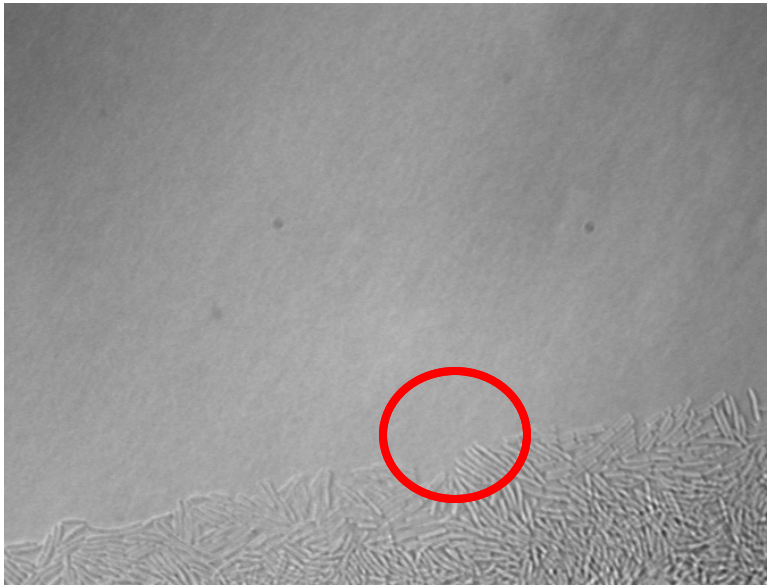
Range Expansions & Spatial Population Genetics

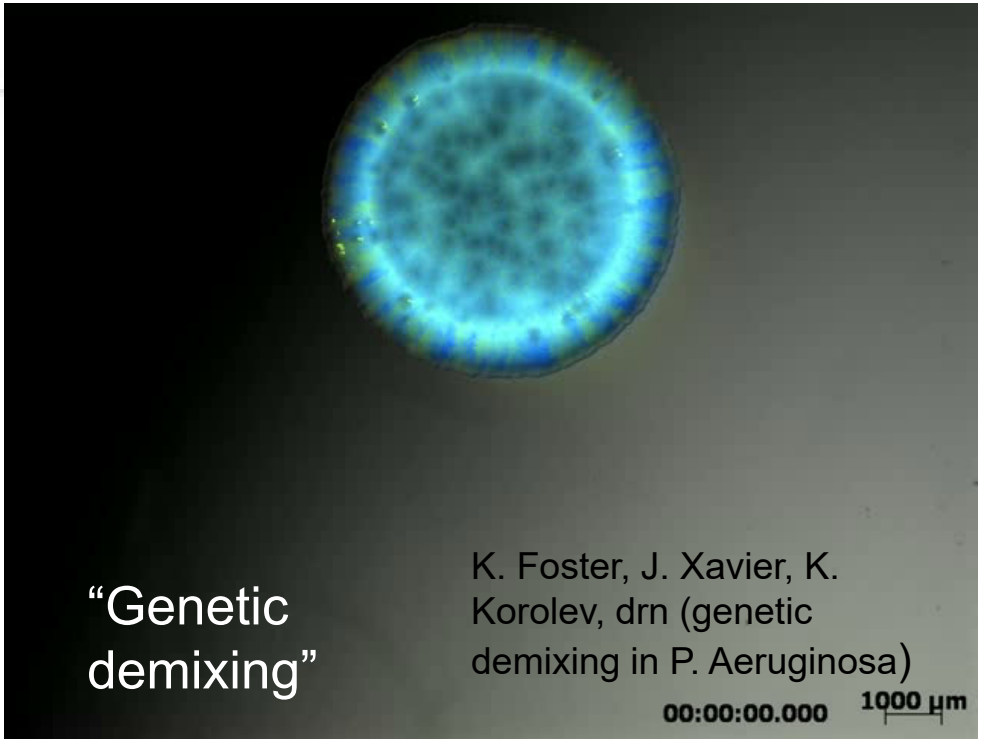
In 500 generations….

Large mammals expand over ~10^4 km

But bacteria (in a Petri dish) only expand ~ 1 cm

Oskar Hallatschek & drn, (E. coli)





Gene Surfing and Survival of the Luckiest

Mutations and competition in a spreading population

J. Xavier
K. Foster
W. Moebius
M. Mueller
A. Murray

Oskar Hallatschek

Kirill Korolev

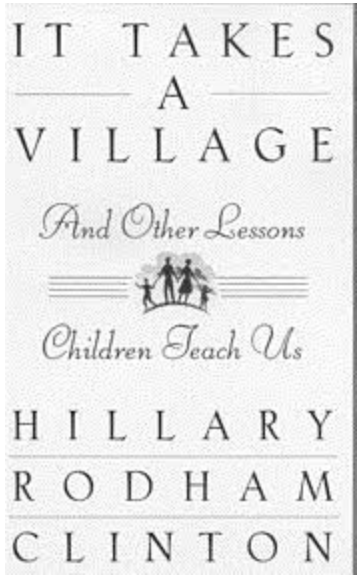
vs.

Is this Biology, Physics, or….?

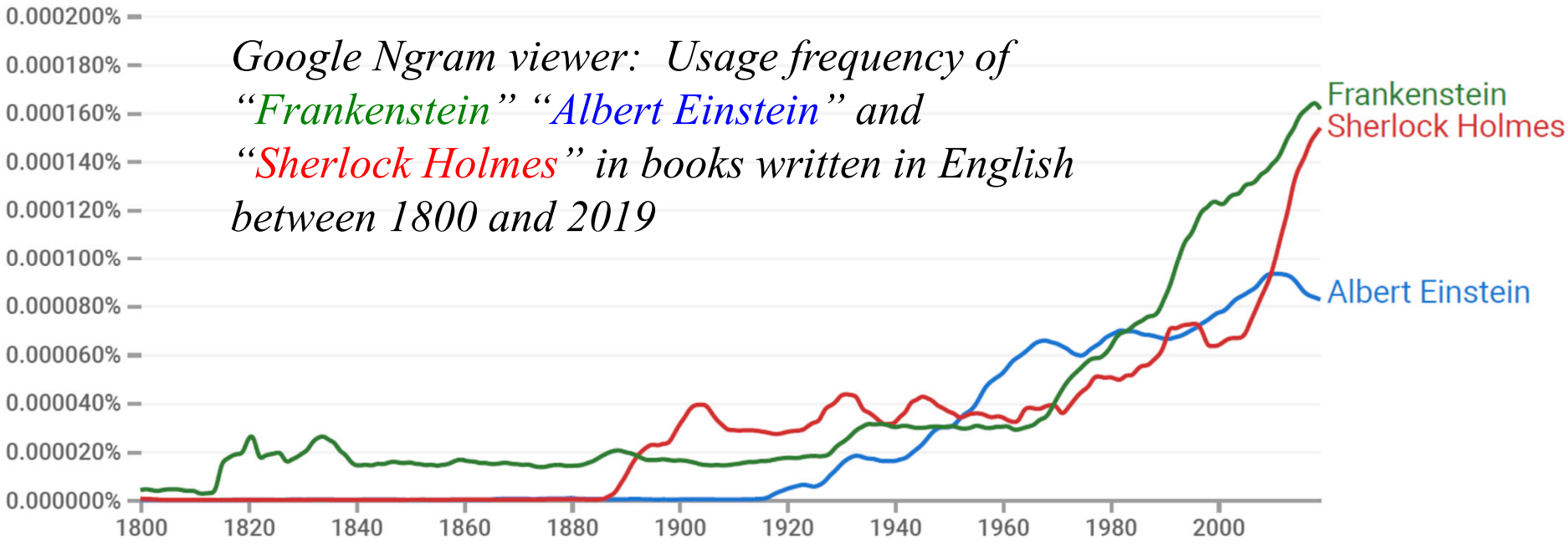
Will the 21st century be the "Century of Biology"?

•Bill Clinton's exchange with his science advisor upon completion of the first draft of the human genome…..

"If, in scientific terms, the twentieth century has been the century of physics, then the twenty-first will surely be the century of biology."



Is this really true?



Google Ngram viewer: Usage frequency of "Frankenstein" "Albert Einstein" and "Sherlock Holmes" in books written in English between 1800 and 2019

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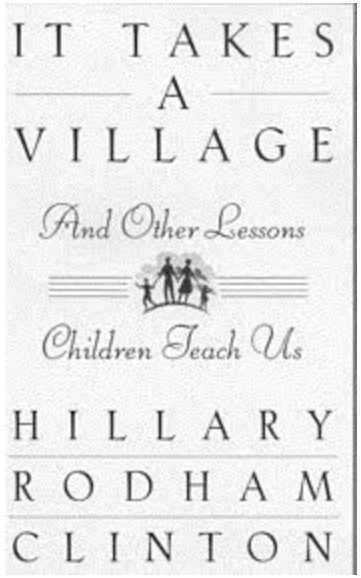
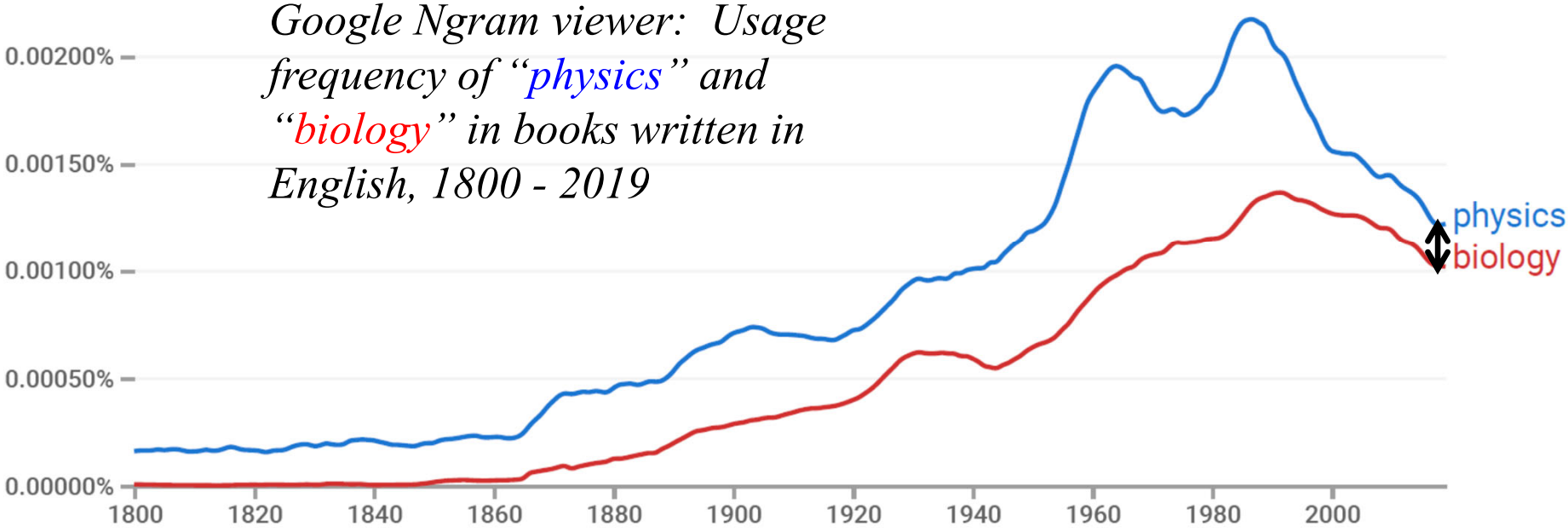


Google Ngram viewer: Usage frequency of "physics" and "biology" in books written in English, 1800 - 2019



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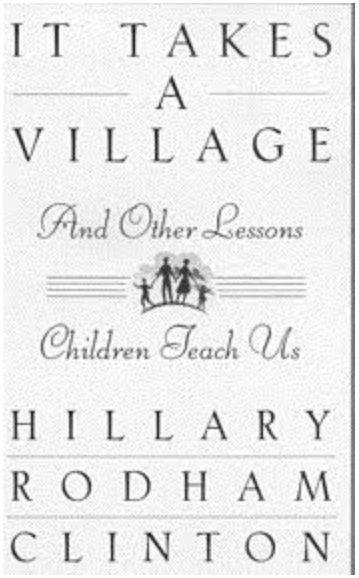
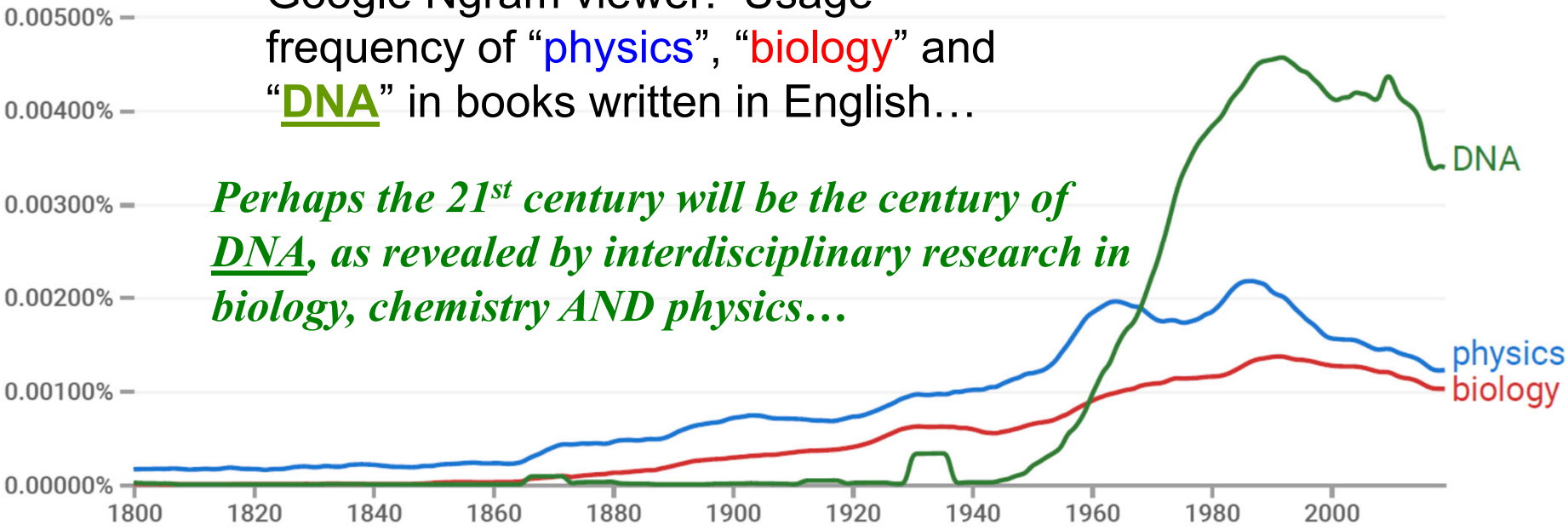


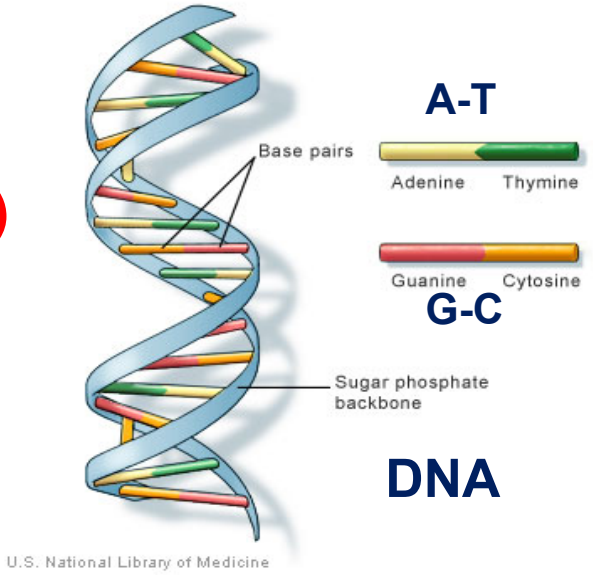
Google Ngram viewer: Usage frequency of "physics", "biology" and "DNA" in books written in English…

Perhaps the 21st century will be the century of DNA, as revealed by interdisciplinary research in biology, chemistry AND physics…

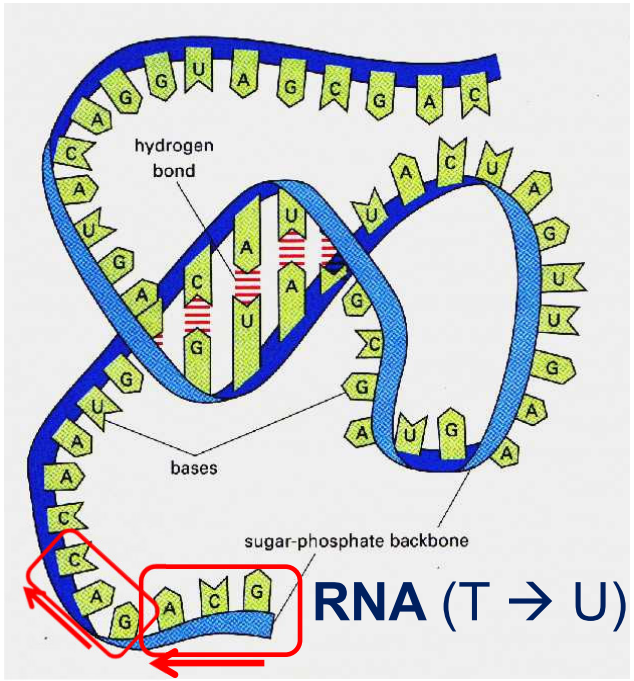


"Central Dogma" of Biology

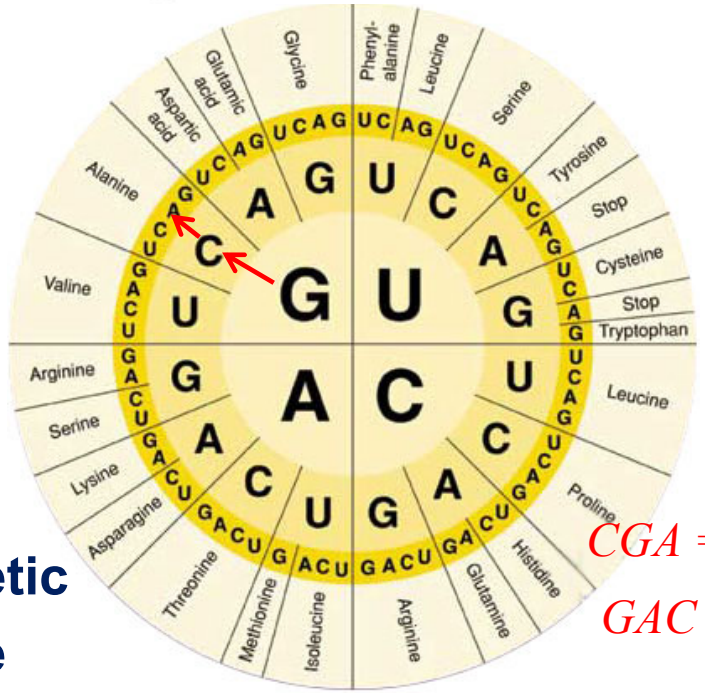
?



