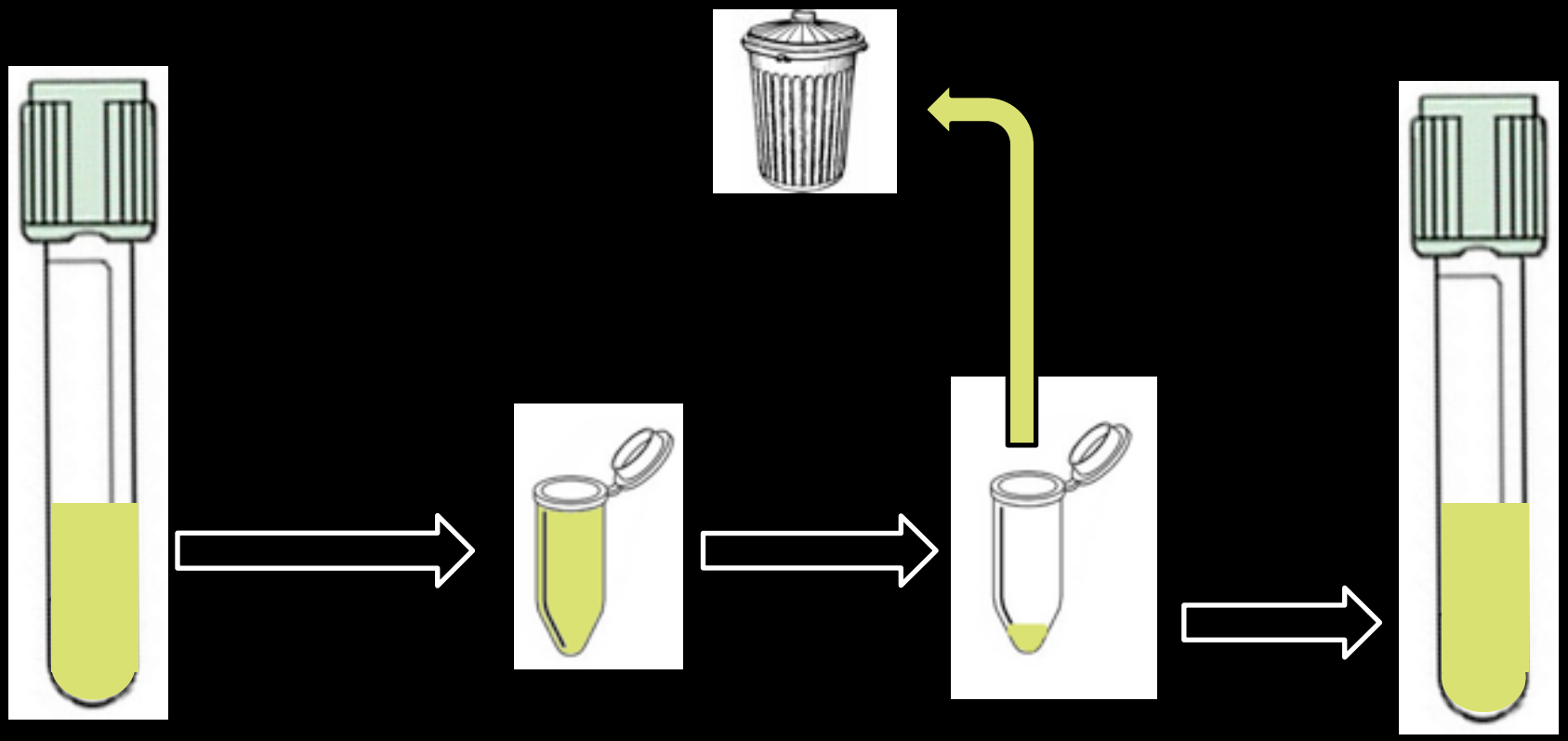
24 hour, shaking incubation

centrifuge 100g for 10 seconds

discard upper 93% of media

Ratcliff, Denison, Borrello, & Travisano. 2012. PNAS

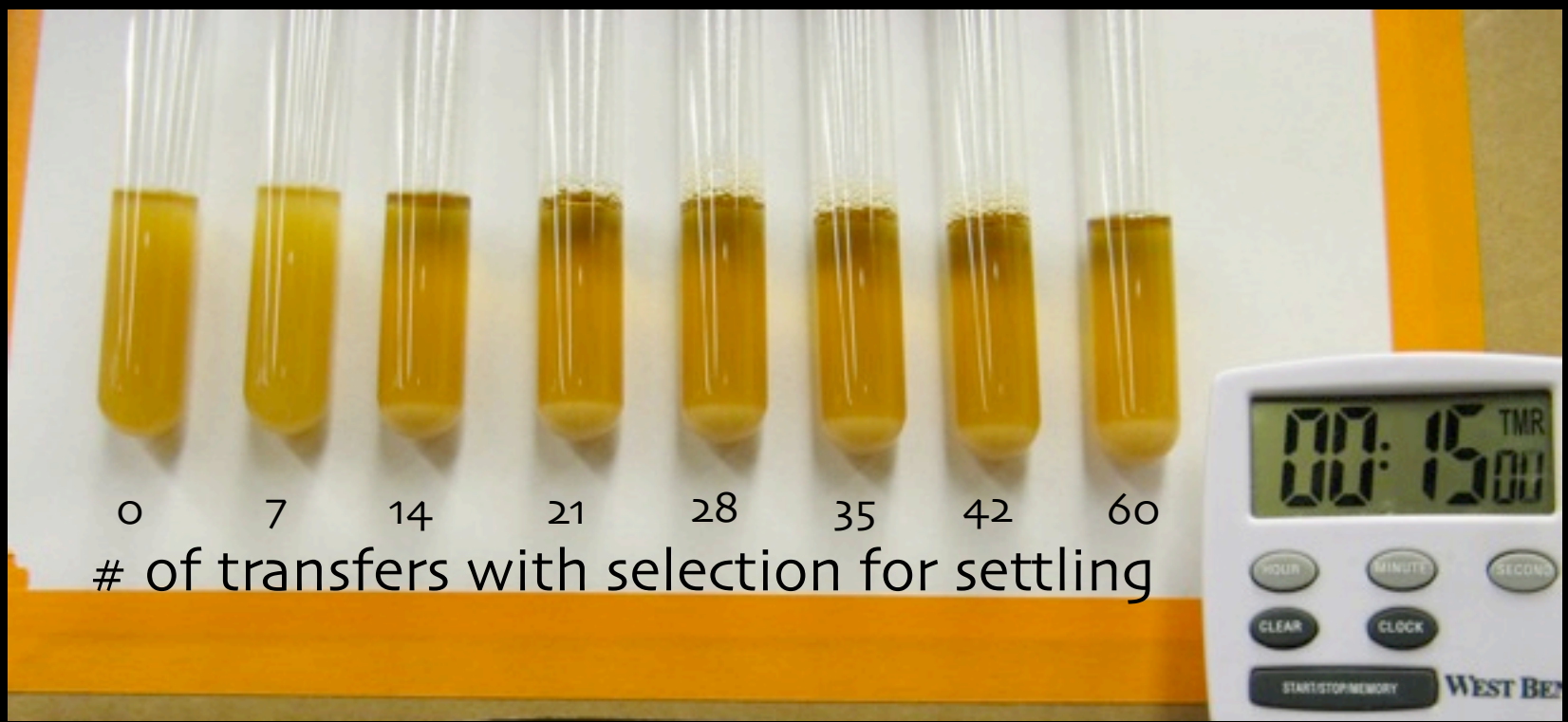
selection scheme



Ratcliff, Denison, Borrello, & Travisano. 2012. PNAS

evolution of rapid settling

time series of a single replicate

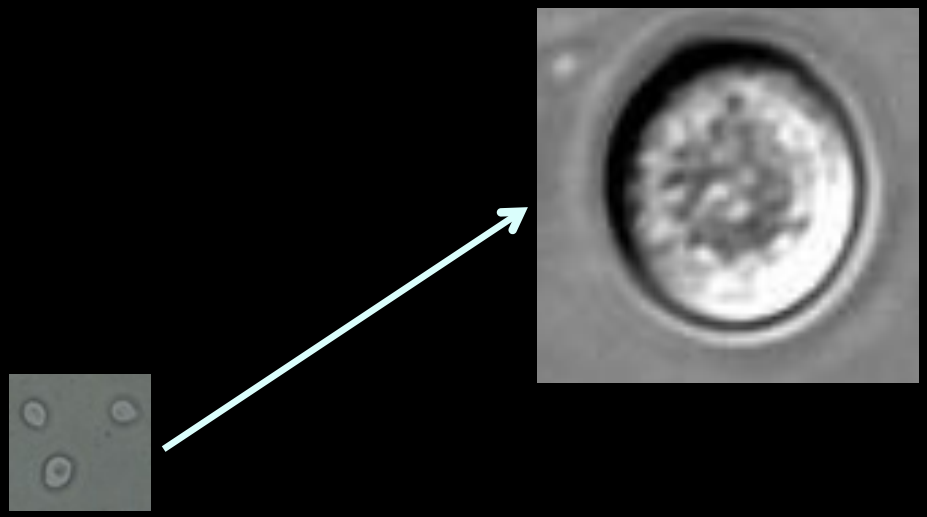


Ratcliff, Denison, Borrello, & Travisano. 2012. PNAS

multicellularity is a simple solution to selection for larger size

Unicellular ancestor

multicellularity is a simple solution to selection for larger size



Giant cells may be
hard to evolve, and may have
negative consequences

Unicellular ancestor

multicellularity is a simple solution to selection for larger size

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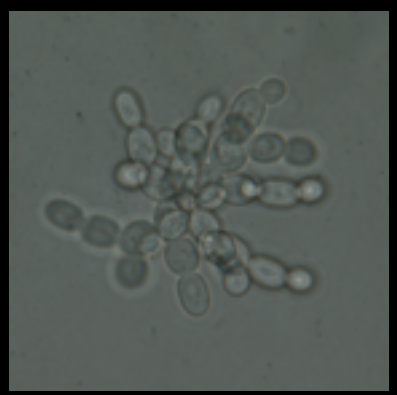


Attached cells may be
easier to evolve, and have
fewer negative consequences

Two routes to faster settling

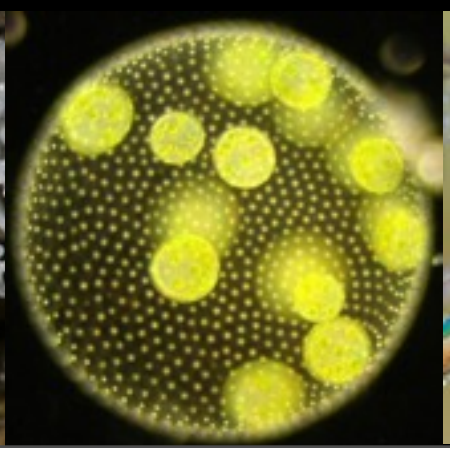
unicellular

normal size cell

large-celled genotype

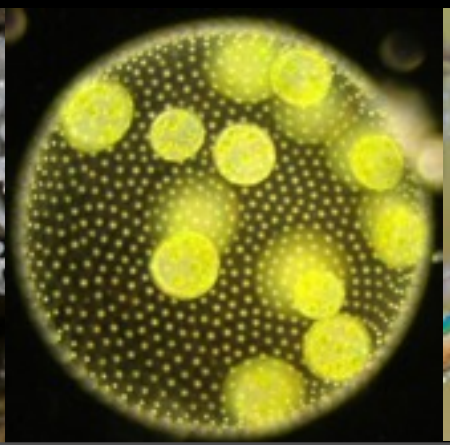
Ratcliff, Denison, Borrello, & Travisano. 2012. PNAS

Characteristics of multicellularity

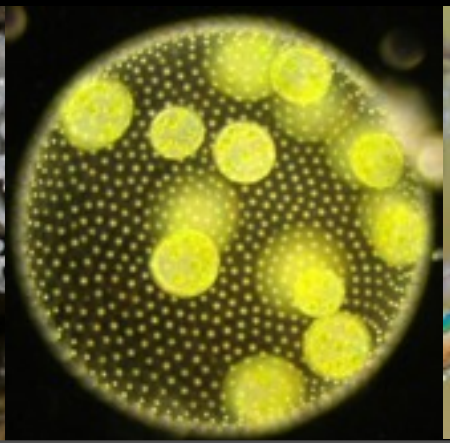
Characteristics of multicellularity

- Physical adhesion between cells

Characteristics of multicellularity

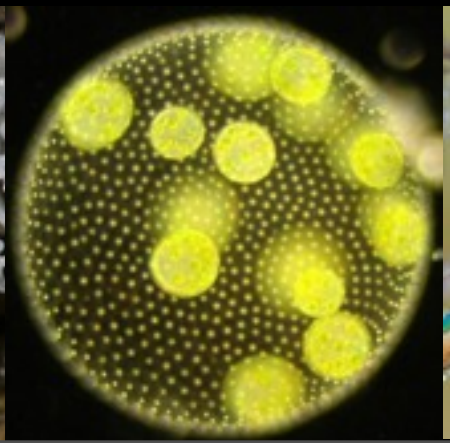
- Physical adhesion between cells
- Multicellular life-history

Characteristics of multicellularity

- Physical adhesion between cells
- Multicellular life-history

  - reproduction

Characteristics of multicellularity

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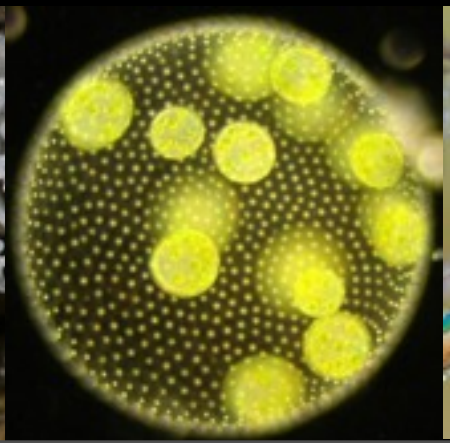
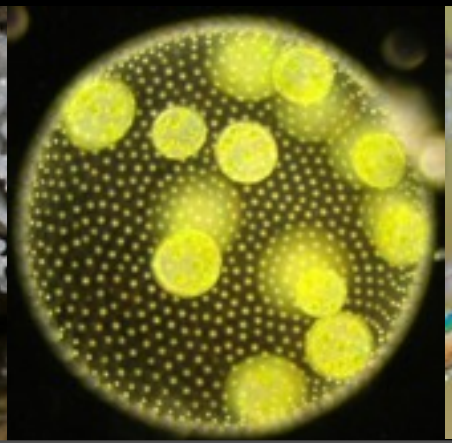
  - juvenile and adult stages

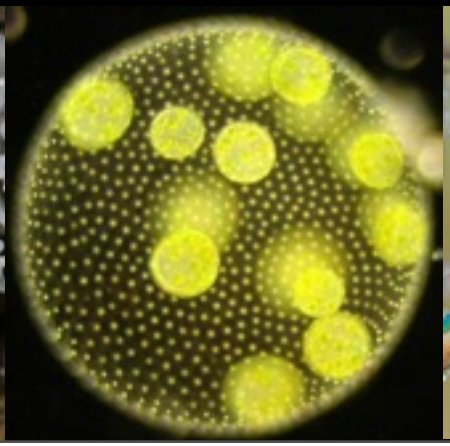
Characteristics of multicellularity

- Physical adhesion between cells
- Multicellular life-history
  - reproduction
  - juvenile and adult stages
- Life history responds to selection

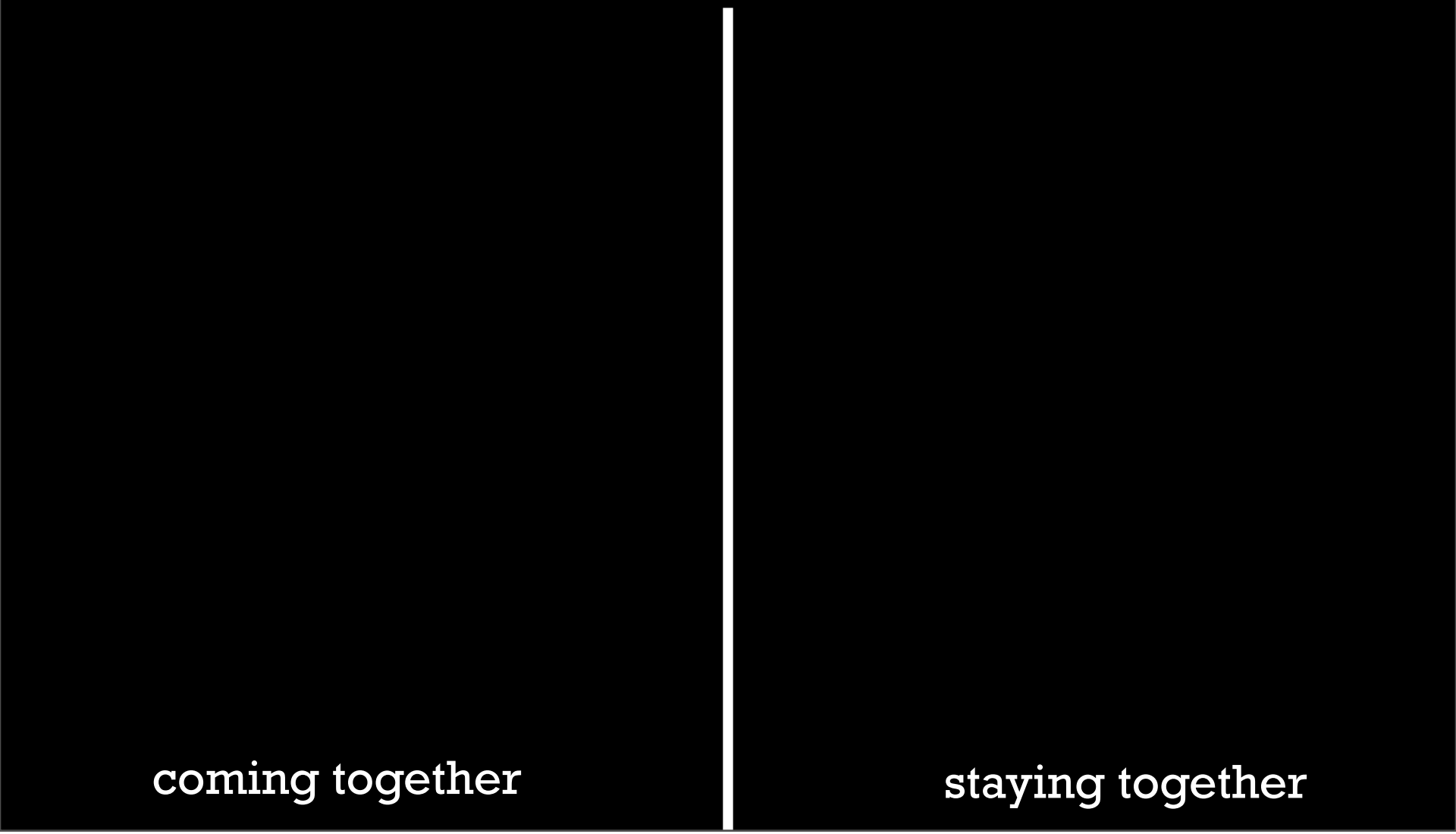



Characteristics of multicellularity

- Physical adhesion between cells
- Multicellular life-history
  - reproduction
  - juvenile and adult stages
- Life history responds to selection
- Division of labor among cells

Modes for Evolution of Multicellularity



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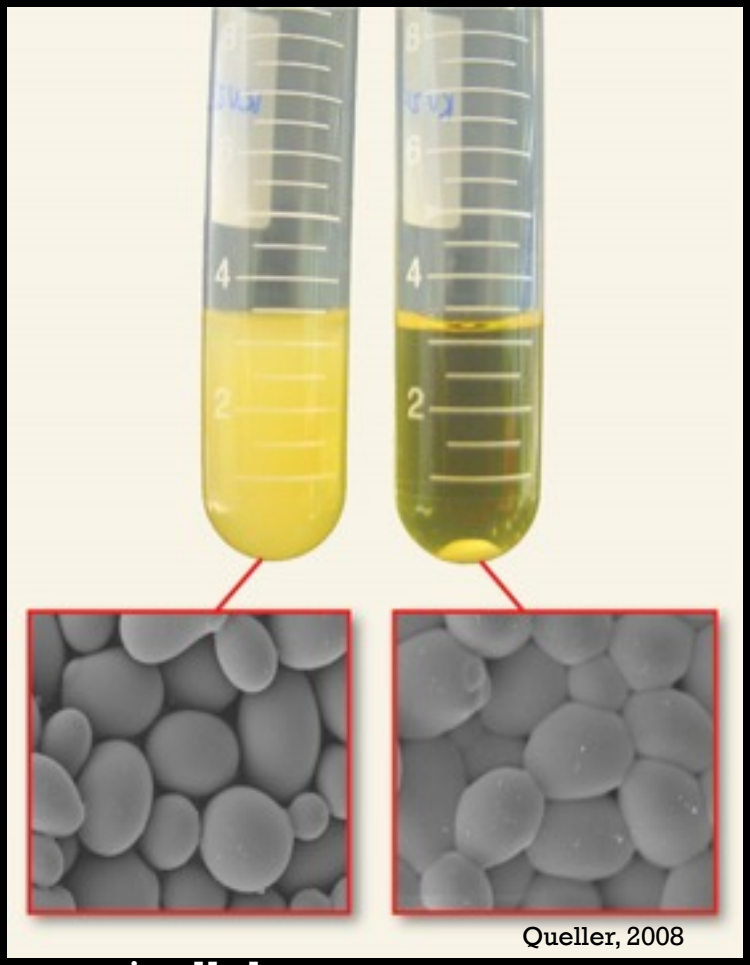


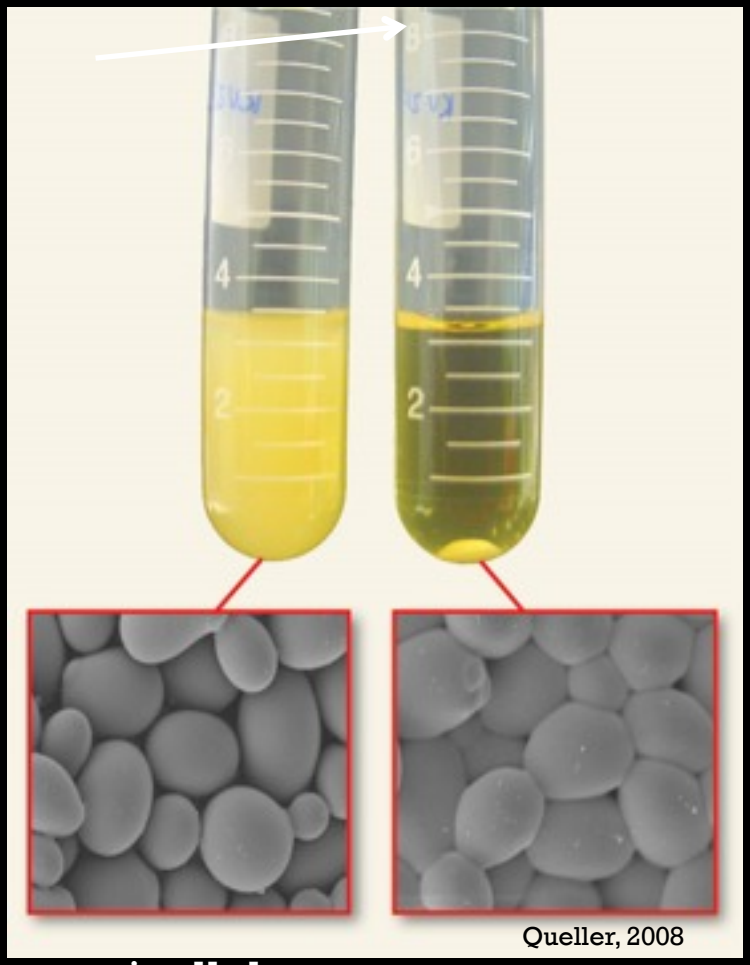
unicellular
wild type

floc +

coming together

staying together

Modes for Evolution of Multicellularity



Queller, 2008

unicellular wild type

floc +

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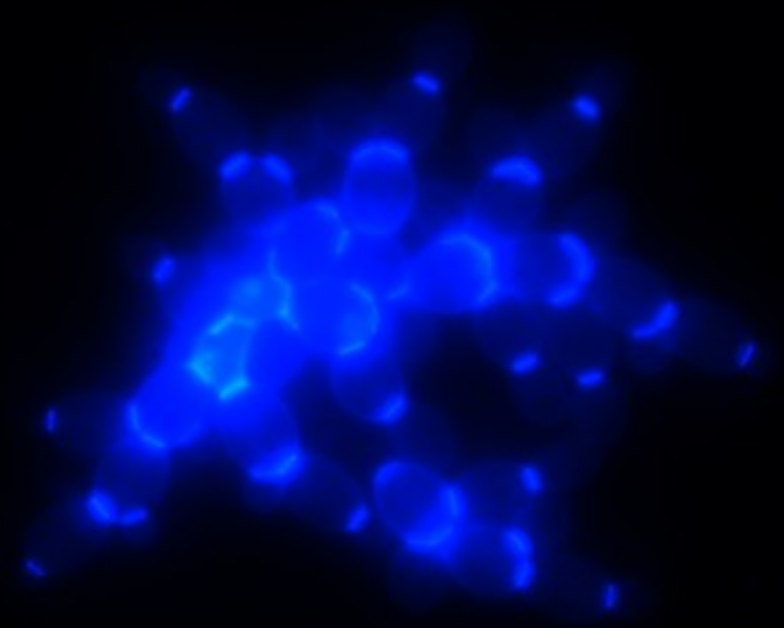
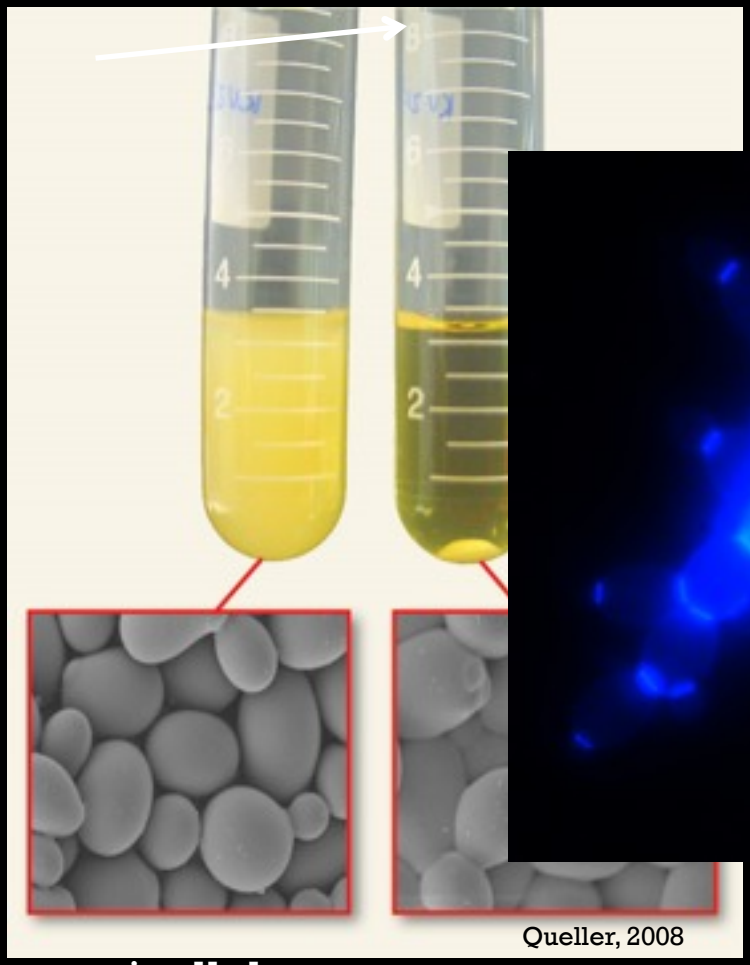