DNA



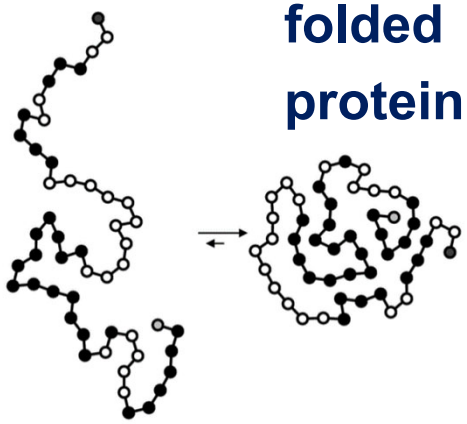
RNA (T → U)



genetic code

CGA = alanine

GAC = aspartic acid

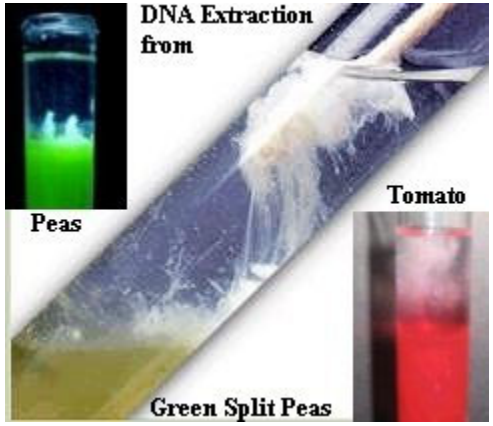


folded protein

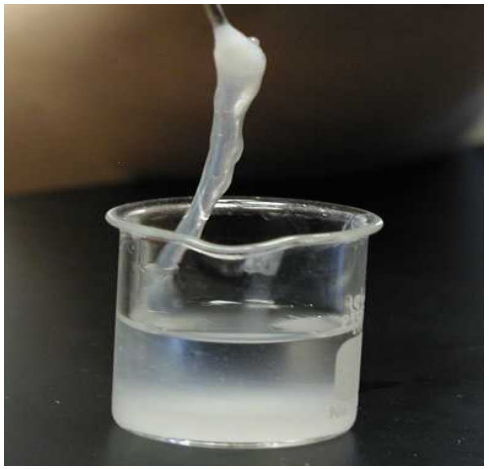
○ = water-loving amino acid

● = water-hating amino acid

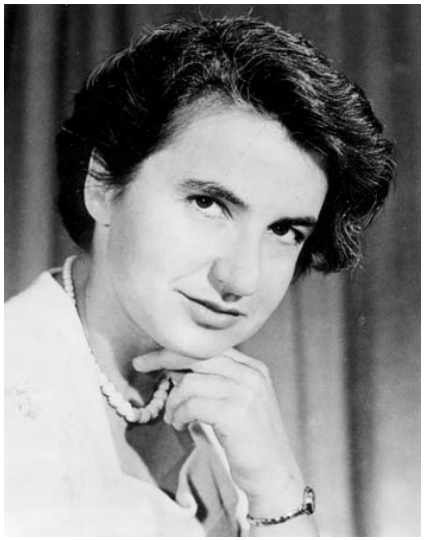
Diffraction from oriented fibers of DNA: "Photo 51"



•*http://universe-review.ca/R11-16-DNAsequencing.htm*

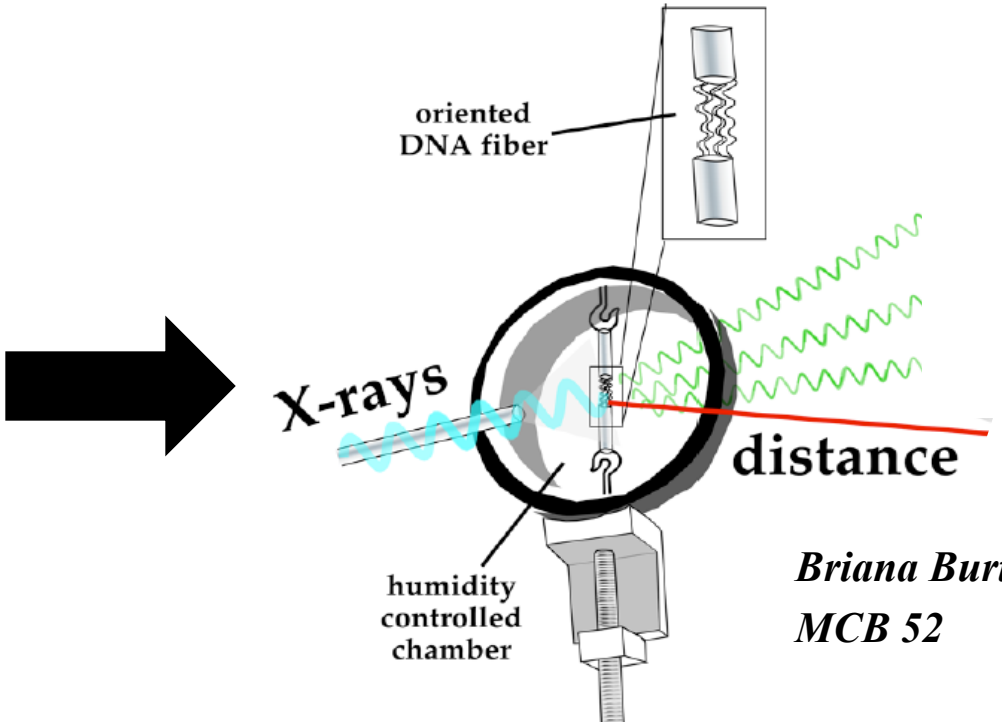


•*http://biology.clc.uc.edu/fankhauser/labs/genetics/dna_isolation/thymus_dna.htm*



Rosalind Franklin

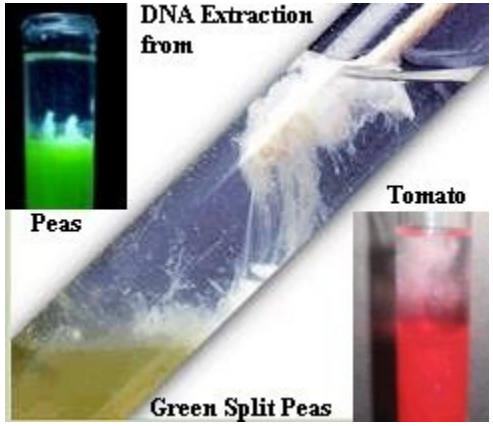
Maurice Wilkins



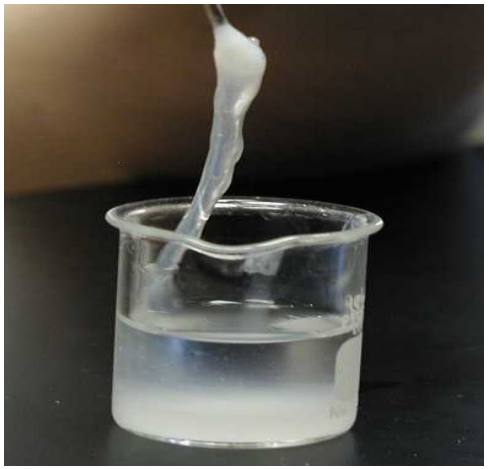
Briana Burton

MCB 52

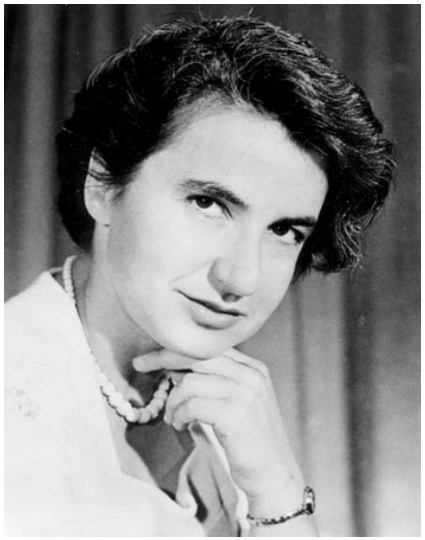
Diffraction from oriented fibers of DNA: "Photo 51"



•*http://universe-review.ca/R11-16-DNAsequencing.htm*



•*http://biology.clc.uc.edu/fankhauser/labs/genetics/dna_isolation/thymus_dna.htm*



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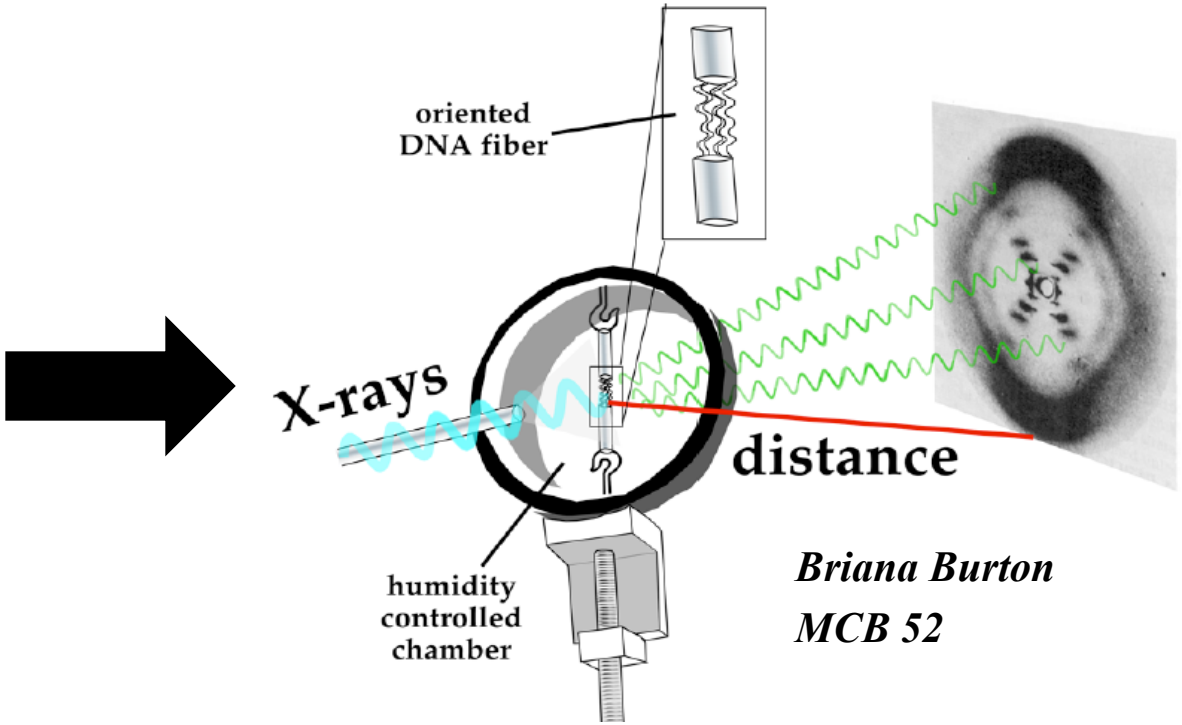
Maurice Wilkins