snowflake phenotype cluster

Ratcliff, Denison, Borrello, & Travisano. 2012

staying together

Modes for Evolution of Multicellularity



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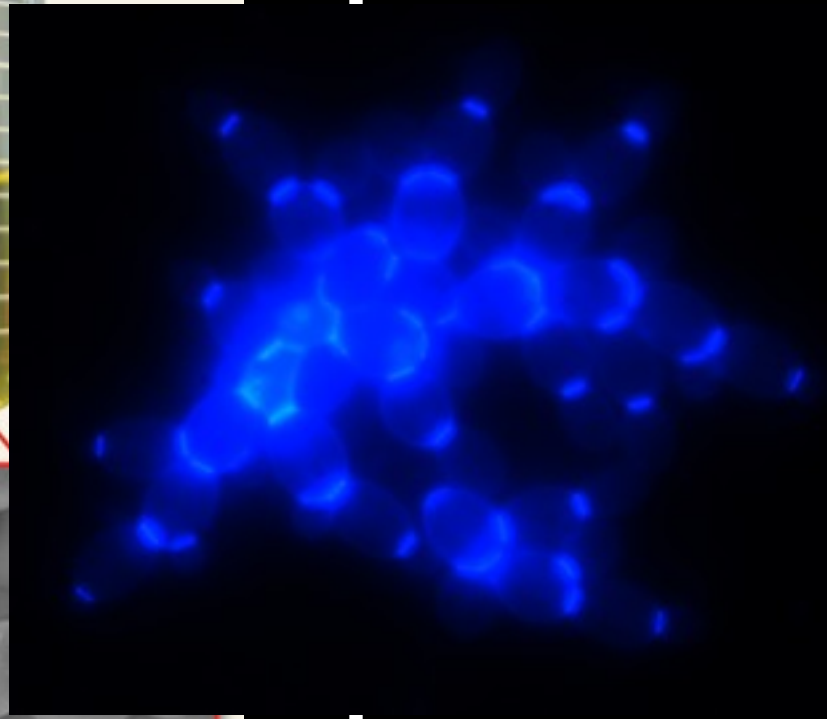

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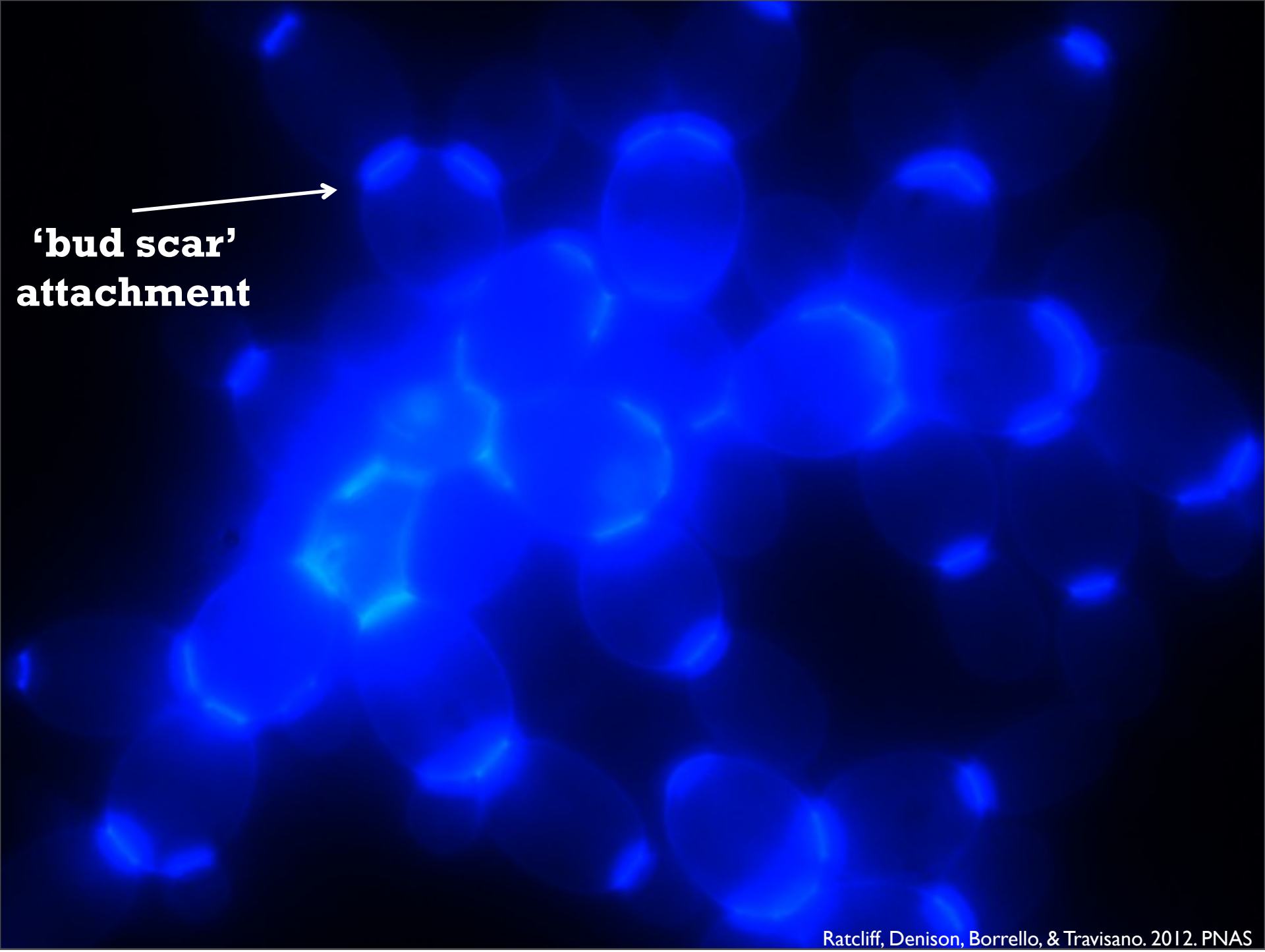
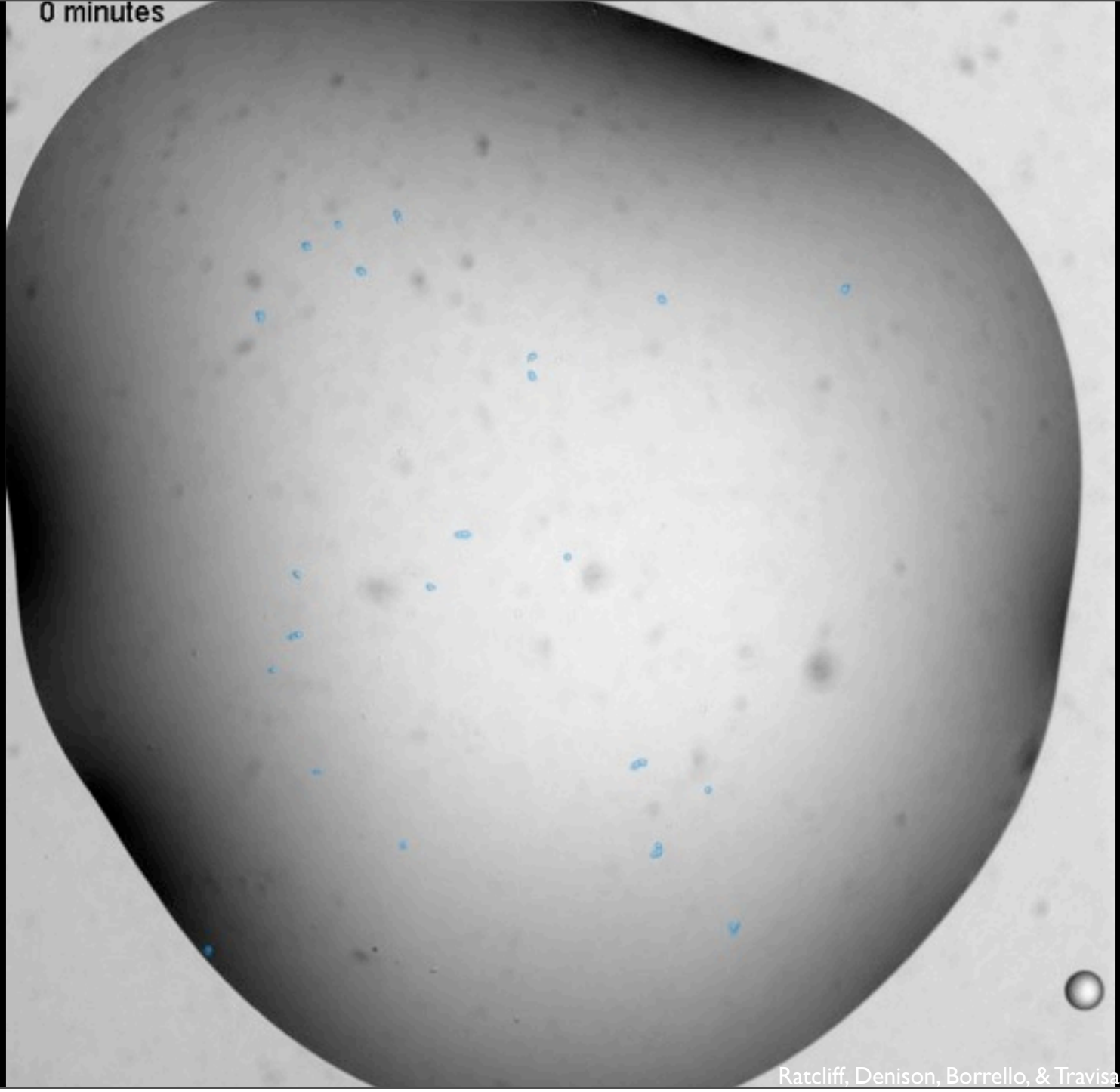


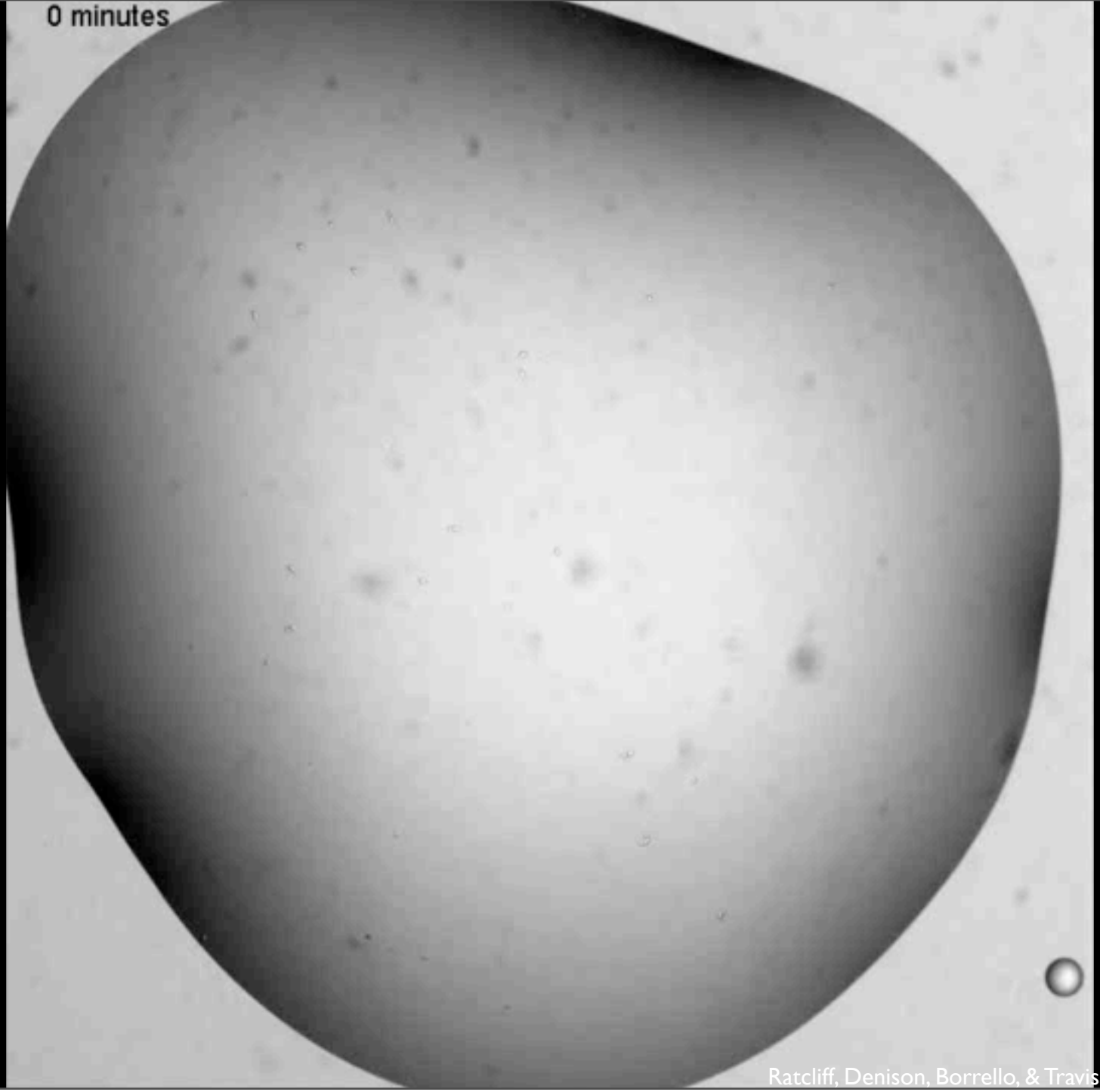
Ratcliff, Denison, Borrello, & Travisano. 2012. PNAS



Ratcliff, Denison, Borrello, & Travisano. 2012. PNAS

ngle cells regenerate cluste

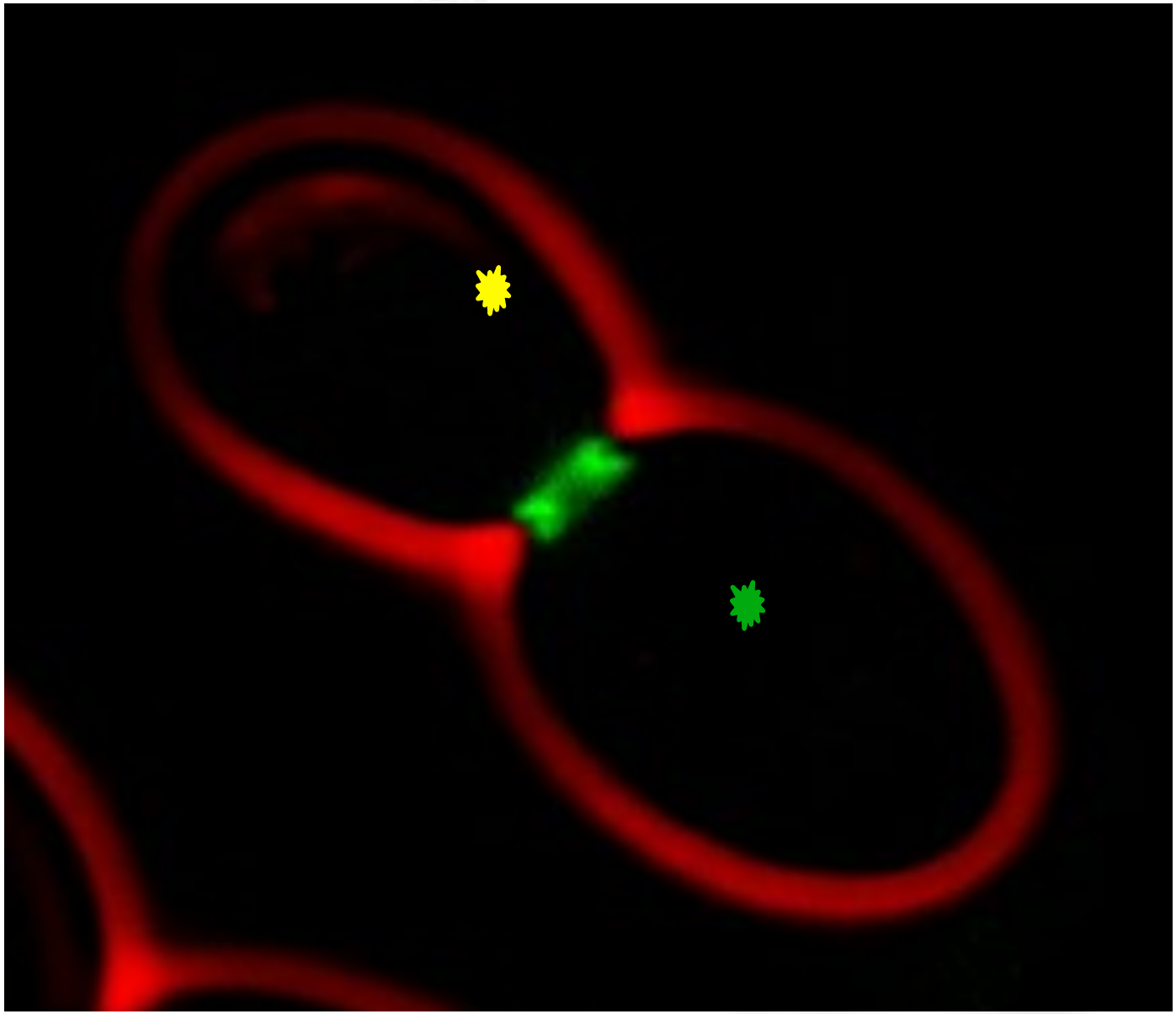
sano. 2012. PNAS



Ratcliff, Denison, Borrello, & Travisano. 2012. PNAS

Molecular Mechanism

ACE2 TF activity impaired but where?



Fluorescent micrograph of *Saccharomyces cerevisiae*
Green: Septum
Red: Cell outline

Spitfire ch, Philippsen Lab, Biozentrum Basel (2006)

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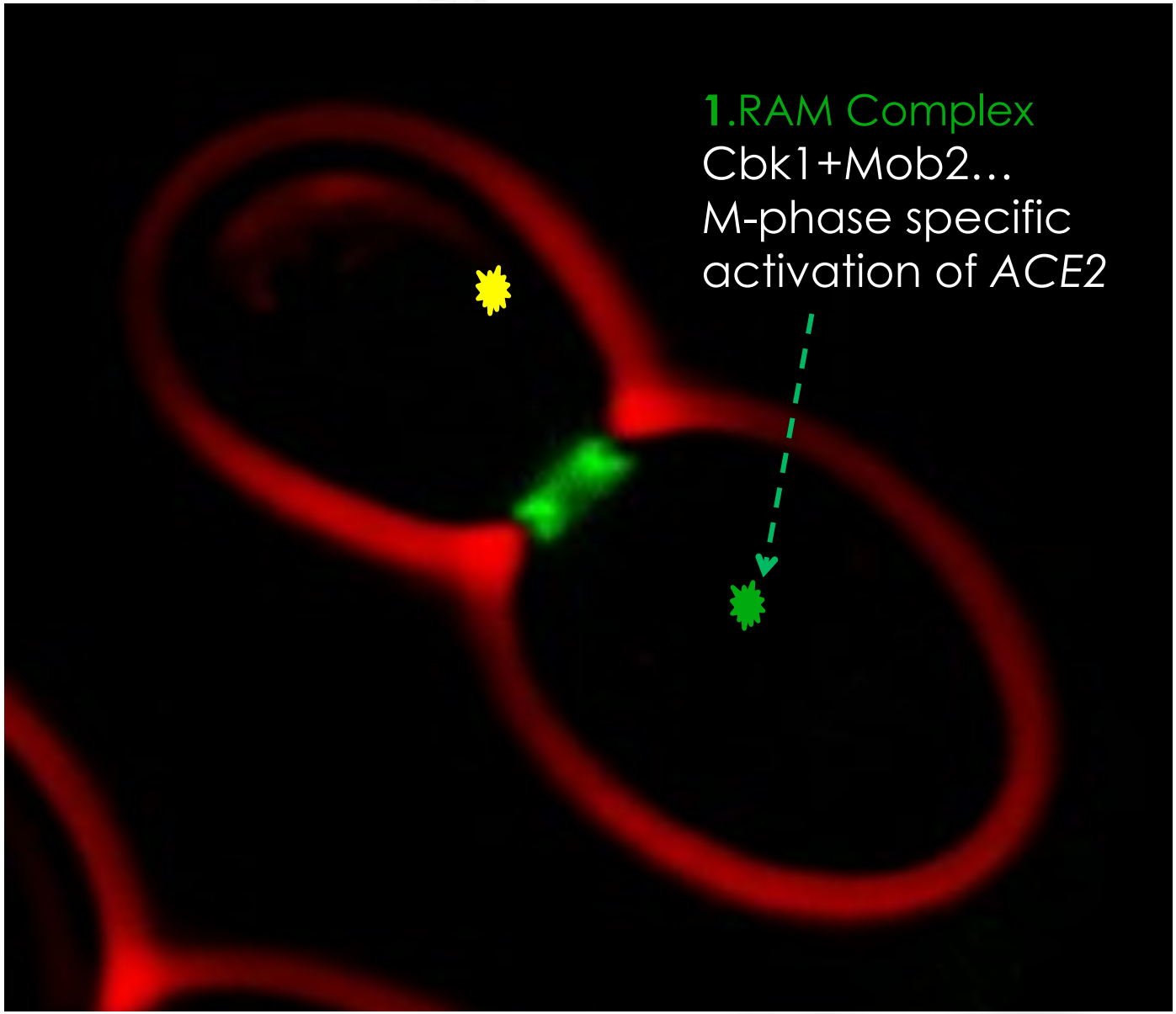

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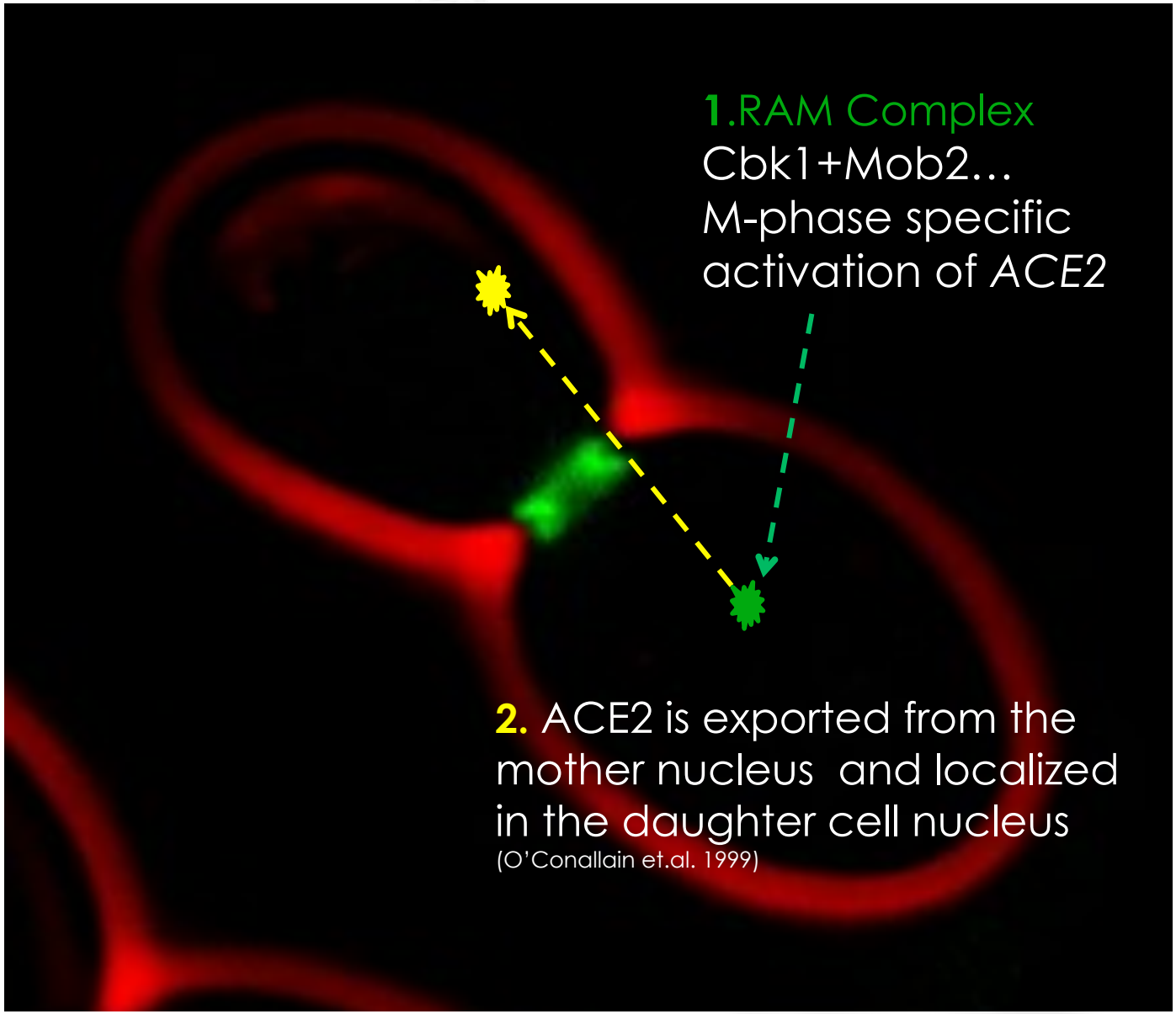