Briana Burton

MCB 52

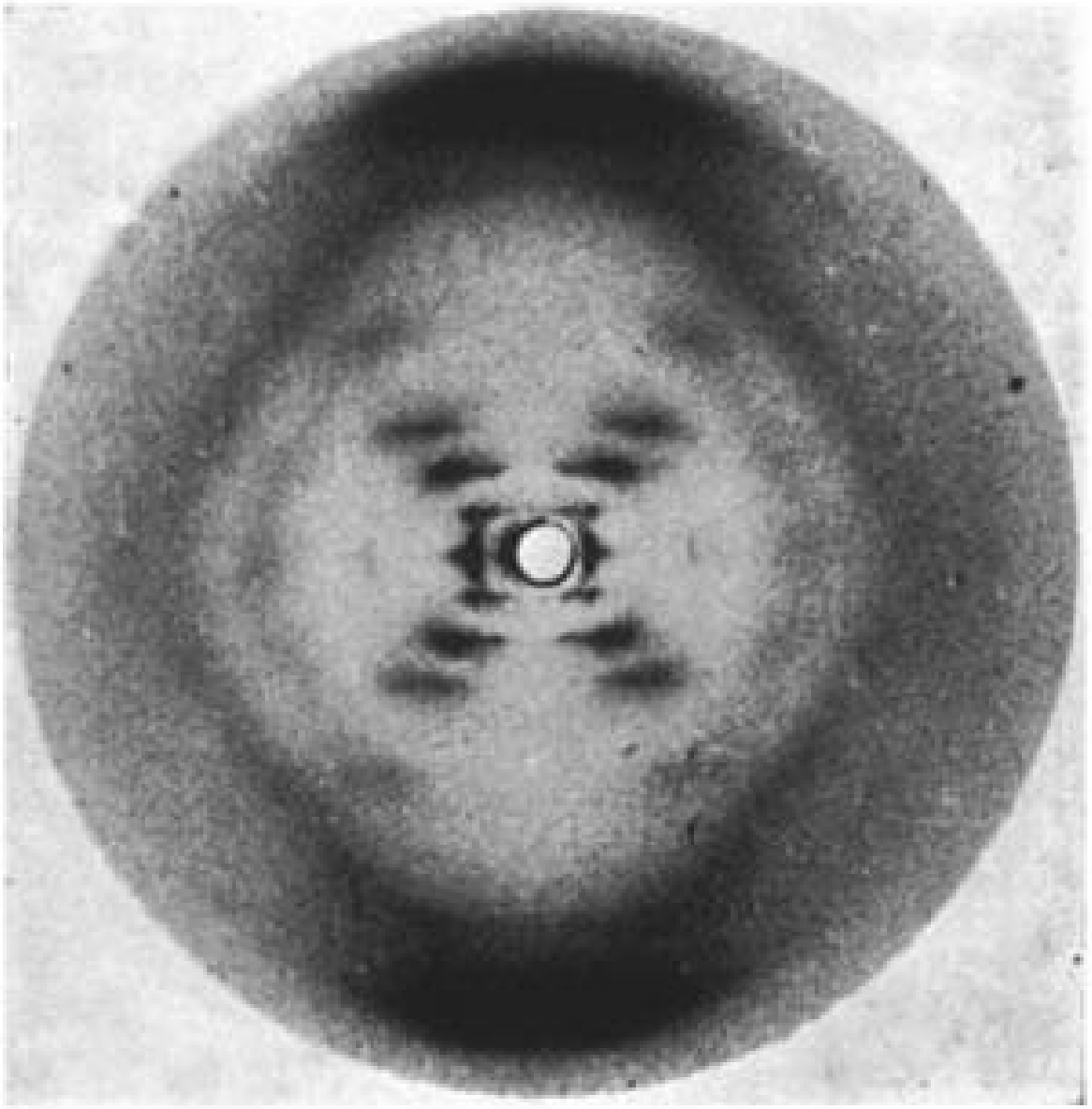
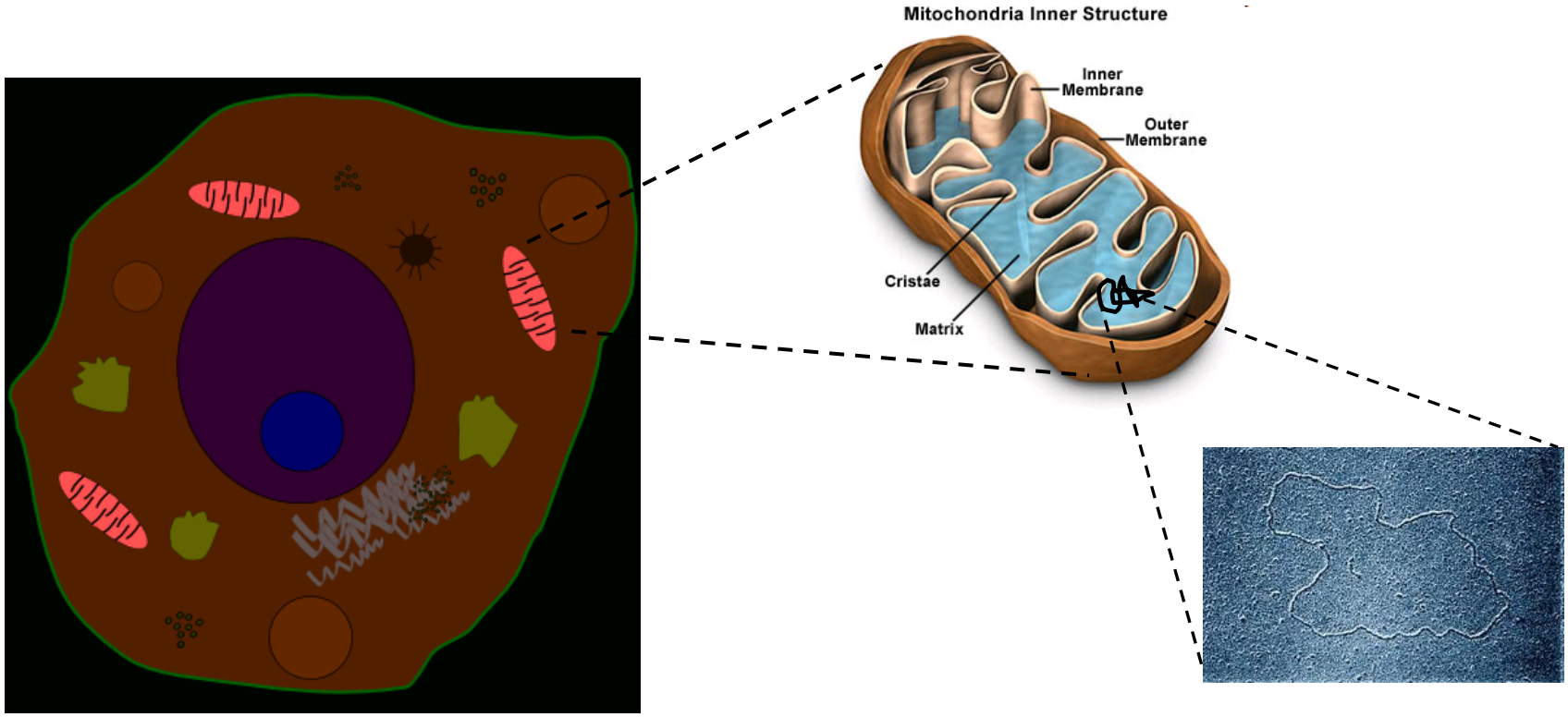


Photo 51: May 2, 1951

Double helix structure of DNA

James Watson and Francis Crick

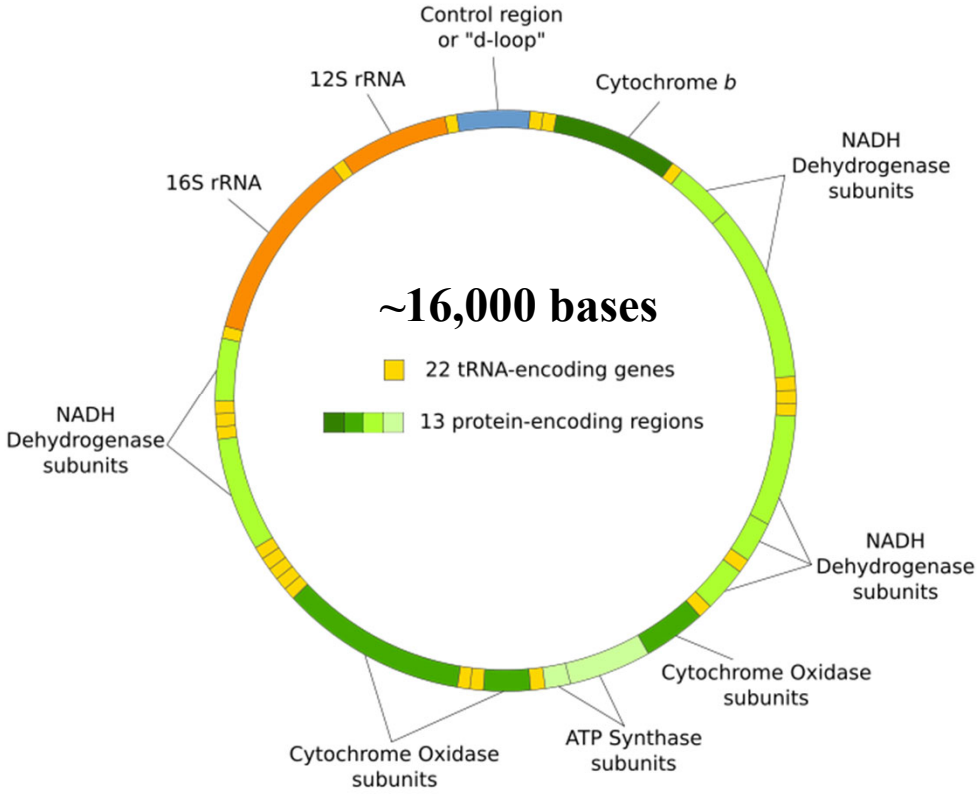
Mitochondria supply energy to plant and animal cells



- ***Each mitochondrion contains a small circular chromosome, with some "junk DNA", as well as genes that allow it to supply energy to the cell.***
- ***100's of mitochondria in each human cell, each with 2-10 copies of a circular genome (~10^3 gene replicas per cell)***
- ***Mitochondria likely have a very ancient origin, and even possess a slightly different genetic code! (different start and stop codons, tryptophan)***

Divergence times from mitochondrial DNA

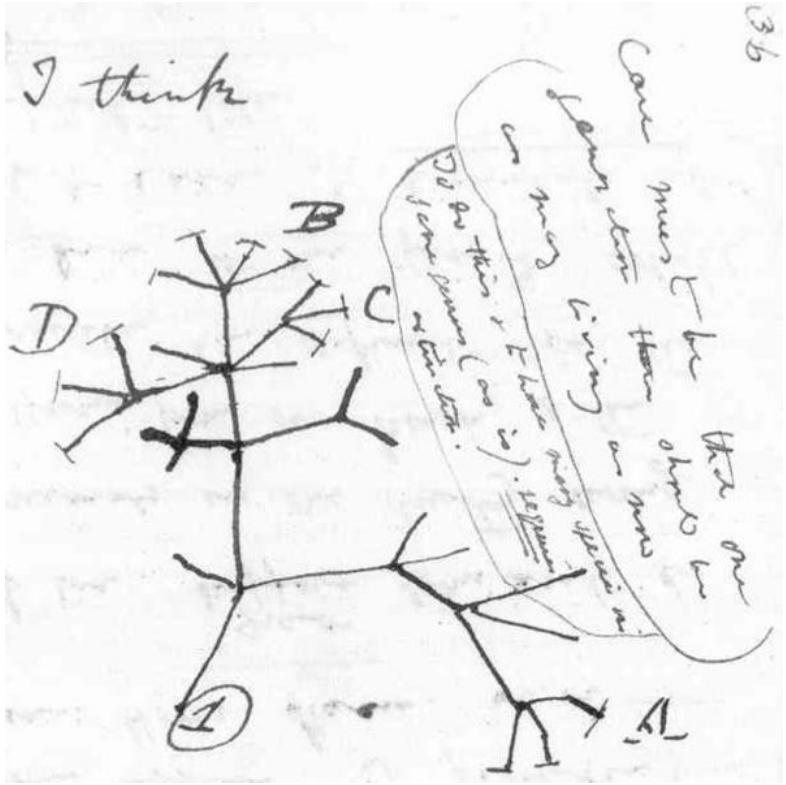
Lynn Margulis



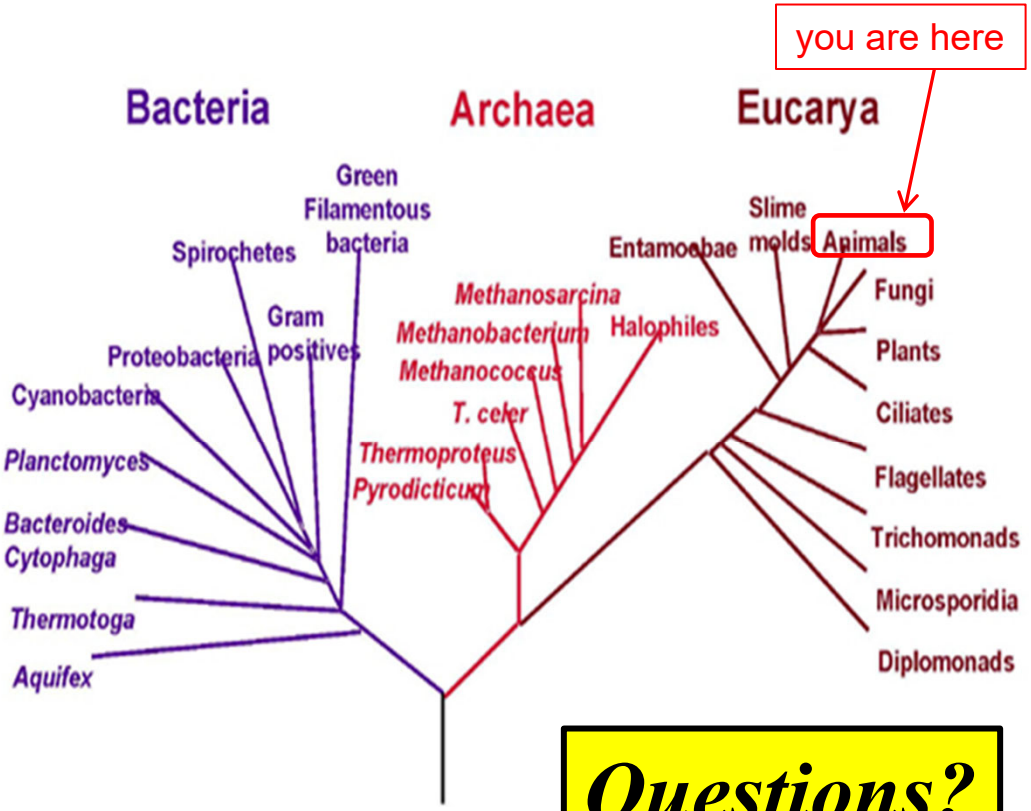
- *Mitochondria descended from bacteria engulfed by ancestral animal cells*
- *Inherited along matrilineal lines*
- *Substitution rate 5-10 faster than nuclear DNA*
- *Conclude, e.g., that chimps and humans diverged about 6-7 M years ago…*

Genes and geneologies

Charles Darwin's sketch of an evolutionary tree of life (circa 1837), Museum of Natural History, NYC



Modern tree of life obtained by sequencing DNA encoding for ribosomal RNA



Questions?

Spatial population genetics

What's in a name?

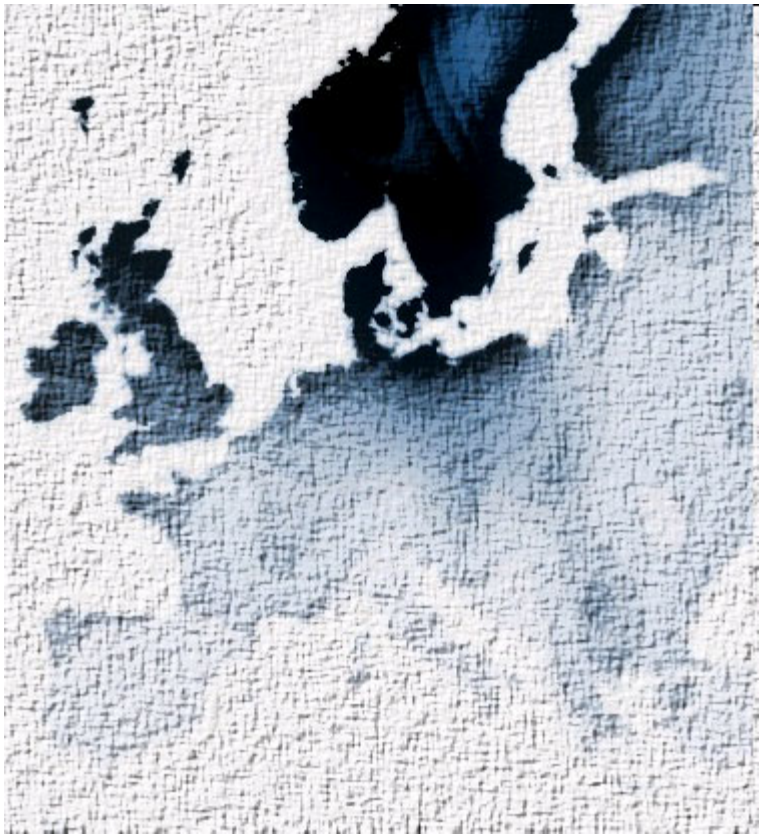
Hyskenstræde 9, 1207
København K. Denmark

I am <u>not</u> *related to the Lord Nelson who fought the Danes at the battle of Copenhagen in 1801....*

What is the distribution of genes in space?

Haplogroup I1 *is a Y chromosome haplogroup occurring at greatest frequency in Scandinavia, associated with SNP ("single nucleotide polymorphism") mutations such as M253.*