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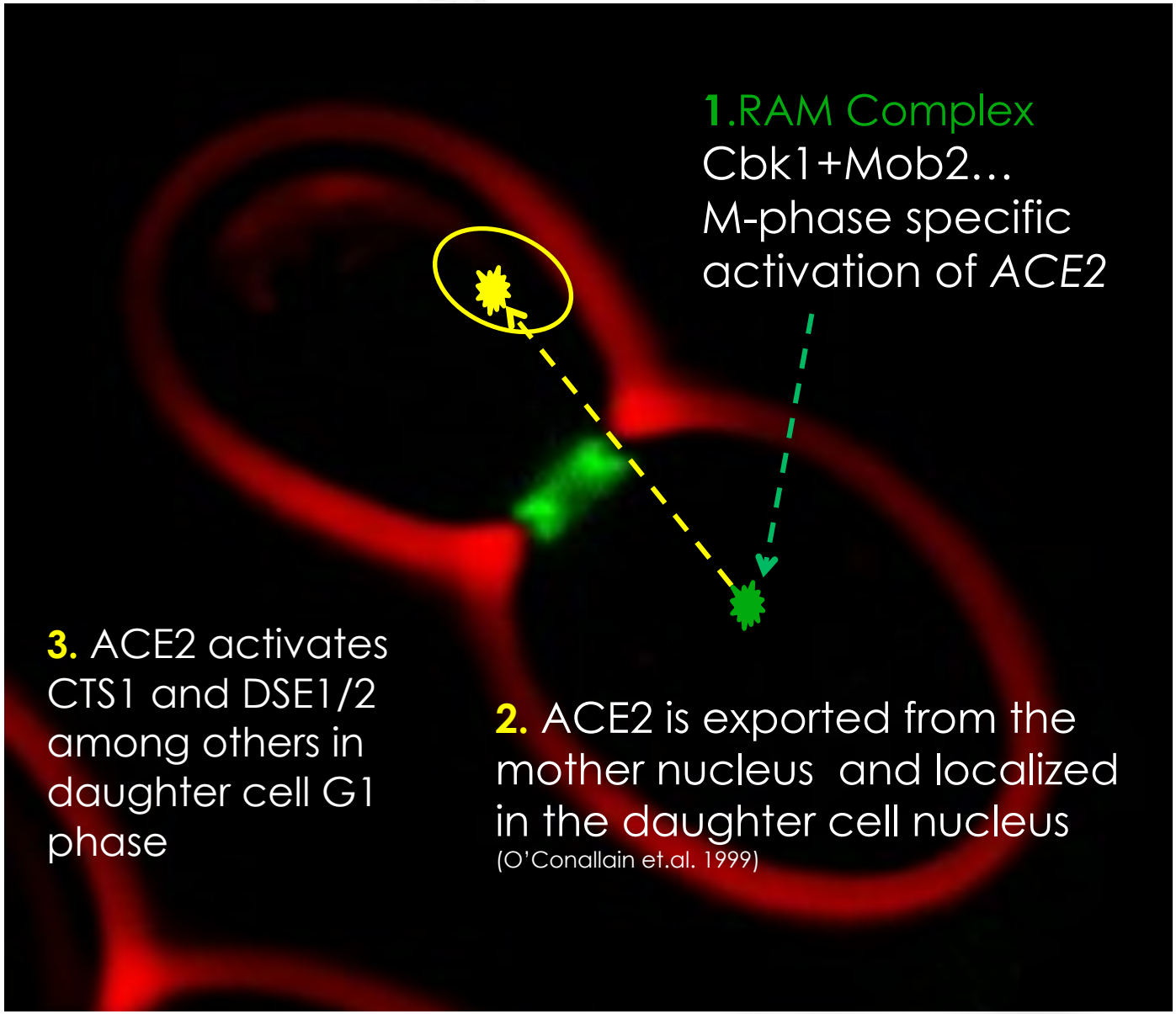

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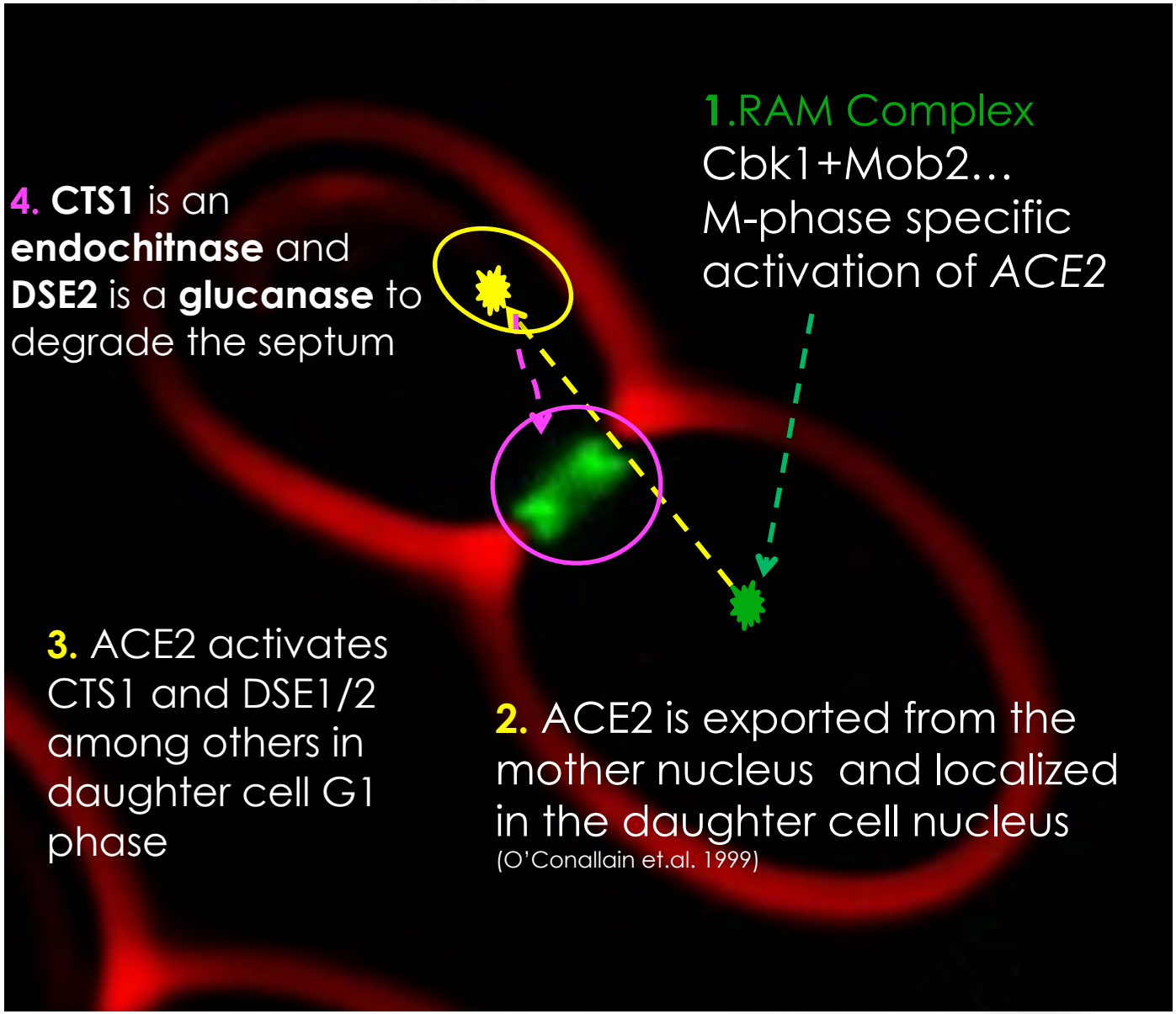

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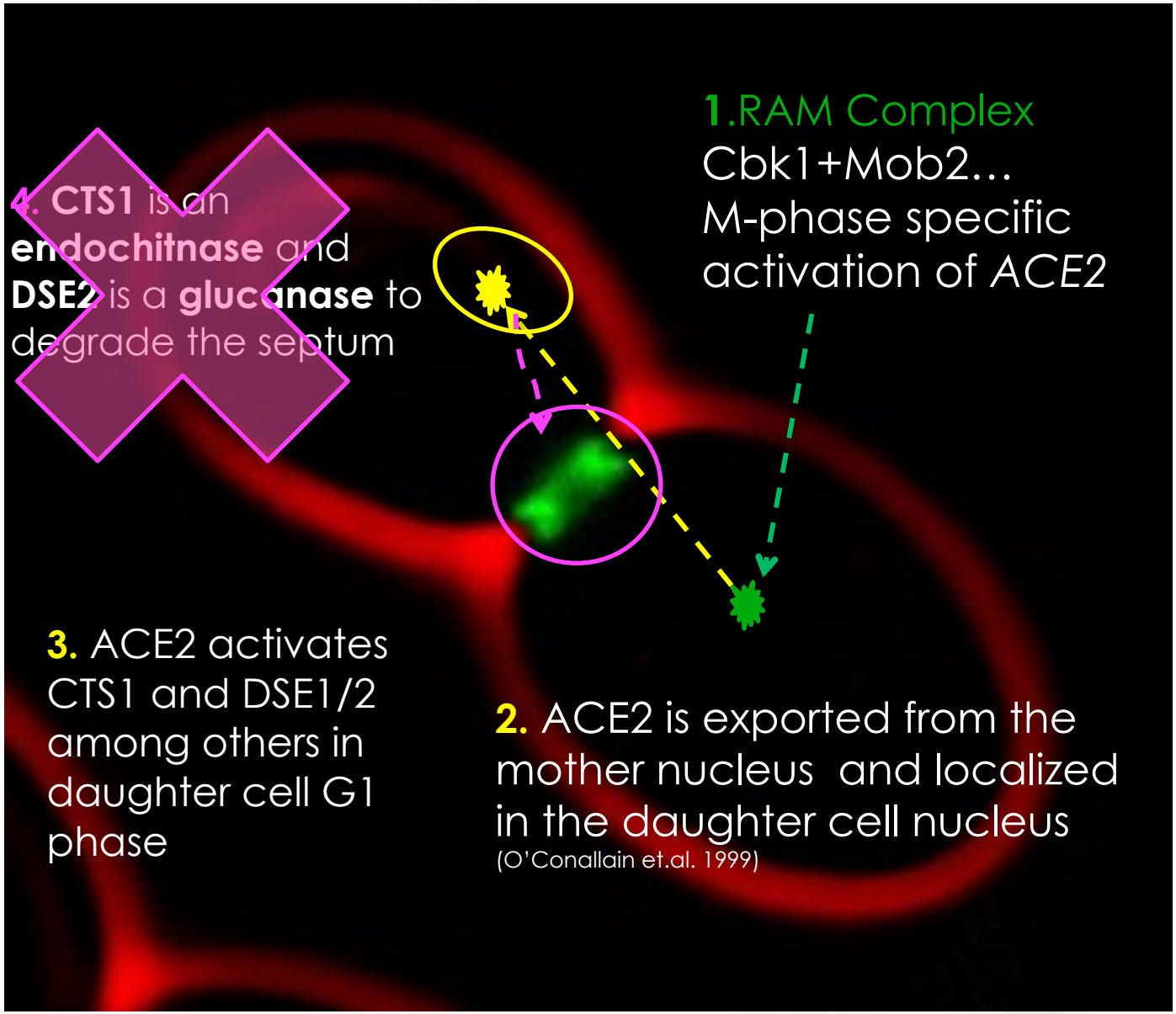

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Are snowflake yeast multicellular?

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- physical adhesion between cells

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  - Reproduction

Ratcliff, Denison, Borrello, & Travisano. 2012. PNAS

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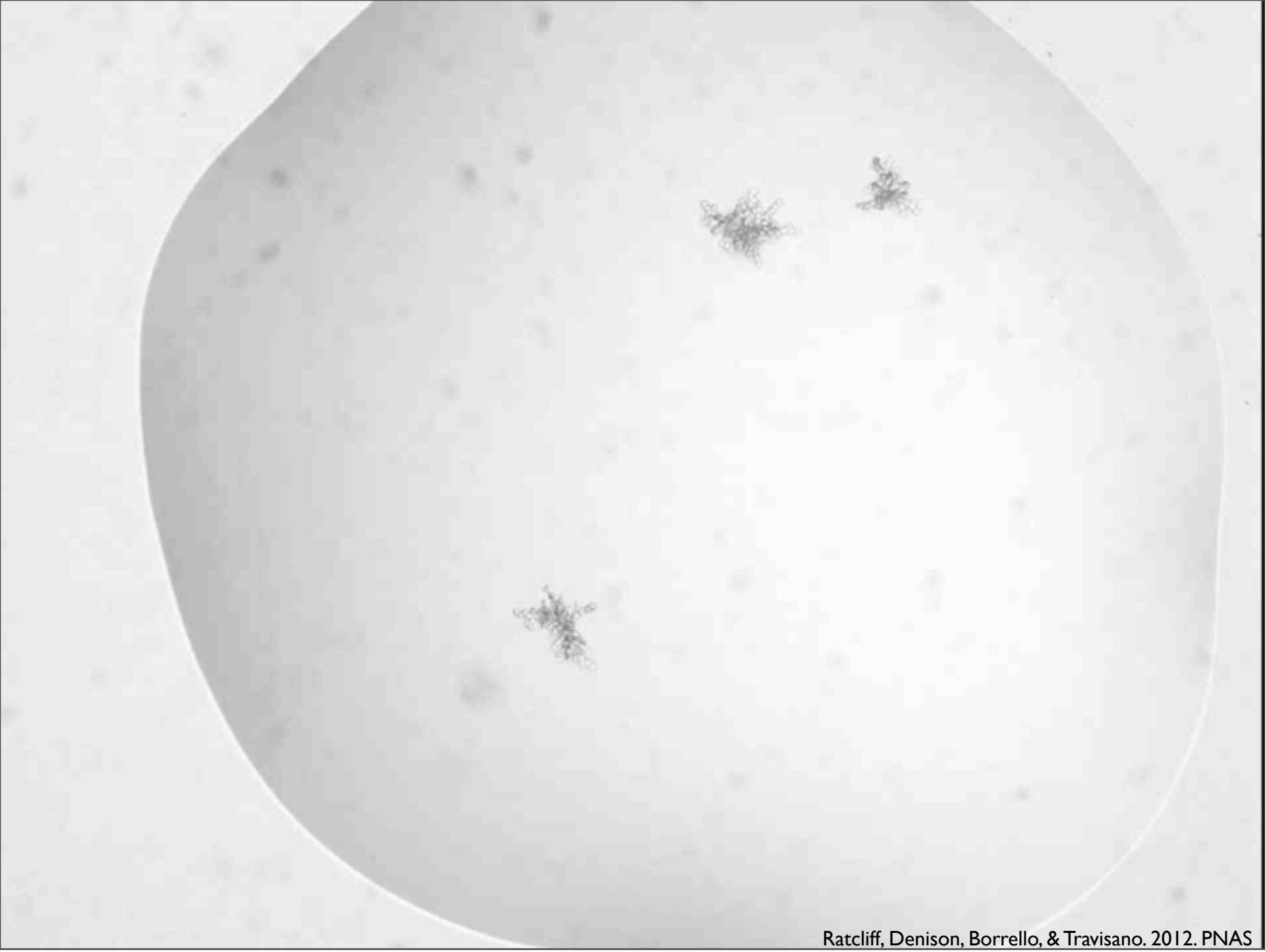
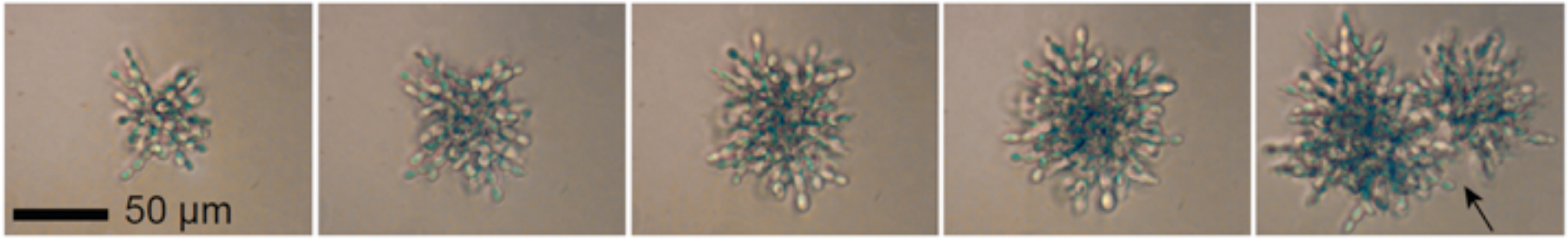


Ratcliff, Denison, Borrello, & Travisano. 2012. PNAS

Offspring are functionally juvenile



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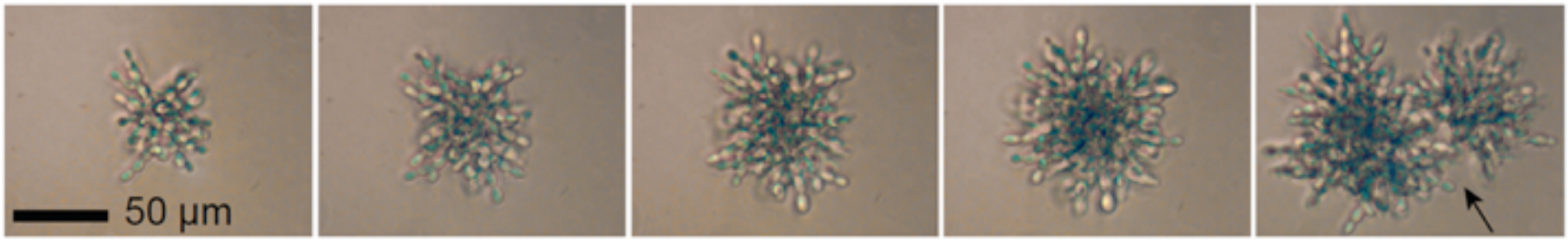

maturation

reproduction

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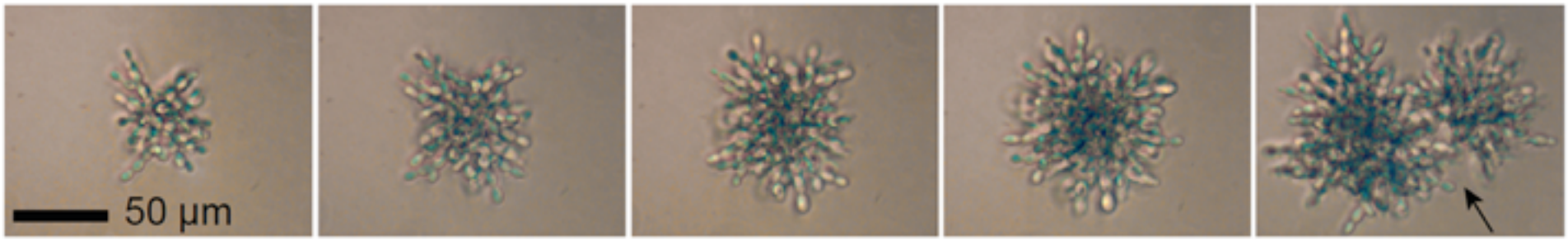
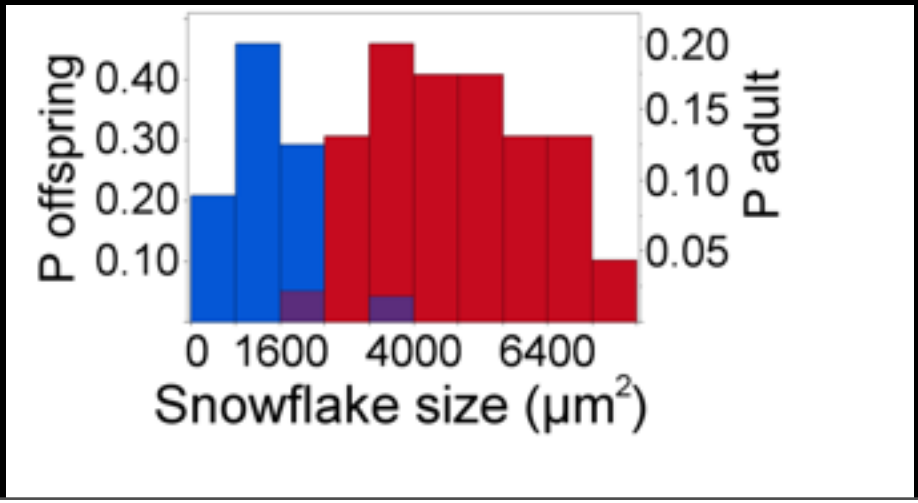


maturation

reproduction

parental size at reproduction

offspring size



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- physical adhesion between cells
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  -Reproduction

  -juvenile and adult stages

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- Life history responds to selection

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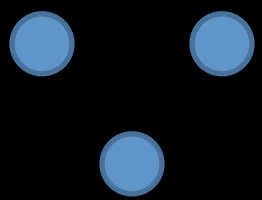
"Major transitions [i.e. multicellularity] are major stages in the evolution of complexity that involve a change in the level of organization, and hence the level of selection."

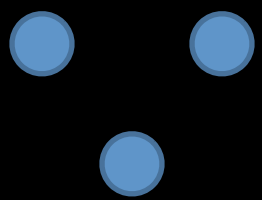
Maynard Smith and Szathmary, 1995

evolutionary theory

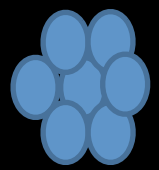


unicellular ancestor

evolutionary theory



individual-level selection for clustering



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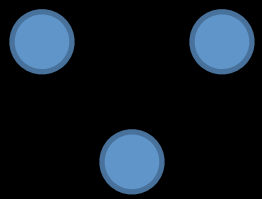

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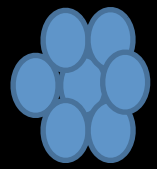
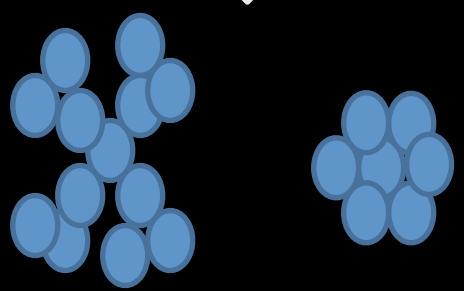
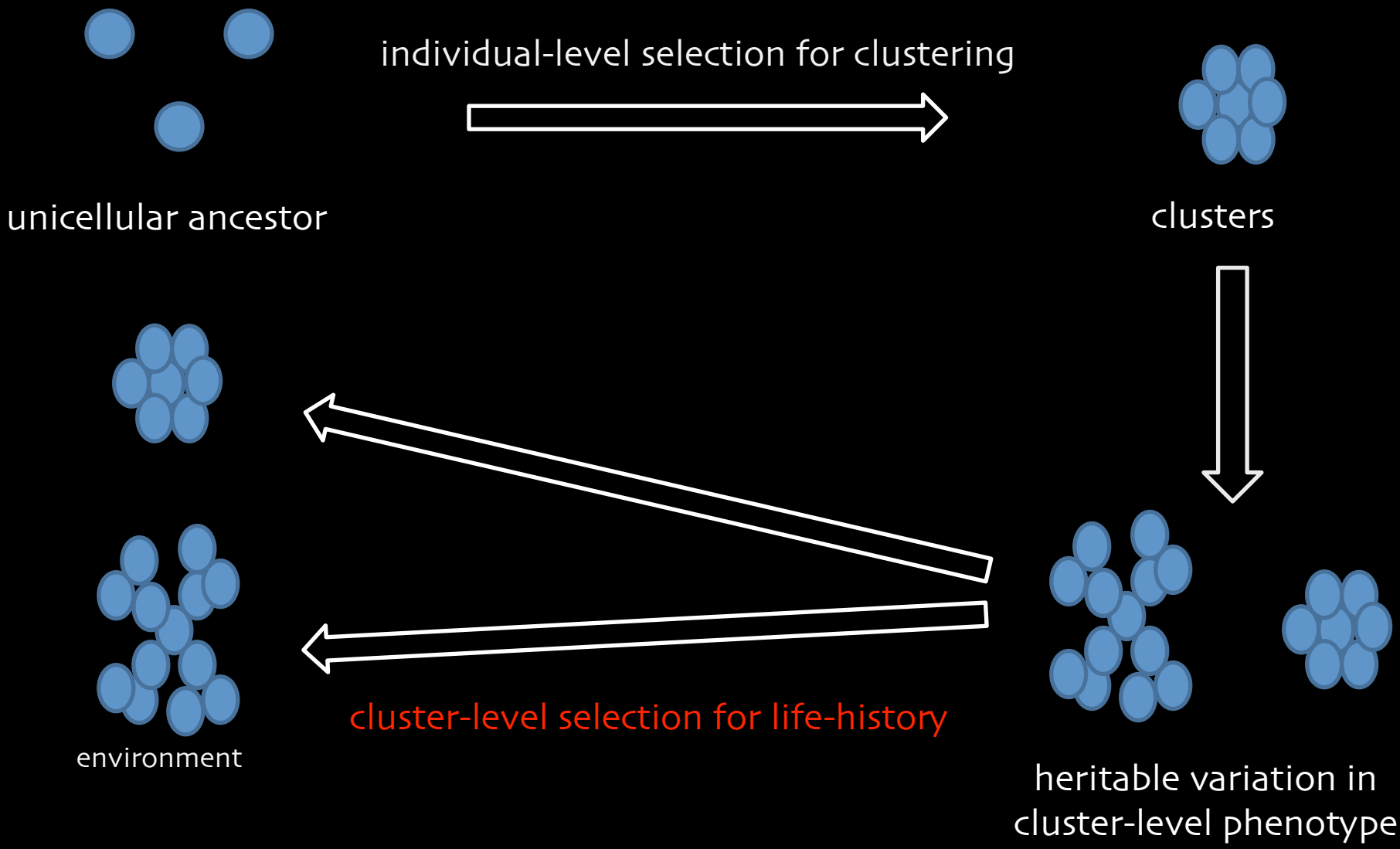


clusters



heritable variation in
cluster-level phenotype

evolutionary theory

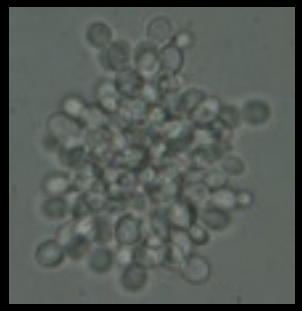


our experiments

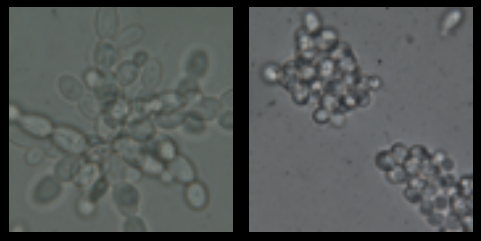
unicellular ancestor

individual-level selection for clustering

rapid settling



clusters



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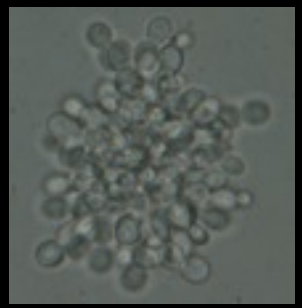


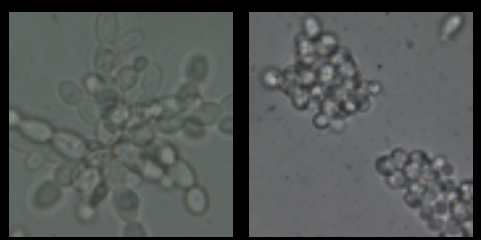
clusters

?