Frequency is about 35% in southern Norway, southeastern Sweden, especially on the island of Gotland, and Denmark



http://en.wikipedia.org/wiki/Haplogroup_I_%28Y-DNA%29

Malthus-Verhulst Theory of Population Dynamics

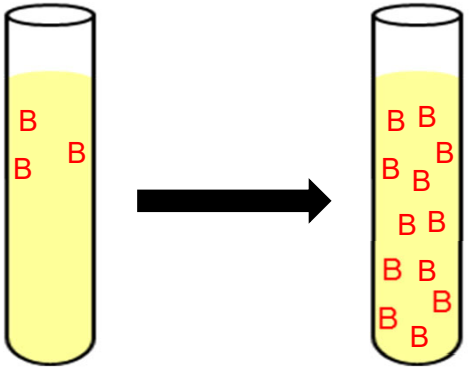
$$\frac{\text{change in population size}}{\text{per unit time}} = \text{births - deaths + "saturation"}$$

c_n = population size at generation n

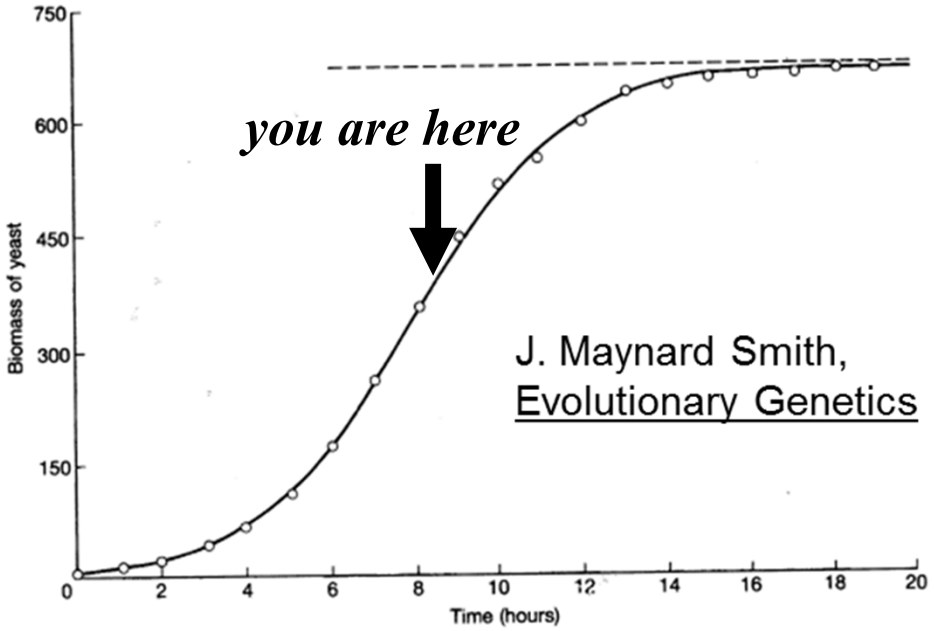
$$c_{n+1} = 2c_n = 2^2 c_{n-1} = \ldots = 2^{n+1} c_0$$

more generally, $c_{n+1} = 2 \cdot (1 - c_n / 2K) \cdot c_n$

in a doubling time, K = carrying capacity



1798 T.R. Matthus



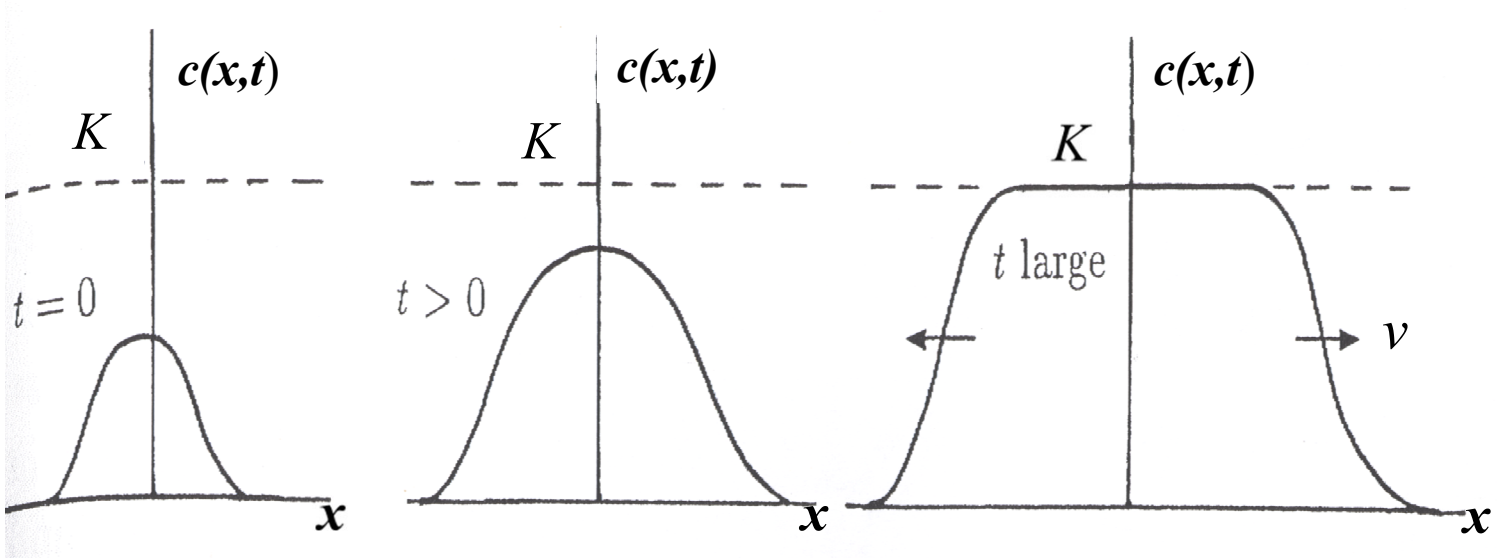
1836 P.F. Verhulst

Fisher Population Waves In One Dimension

$$\frac{\text{change in population size}}{\text{per unit time}} = \text{births - deaths + saturation + spatial diffusion}$$

Let ***c(x,t)*** be the density of organisms at position ***x*** at time ***t***…

$$\frac{\partial}{\partial t}c(x,t) = D\frac{\partial^2}{\partial x^2}c(x,t) + ac(x,t) - bc^2(x,t); \quad let\ c(x,t) = f(x - vt)$$

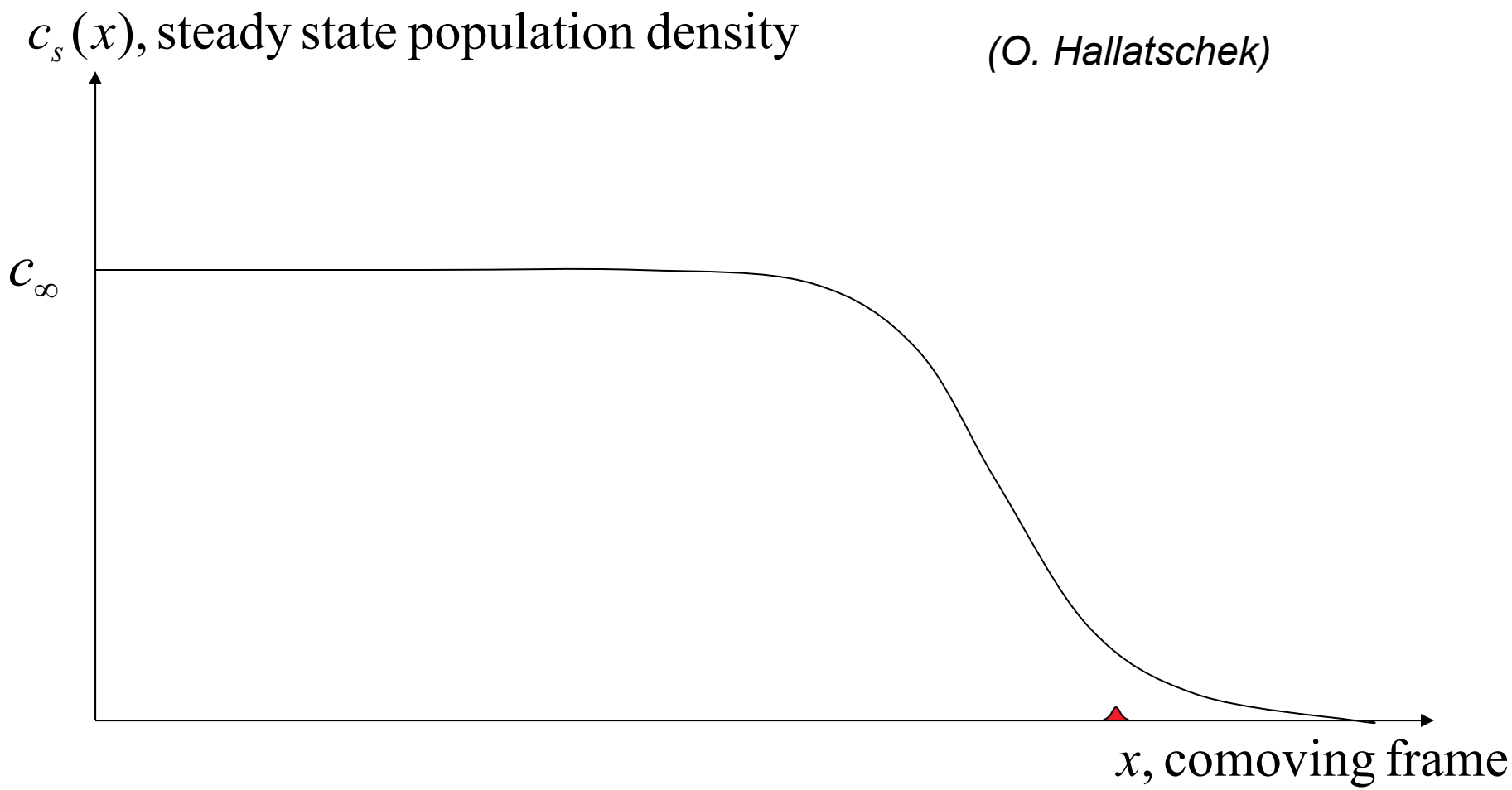


Schematic time development of a wavefront solution of Fisher's equation on the infinite line. (J.D. Murray, Mathematical Biology)

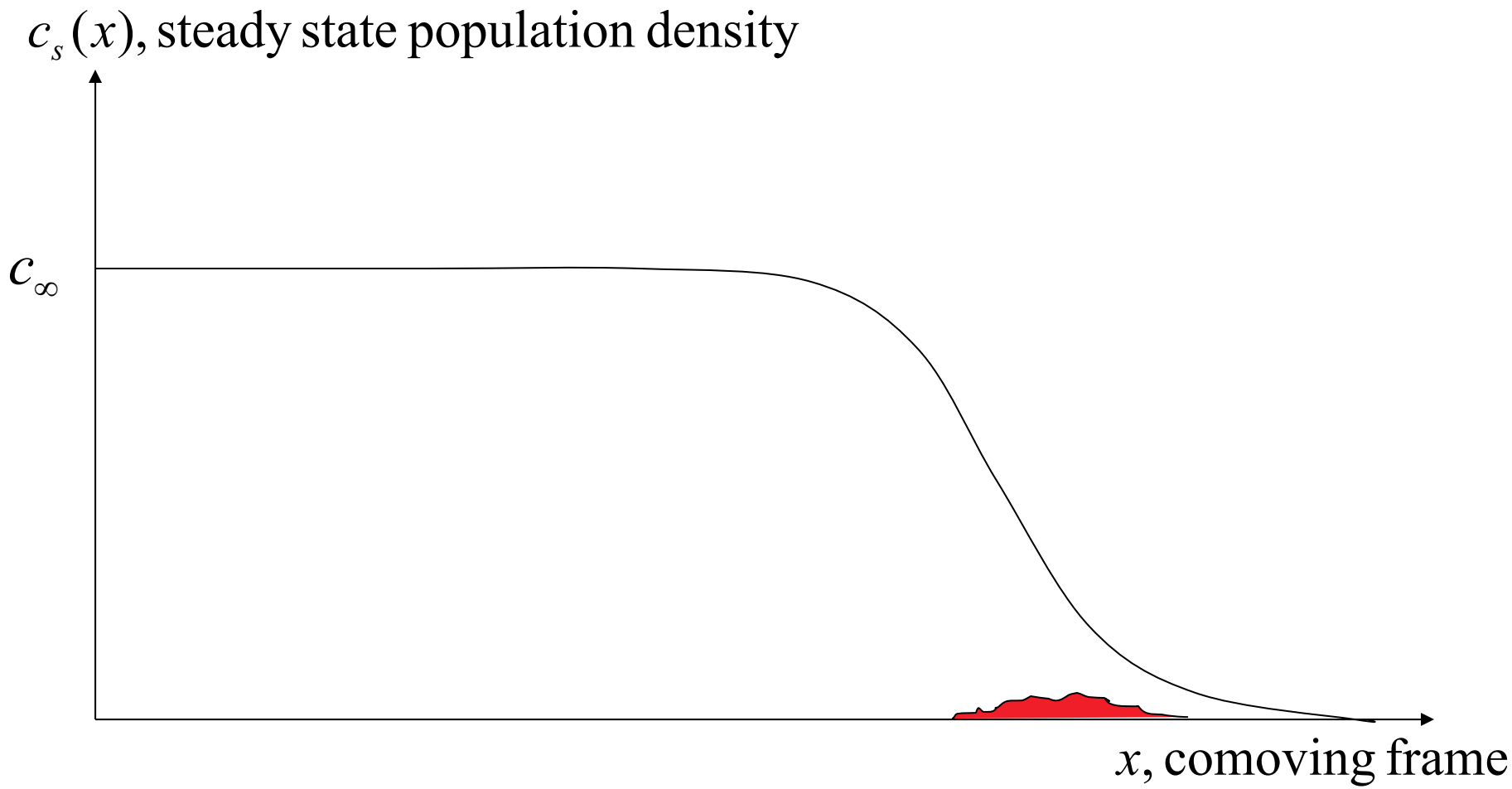
1932

R. A. Fisher

Successful Surfing (1d)



Successful Surfing (1d)



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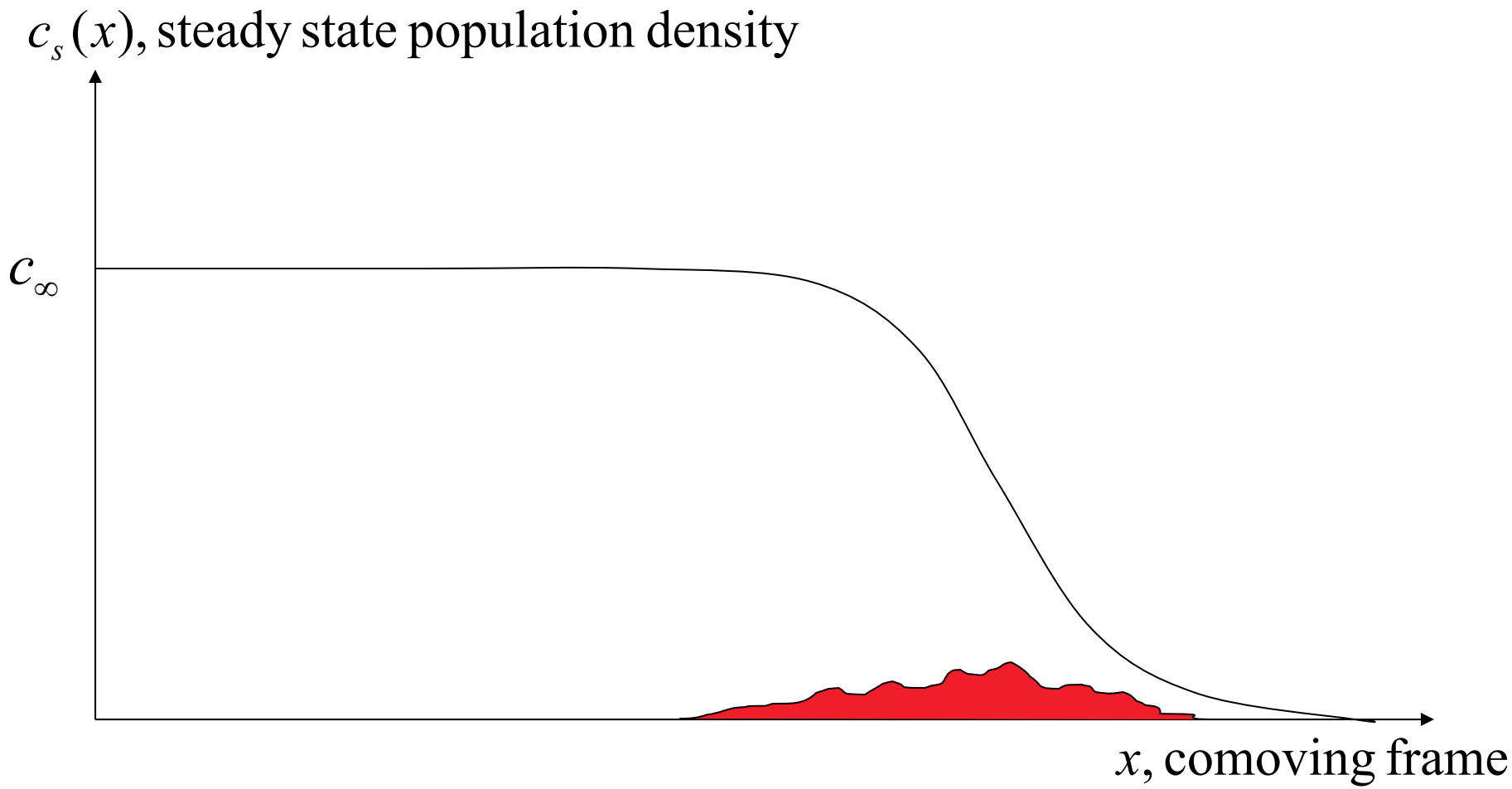

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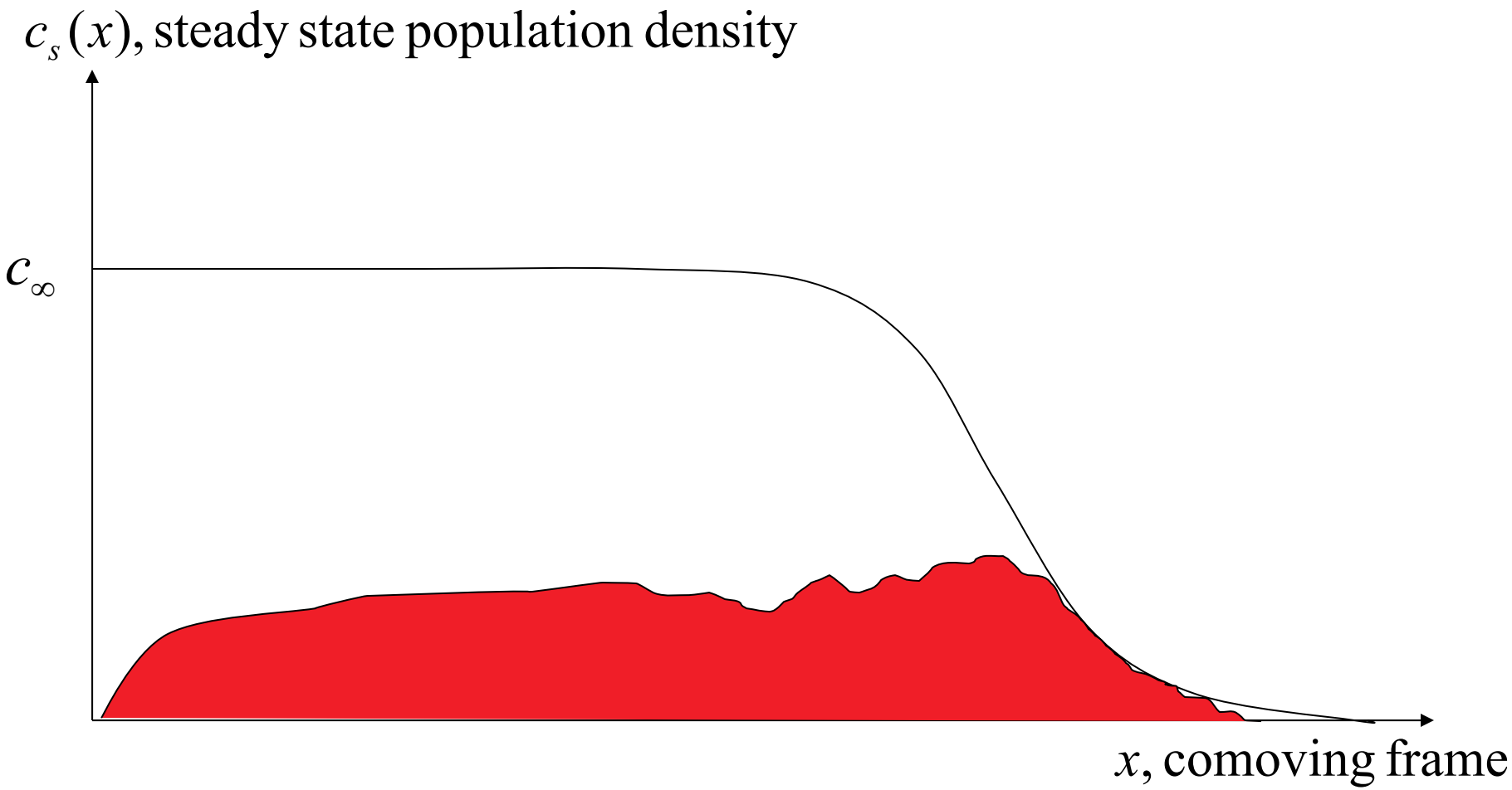

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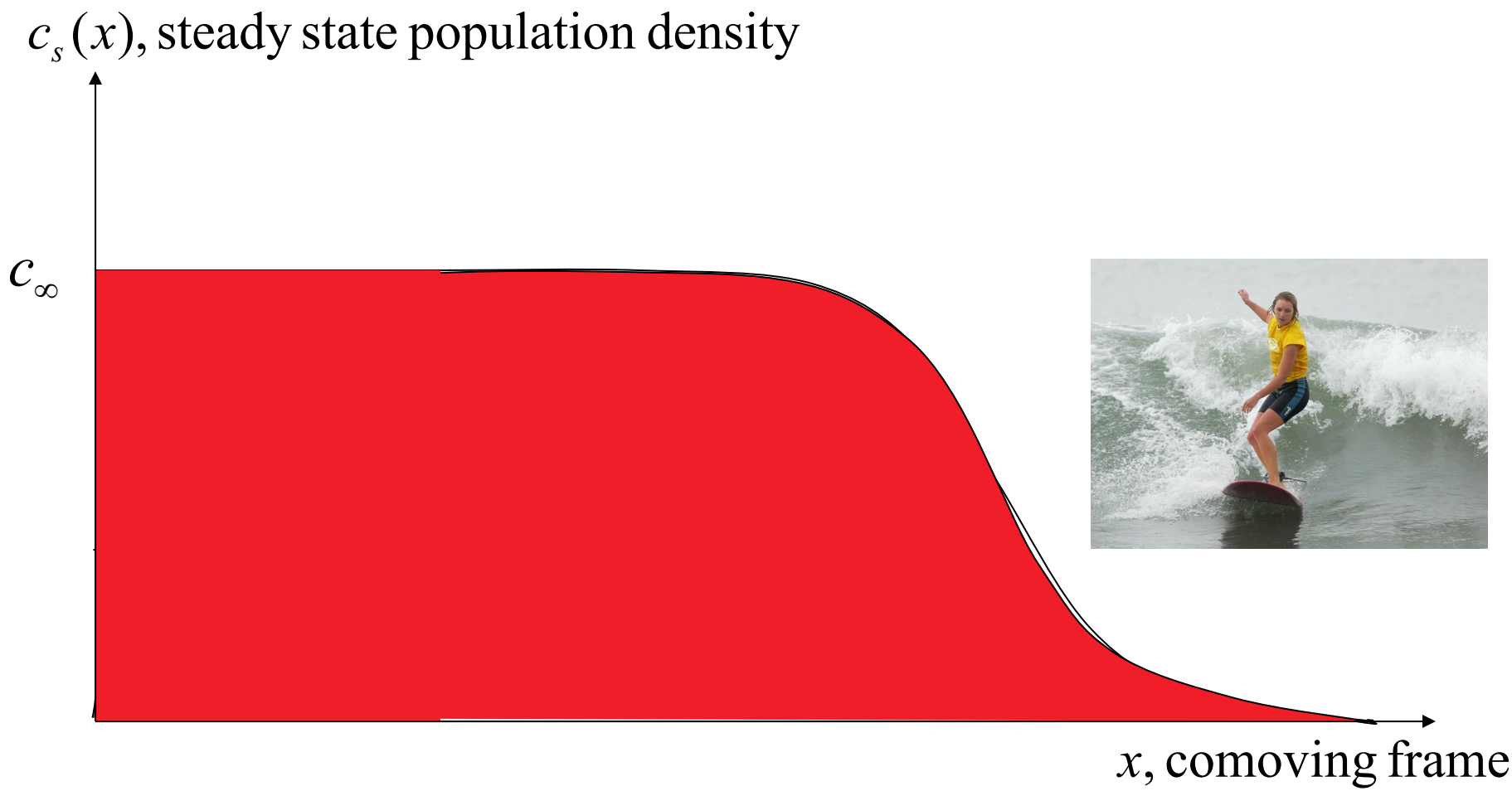
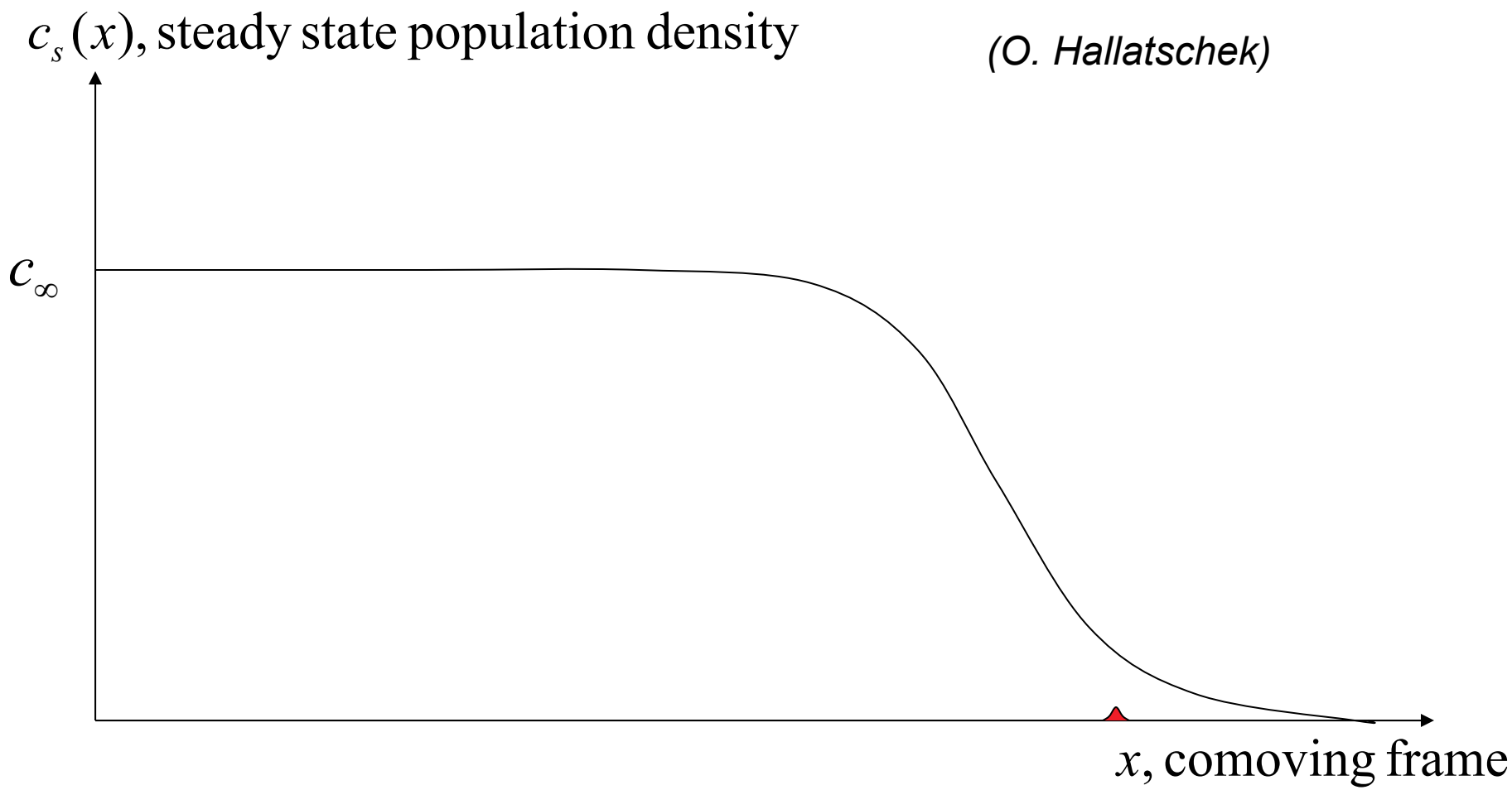


Often however …



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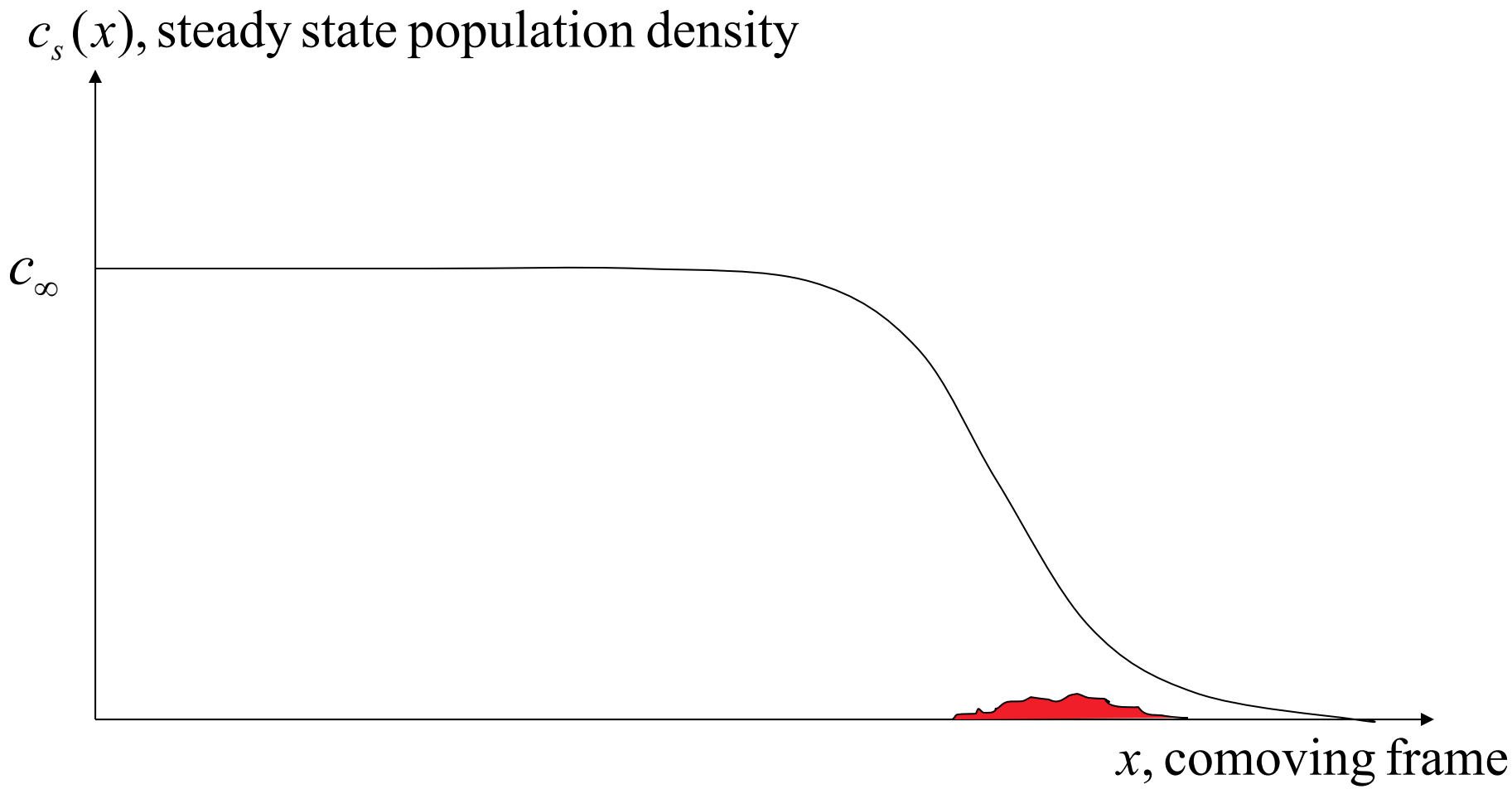

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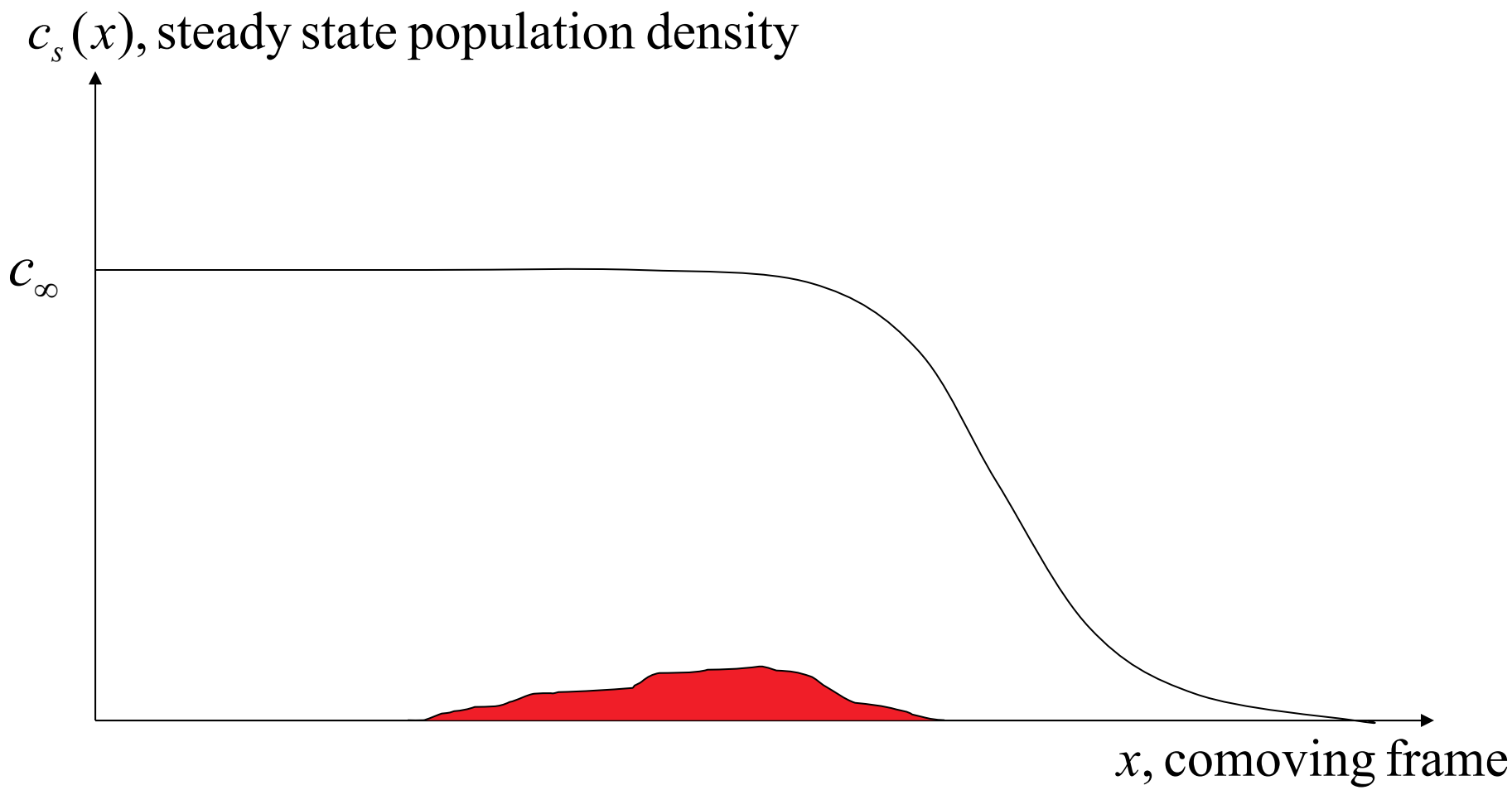