?

cluster-level selection for life-history

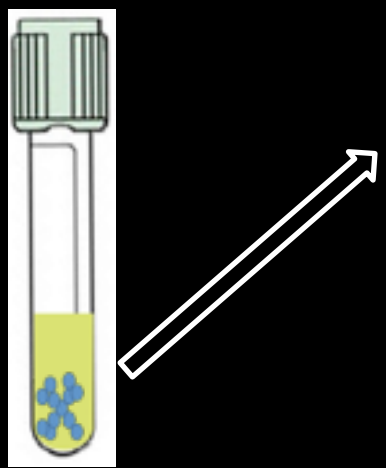
adaptation at the cluster-level



heritable variation in cluster-level phenotype

divergent selection on settling rate

starting population

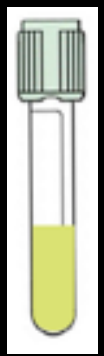


Ancestral snowflake
30 transfers

selection

5 minutes settling

transfer to fresh media



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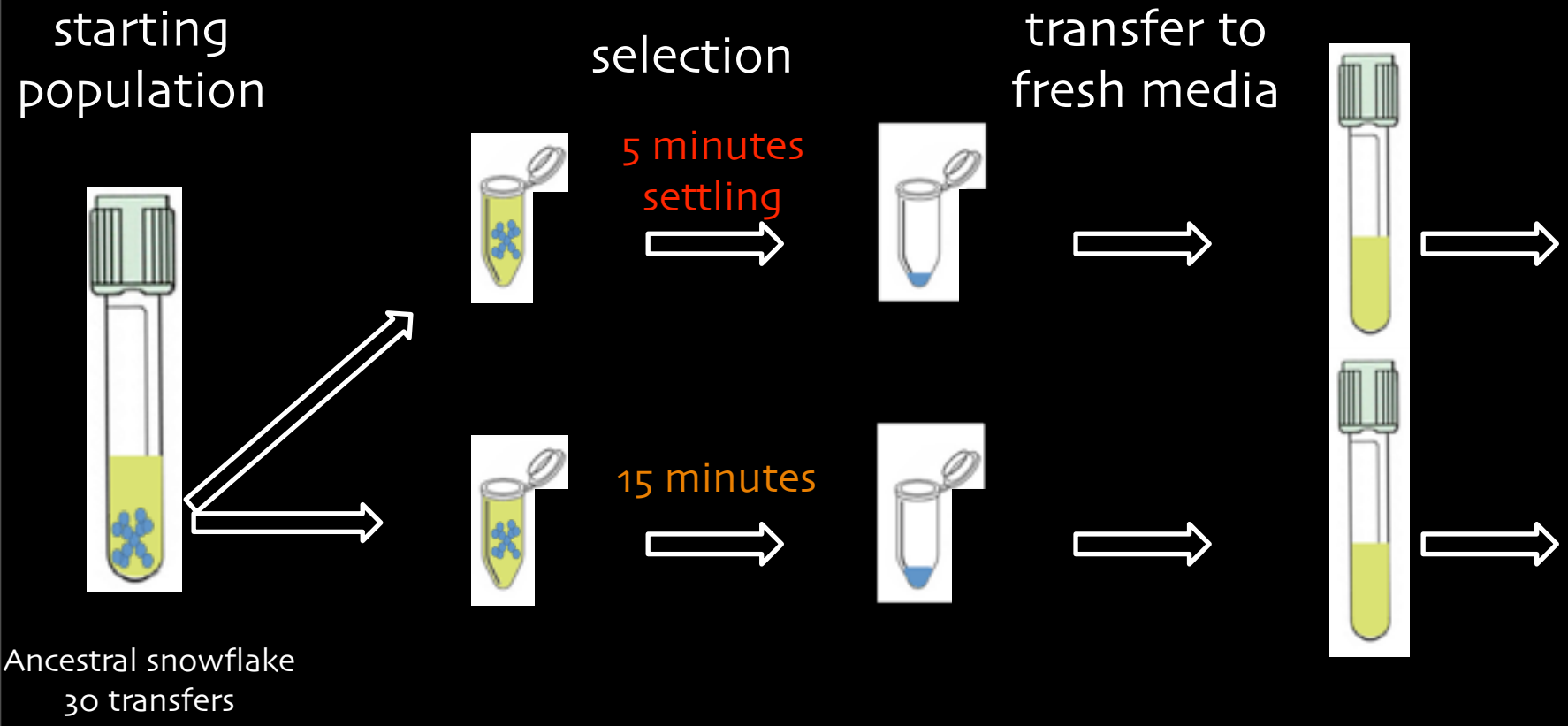

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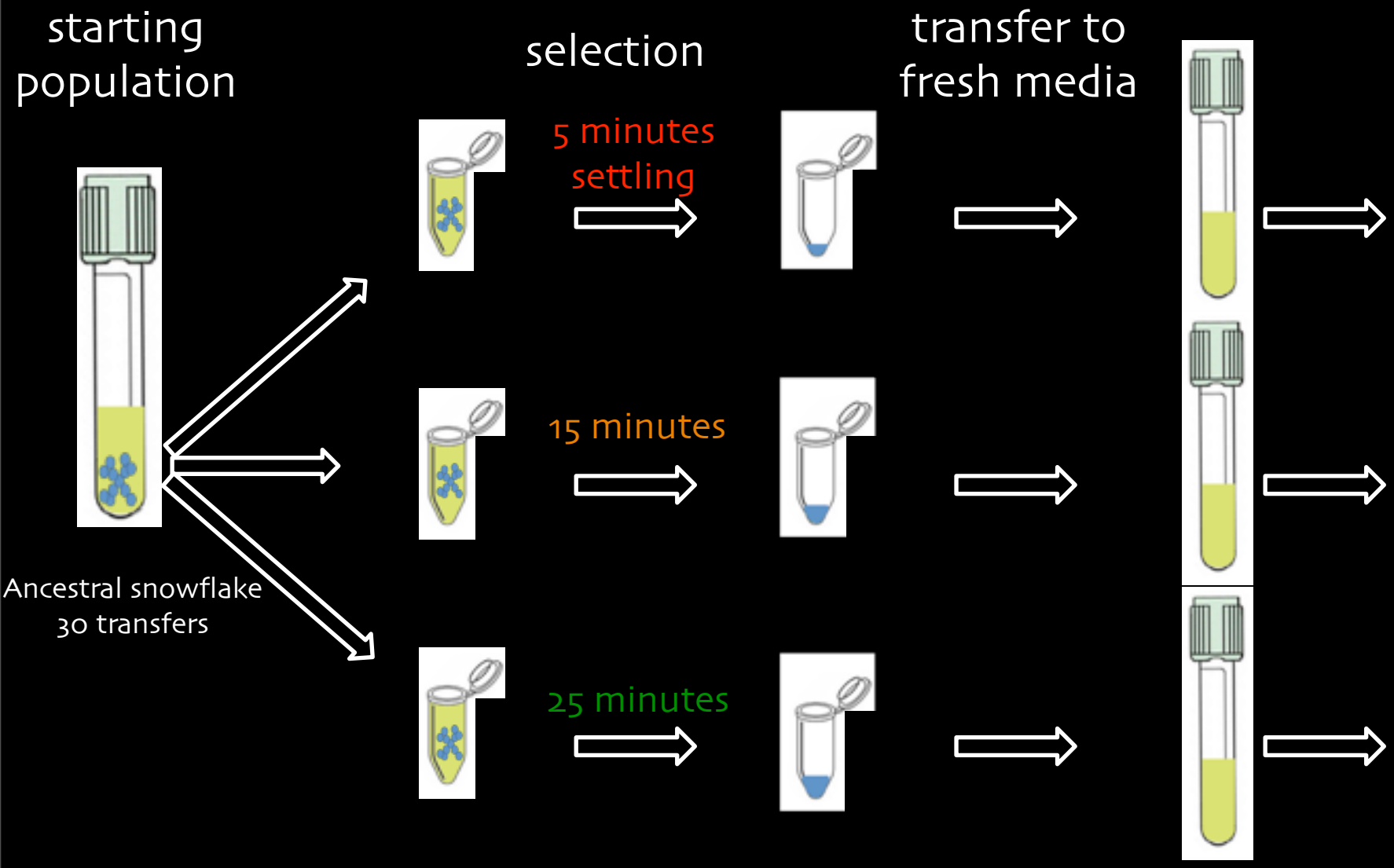
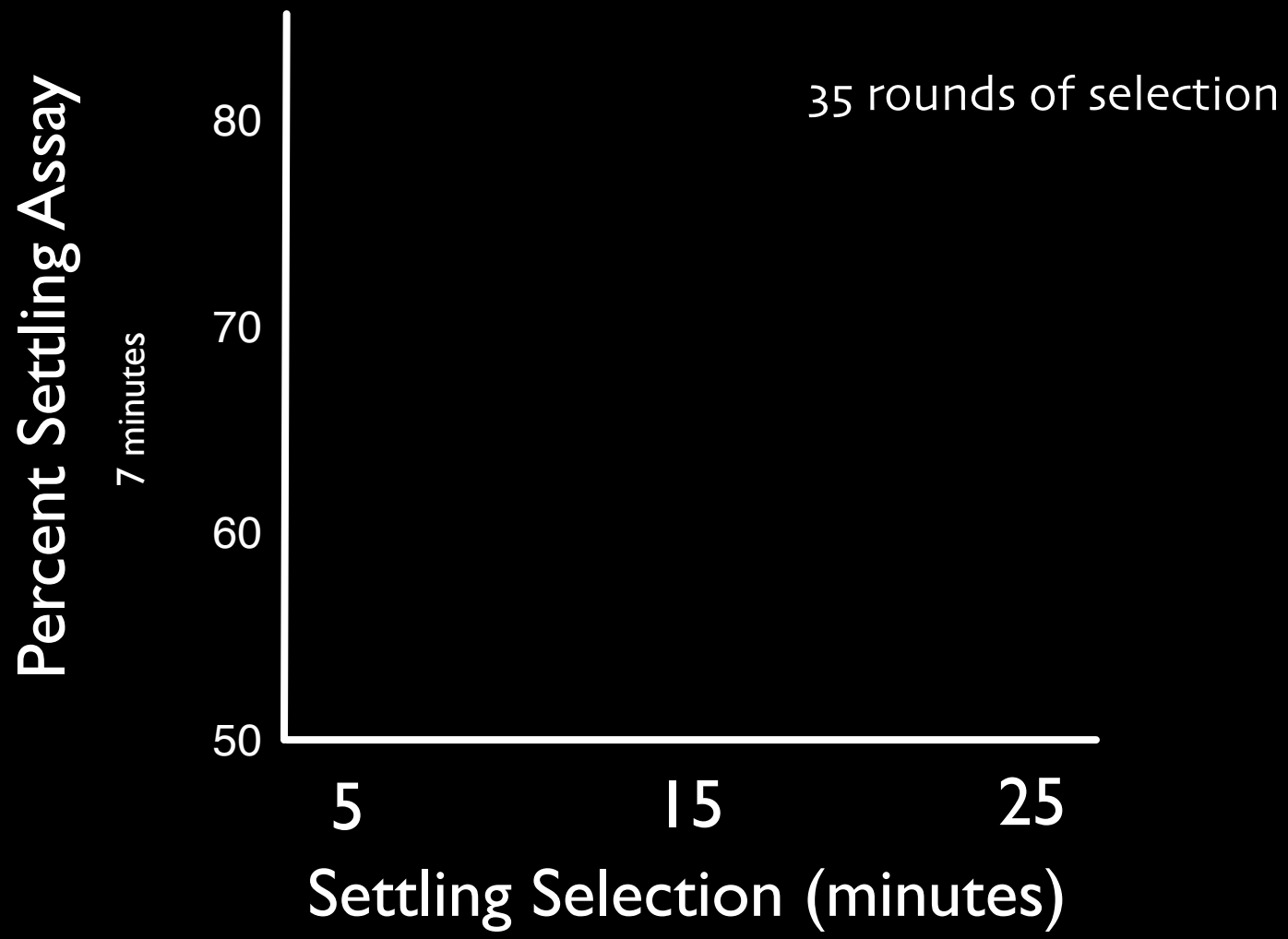
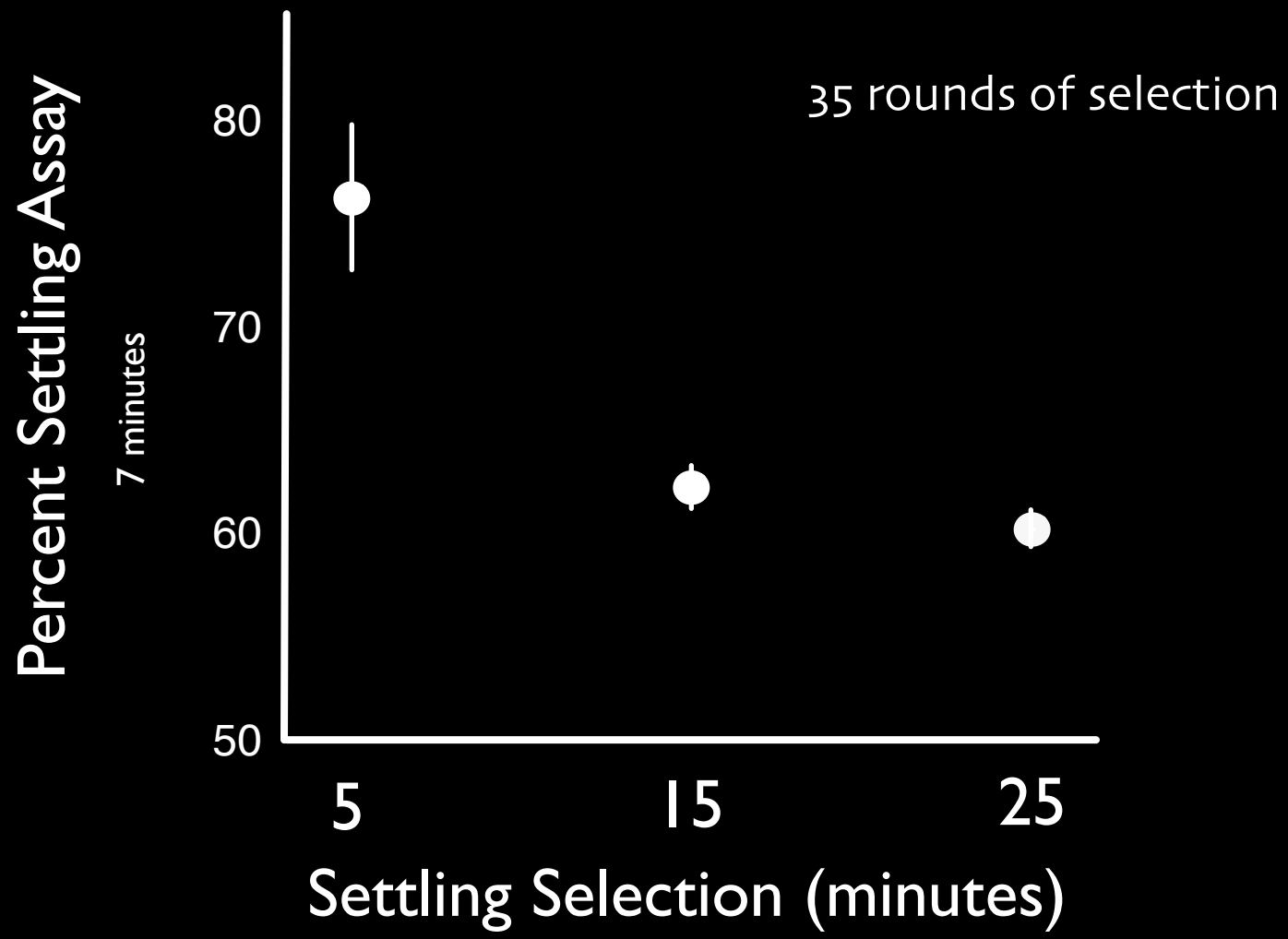