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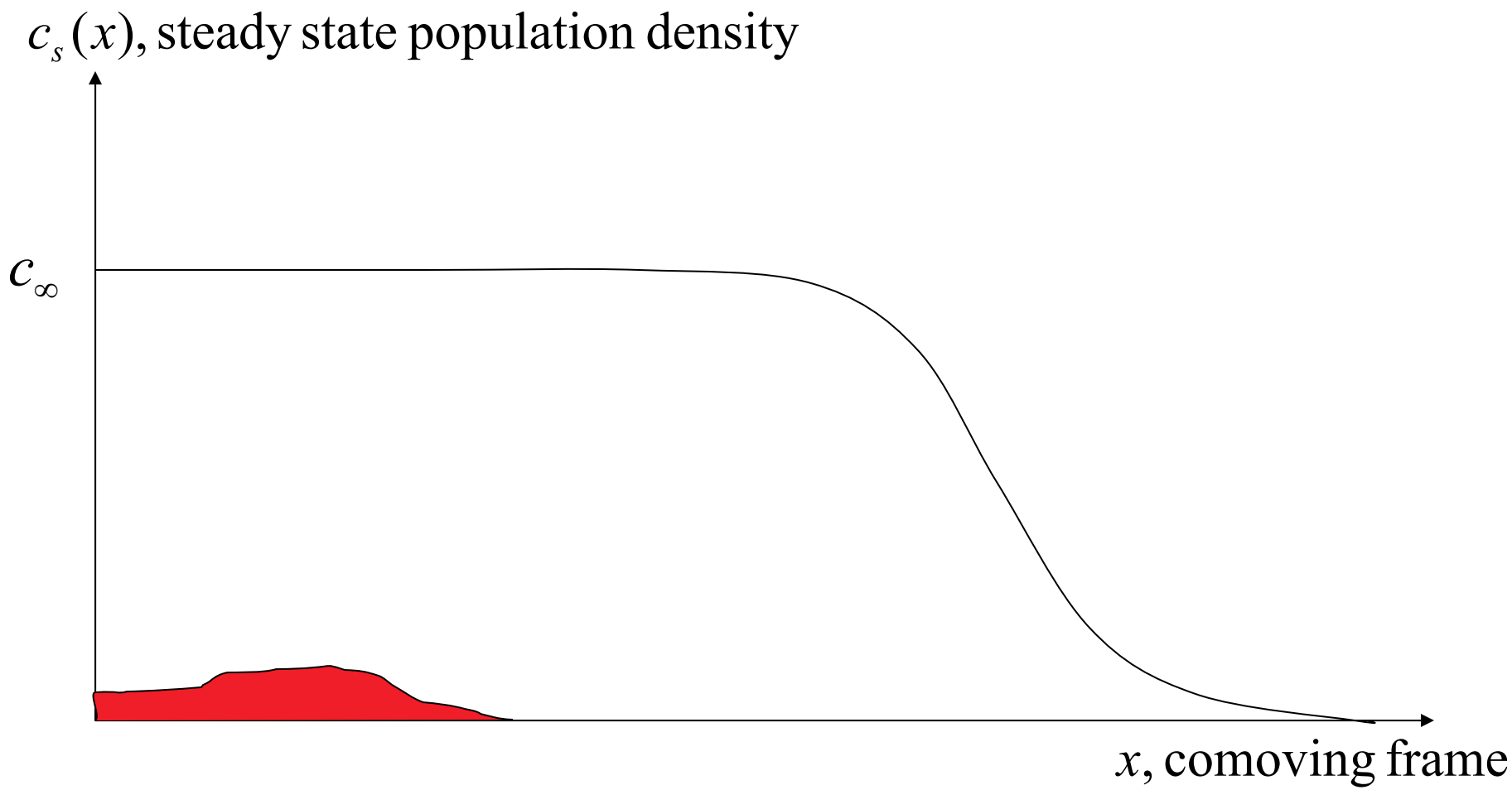
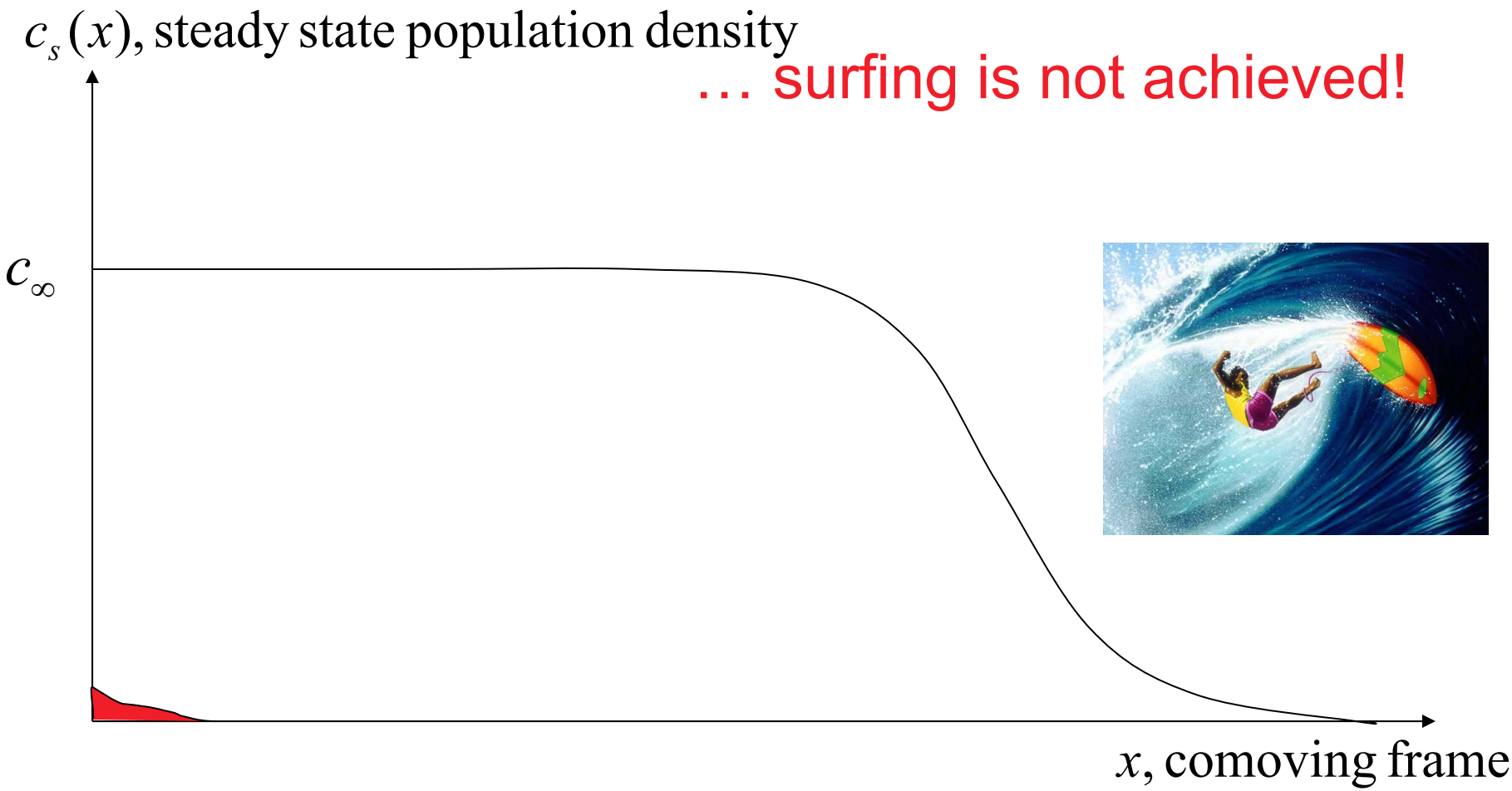
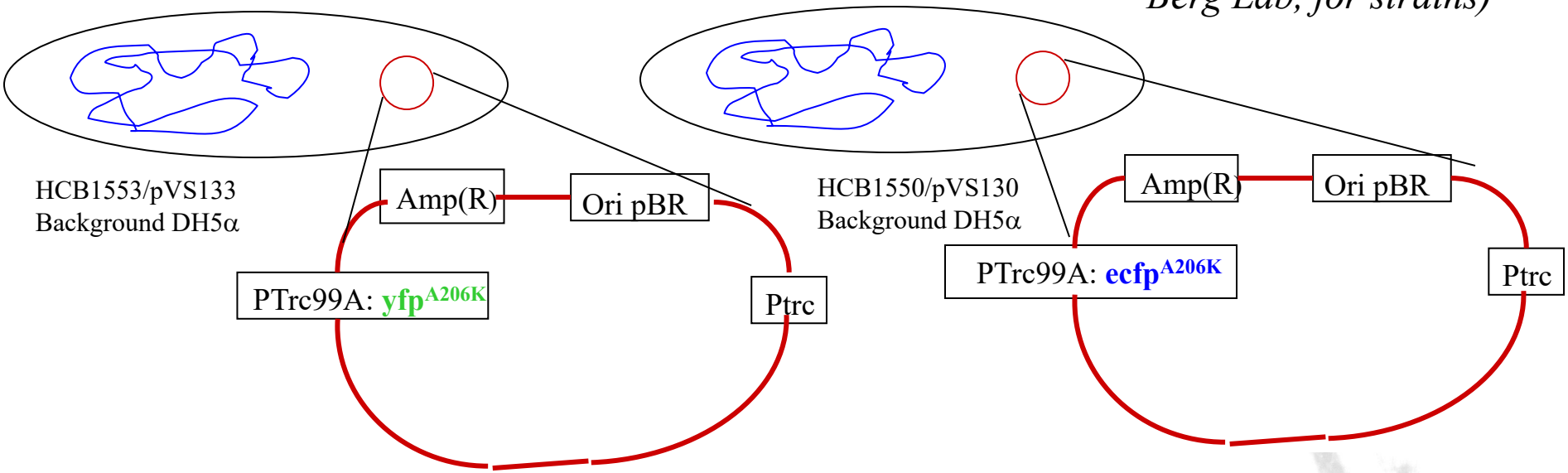


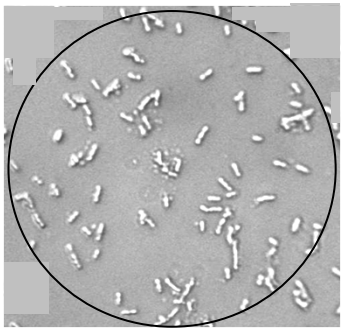
Often however …



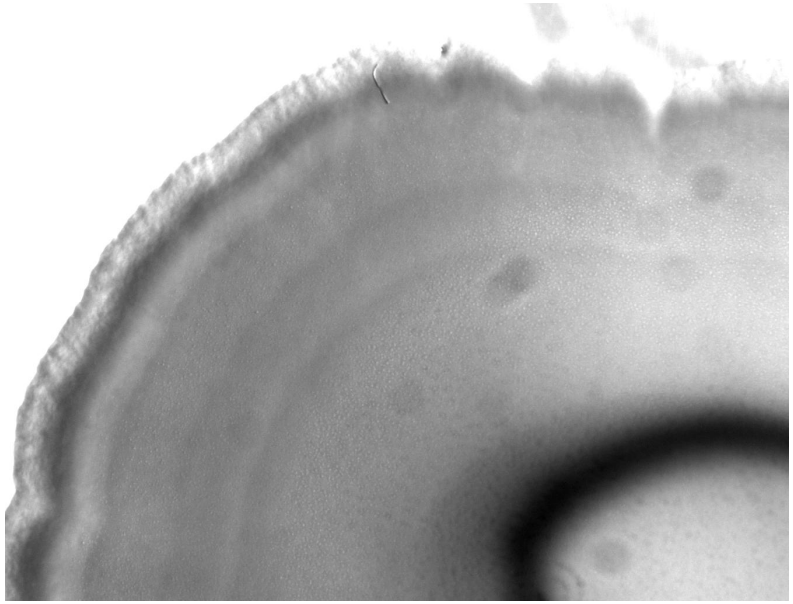
Genetic demxing in bacteria (E. coli)

(thanks to Tom Shimizu, Berg Lab, for strains)





50-50 mixture,
1550/1553



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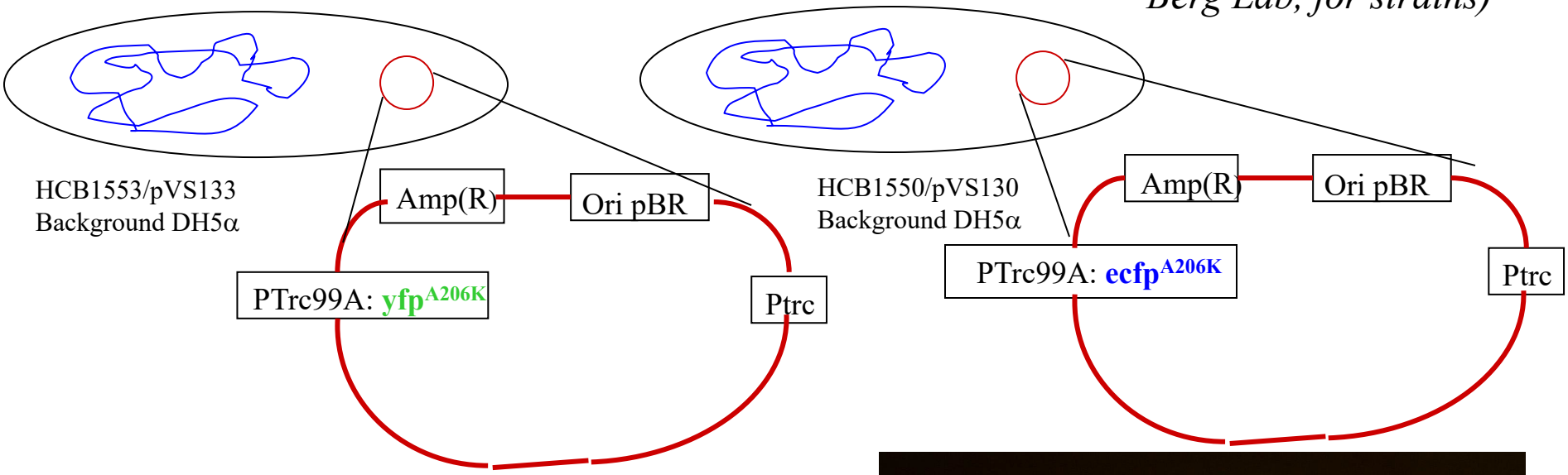

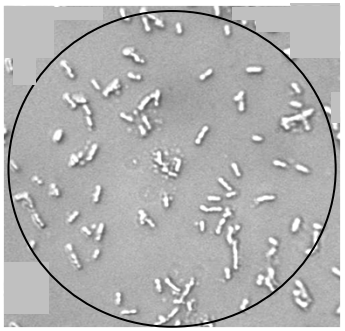

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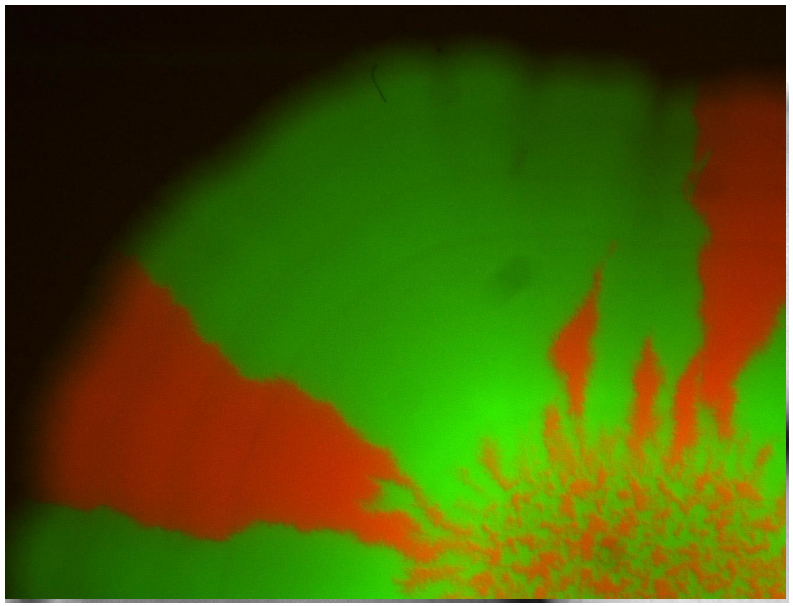

Cyan → Red

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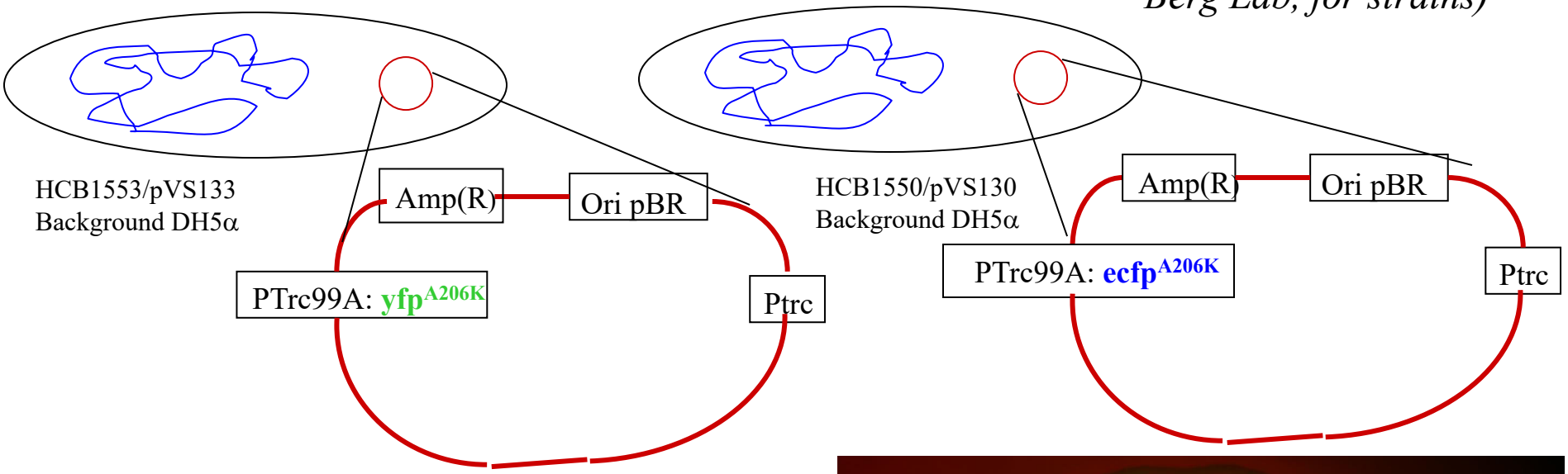
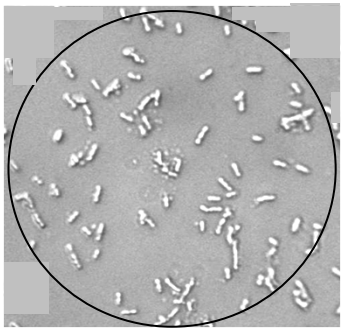
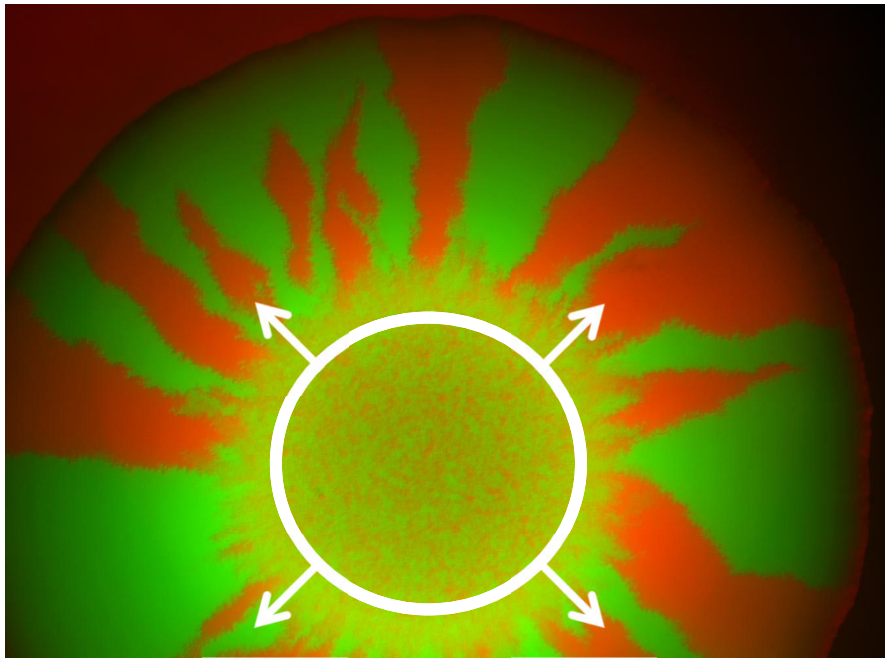


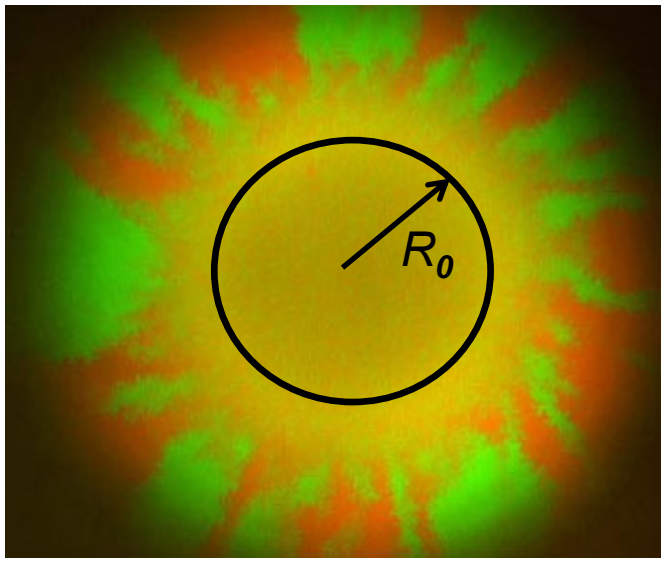


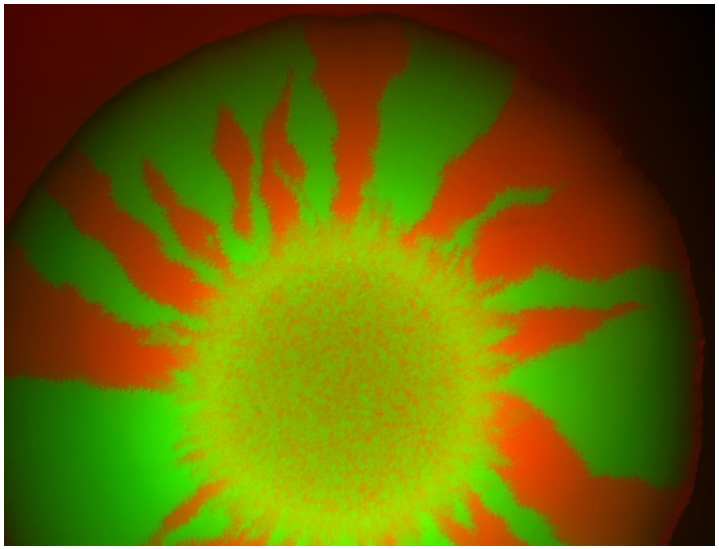
50-50 mixture,
1550/1553

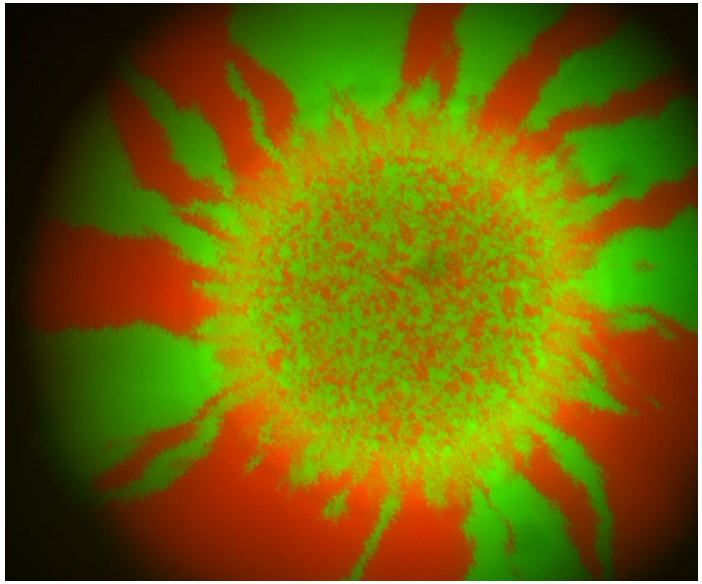


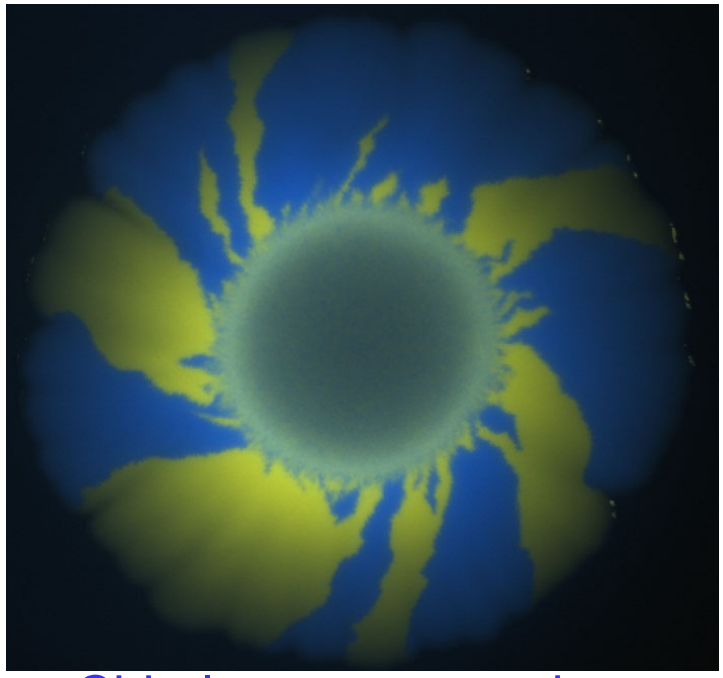
Cyan → Red

What would happen if we could "replay the tape of life"?



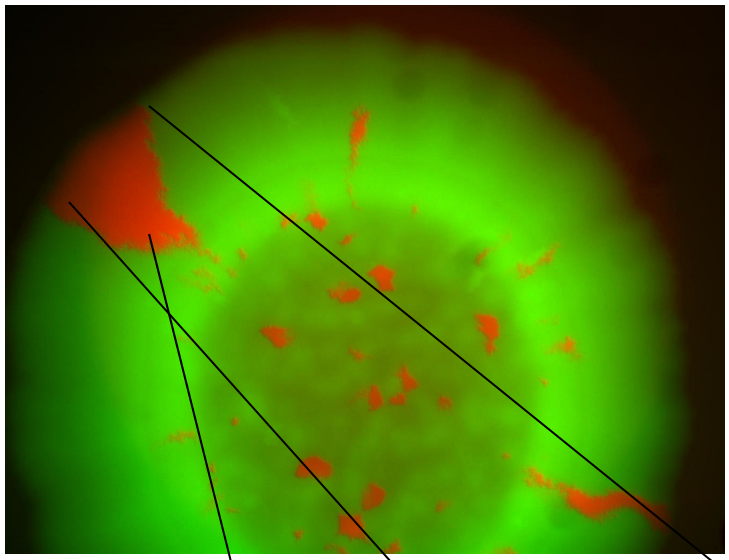




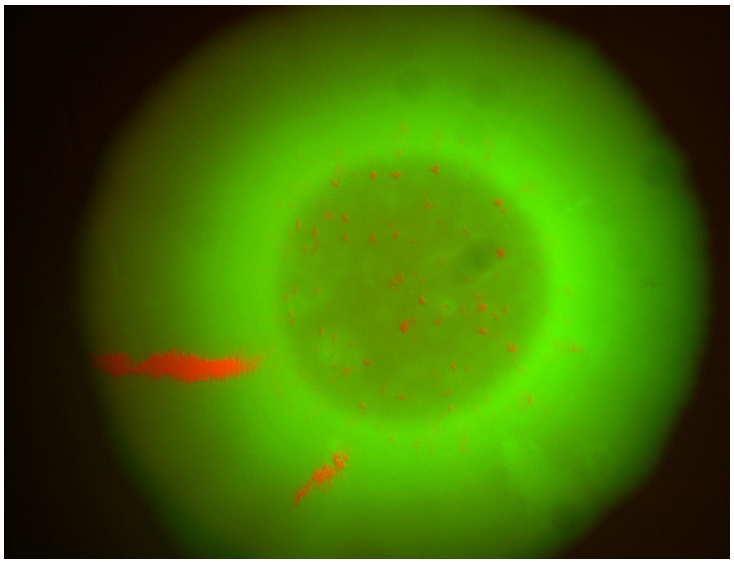


Chiral range expansions

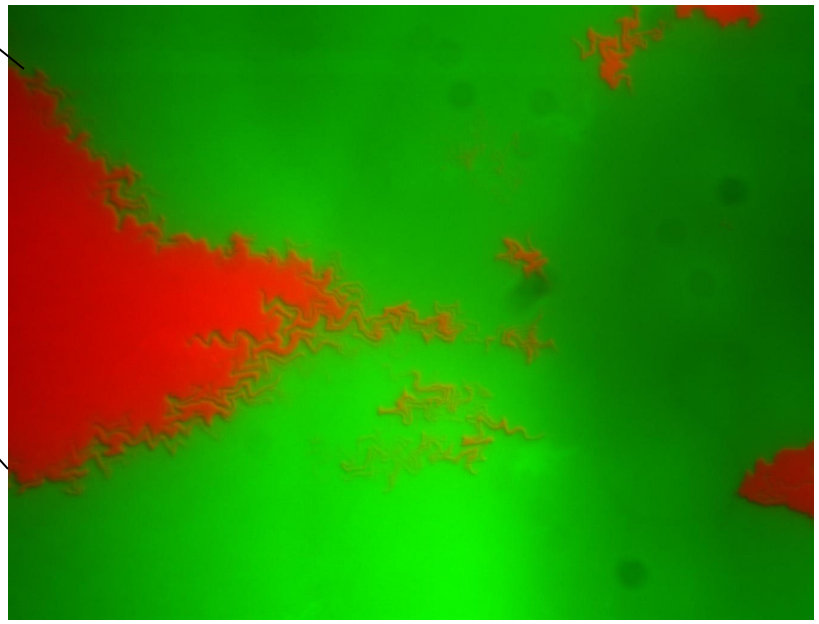
Gene surfing in the dilute limit: "survival of the luckiest"



95%-5% mixture, founder population ~ 500



98%-2% mixture, founder population ~ 5000



Questions & Break

But… life probably evolved first in a *liquid* environment

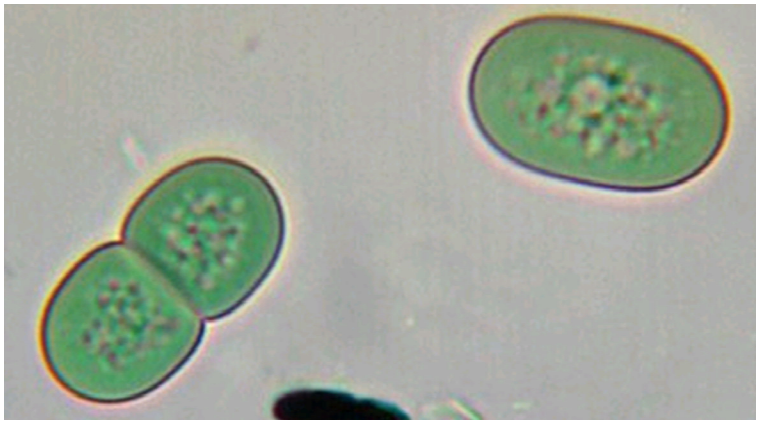
- ***~2-3 billion years ago, water covered most of the earth***

- ***Fossilized, oxygen-producing cyanobacteria have been dated at ~2.8-3.5 billion years ago.***

- ***Oxygenic cyanobacteria transformed the atmosphere via photosynthesis***

- ***Spatial growth and evolutionary competition took place at high Reynolds numbers***

- ***These photosynthetic organisms can control their bouyancy to resist down welling currents and stay close to the ocean surface.***



Cyanobacterium *Synechococcus*
www.dr-ralf-wagner.de/Blaualgen-englisch.htm

Bloom of cyanobacteria in Lake Atitlán, Guatemala
NASA Earth observatory

Life probably evolved first in a *liquid* environment

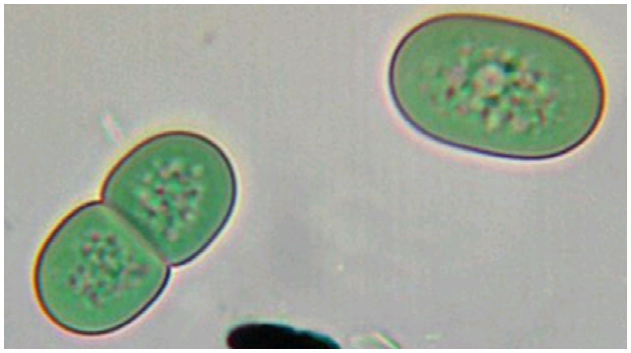
•~2-3 billion years ago, like today, water covered most of the earth

•Fossilized, oxygen-producing cyanobacteria have been dated at ~2 billion years ago.