Strong response to selection



strength of selection for rapid settling	strong	moderate	weak

Strong response to selection



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this was due to the evolution of larger clusters

Duration of settling in evolution experiment

5 minutes

25 minutes

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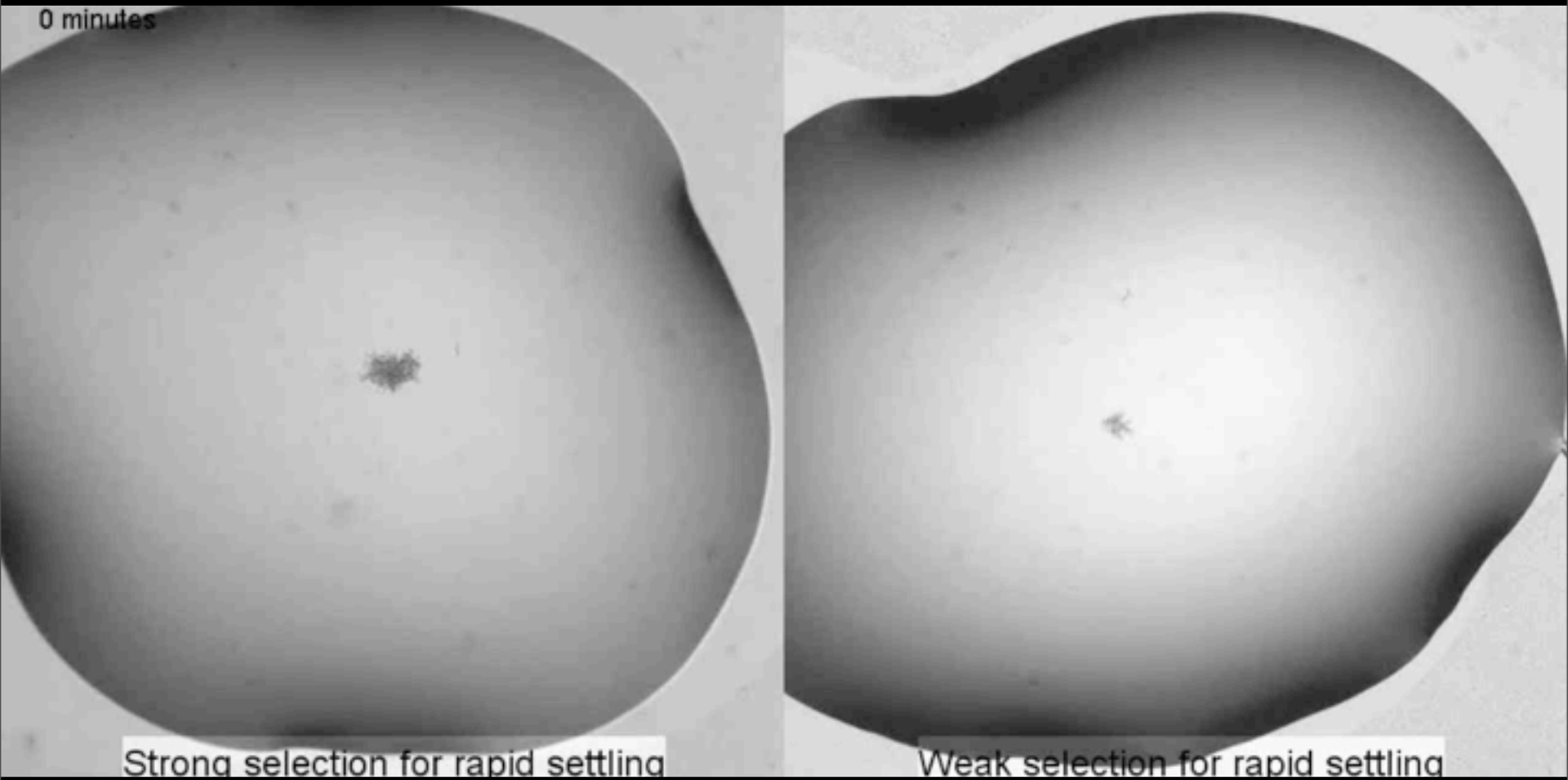

Duration of settling in evolution experiment

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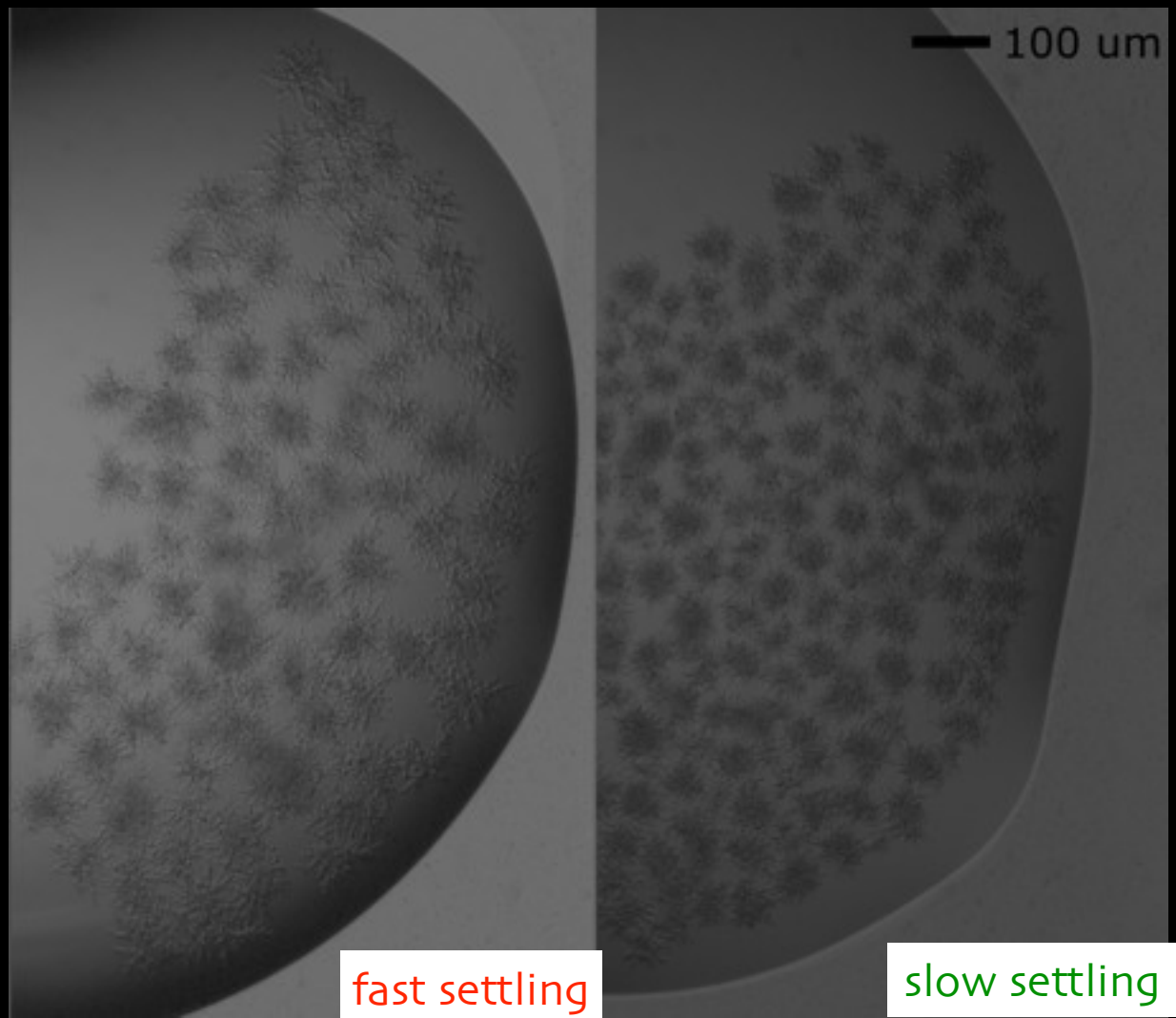
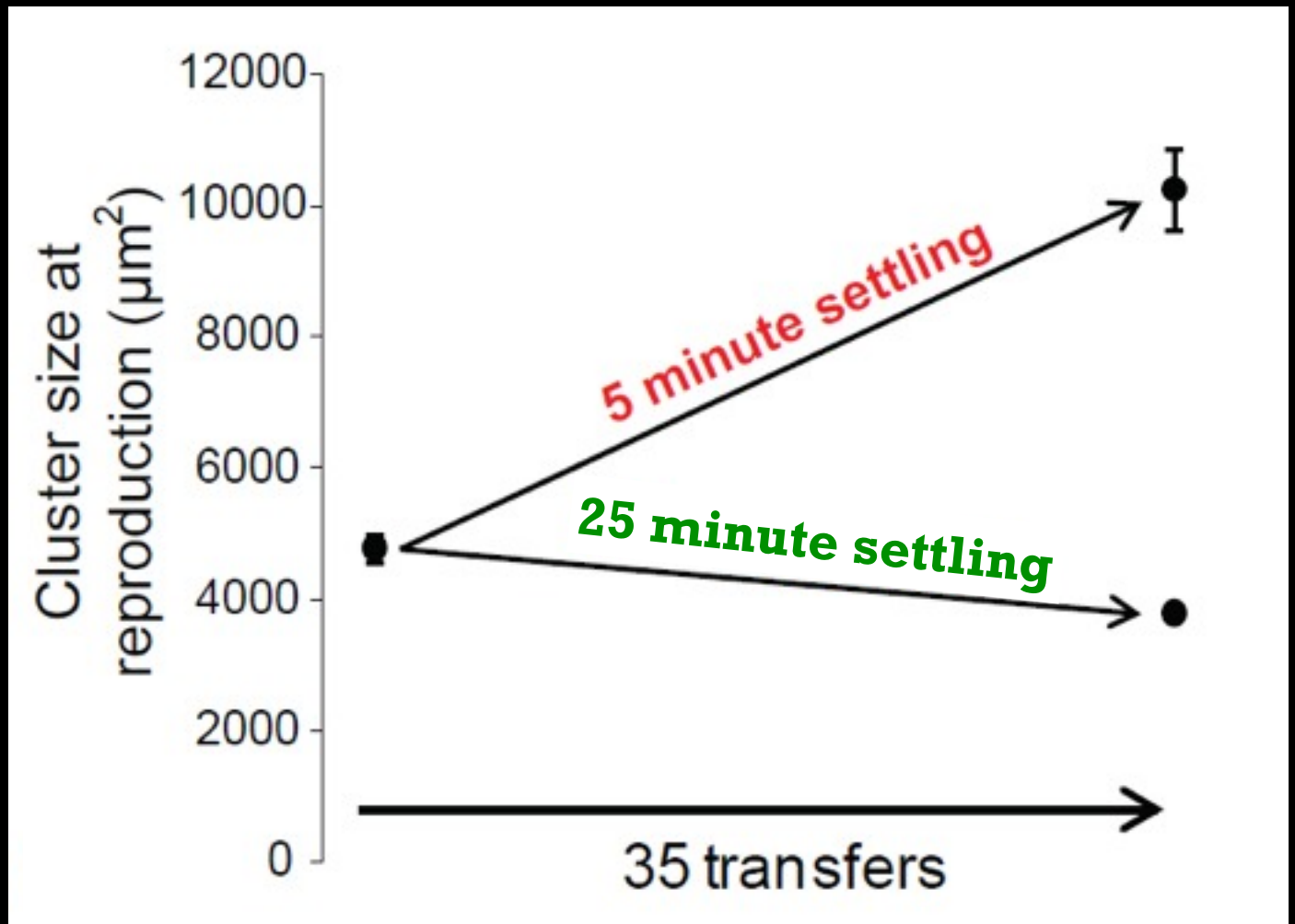
25 minutes

7 generations of growth from a single cluster



The multicellular life-history responded to selection



characteristics of multicellularity

- physical adhesion between cells
- multicellular life-history
  -propagule production
  -juvenile and adult stages

- this life history responds to selection

characteristics of multicellularity

- physical adhesion between cells
- multicellular life-history
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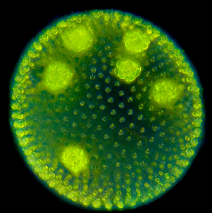
- this life history responds to selection

- division of labor among cells ?

Evolution of programmed cell death in snowflake yeast

Questions about multicellularity



1. Why were there multiple origins?

2. Why is it ongoing process?

3. How? Not directly predicted by Natural Selection.

'the metazoan brain trust'

Will Ratcliff

R. Ford Denison

Mark Borrello

graduate and undergraduate students

Kristin Jacobsen

Maria Rebolleda Gomez

Amanda Muehlbauer

Jennifer Pentz

Jonathan Fankhauser

Chelsea Du Fresne