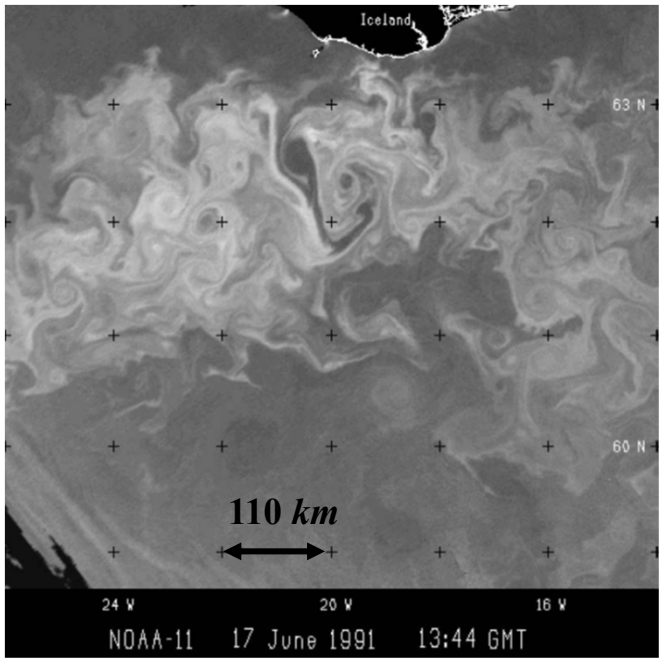
•Oxygenic cyanobacteria transformed the atmosphere via photosynthesis

•Their spatial growth and evolutionary competition took place in <u>liquid</u> environments at both high and low Reynolds numbers

•These photosynthetic organisms control their height to resist down welling currents and stay close to the ocean or lake surface.



Cyanobacterium *Synechococcus*



A. P. Martin, Prog. Oceanography **57**, 125 (2003)

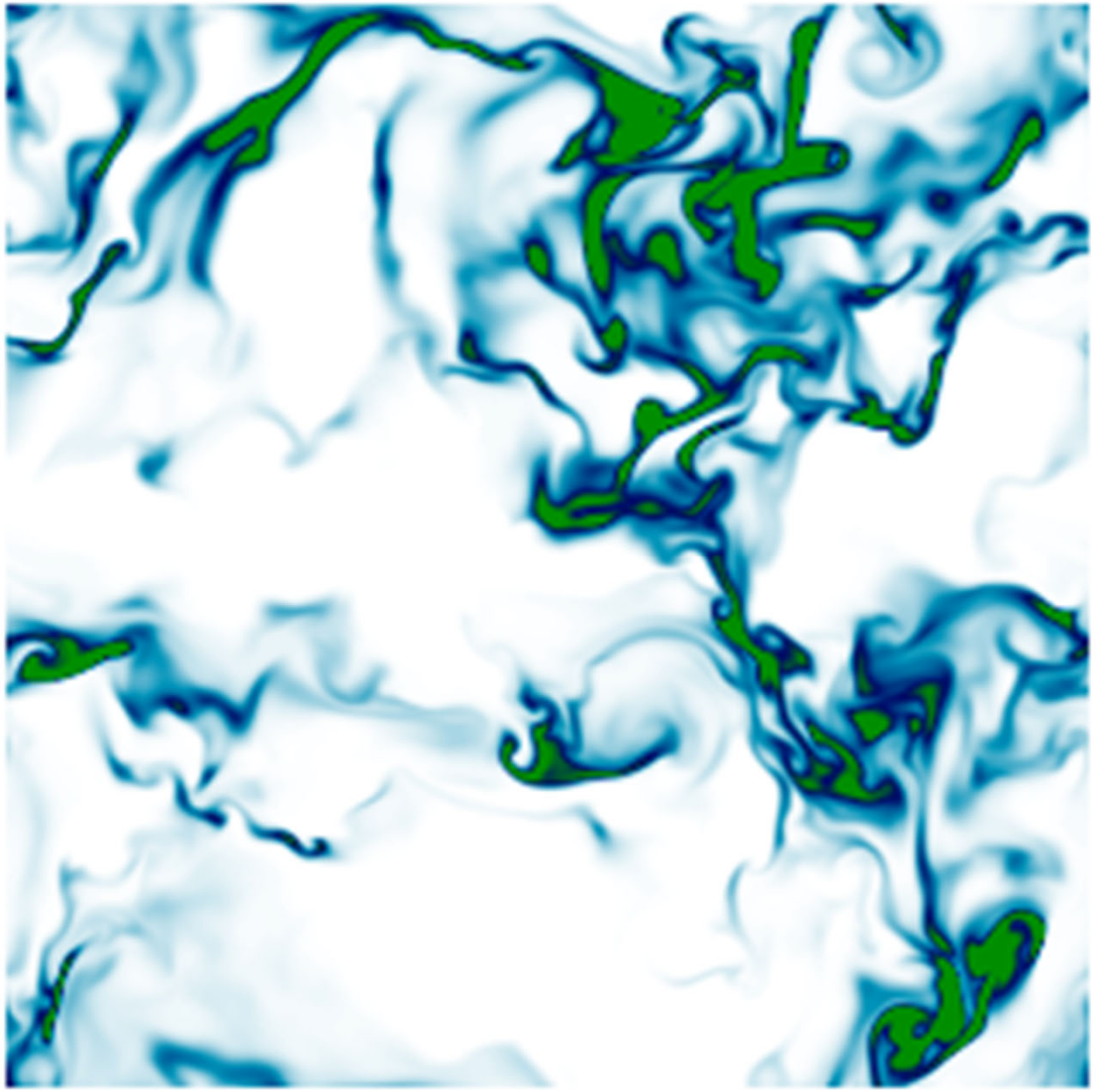
$\mathrm{Re} = LU/\nu = 10^8 - 10^9$

Large eddy turnover time $\approx$ 50 days

Small eddy turnover time $\approx$ 5 minutes

Plankton doubling time $\approx$ 12-24 hours

Buoyant population dyanamics in Silico (Perlekar, Toschi, Benzi, drn)



$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \vec{\nabla} \vec{u} = -\frac{1}{\rho} \vec{\nabla} p + \nu \nabla^2 \vec{u} + \vec{f}$$

project onto a 2d plane $\rightarrow \vec{\nabla} \cdot \vec{u}_{2d} \neq 0$

$$\frac{\partial c}{\partial t} + \nabla \cdot (\vec{u}_{2d} c) = D \nabla^2 c + \mu c (1 - c)$$

Reynolds number

$$Re = \frac{u_{\mathrm{rms}} L}{\nu}$$

Schmidt number

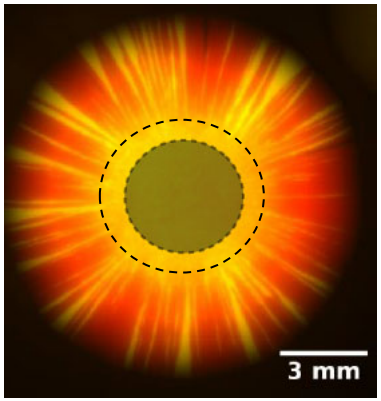
$$Sc = \frac{\nu}{D}$$

Doubling time/eddy turnover time

$$\tau_2 / \tau_{eddy} \sim 1/(\mu \tau_{eddy})$$

Microorganisms grown on liquid but highly viscous substrates create their own flows (without pumps and syringes!)

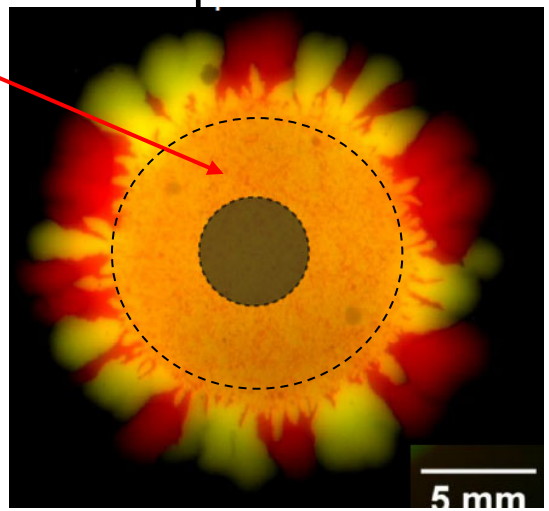
Hard Agar



Genetic demixing of yeast on a 1% hard agar YPD plate (viscosity $\eta = \infty$)

Epoch of genetic demixing stretched out….

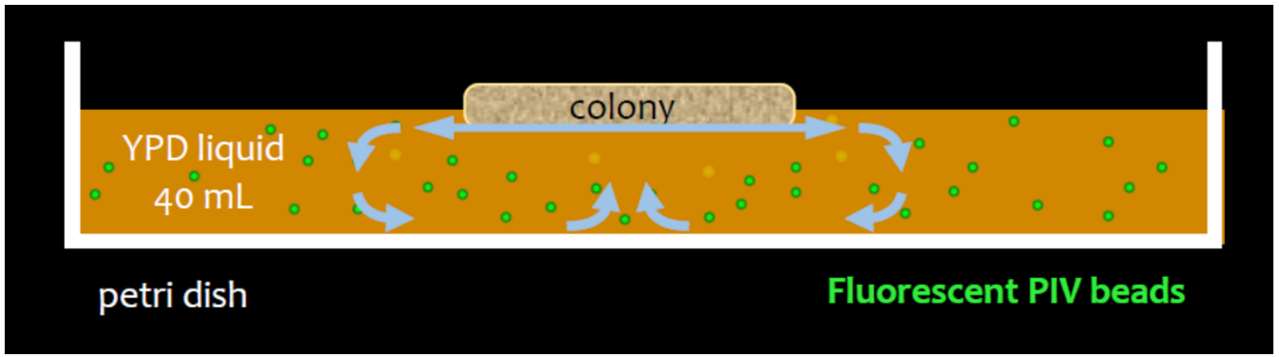
Liquid Media



Yeast on a liquid but highly viscous YPD media with 3% cellulose ($\eta \approx 600$ Pa-s)

Cellulose % (w/v)	Viscosity (Pa·s)
1.8	22 ± 3
2.0	51 ± 6
2.2	81 ± 9
2.4	120 ± 10
2.6	340 ± 50

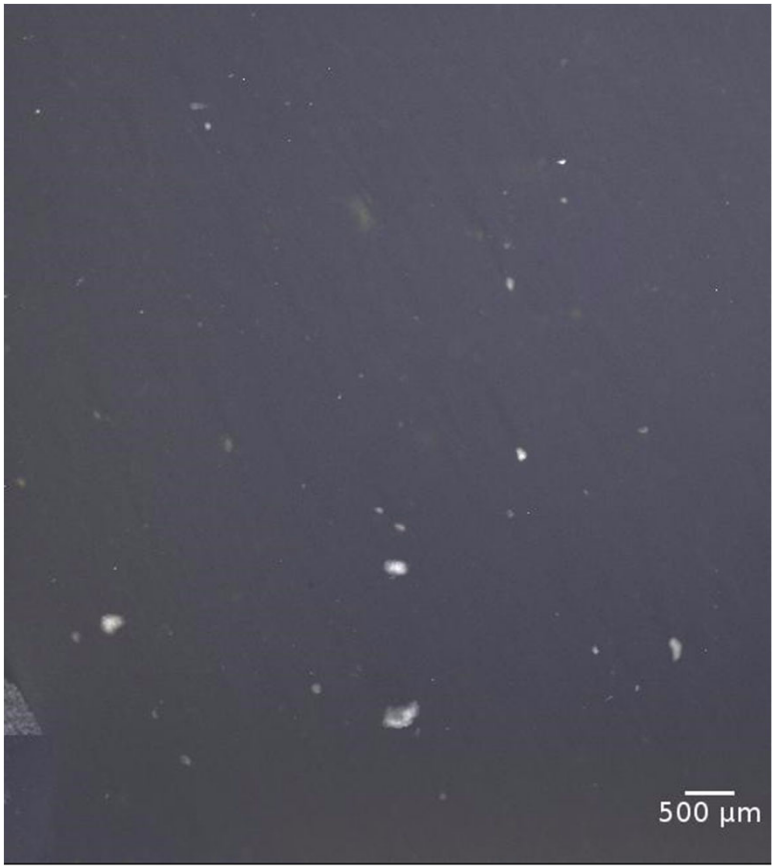
(the viscosity of water is $\eta \approx 10^{-3}$ Pa-s; our viscosities are $10^4 - 10^5$ times larger)

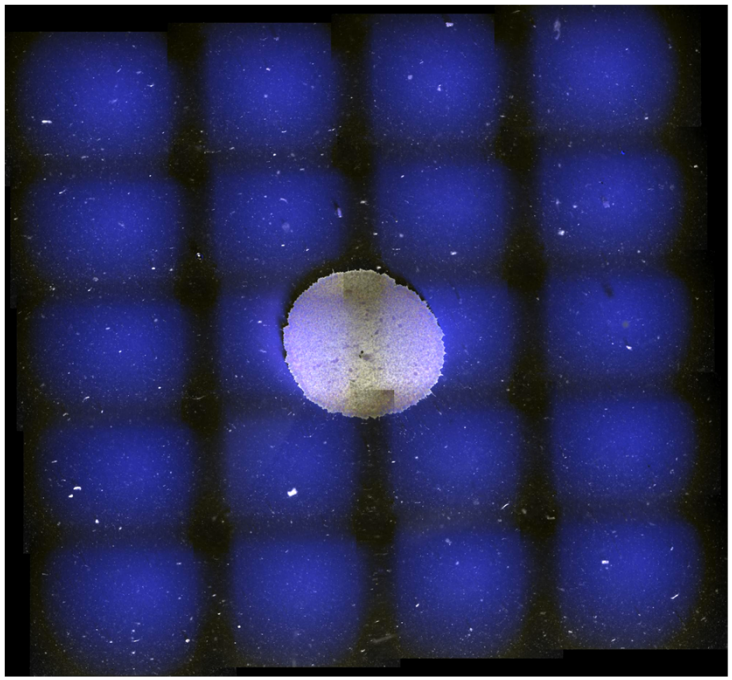


The colony itself generates flows that dilate the growing cell mass radially!

Enhancing the radial flow field...

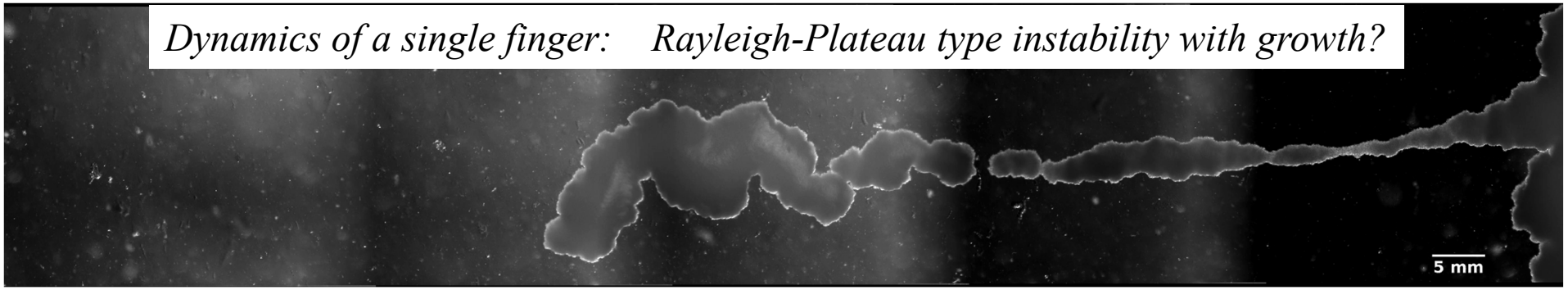
(moderate substrate viscosity η≈450 Pa-s)



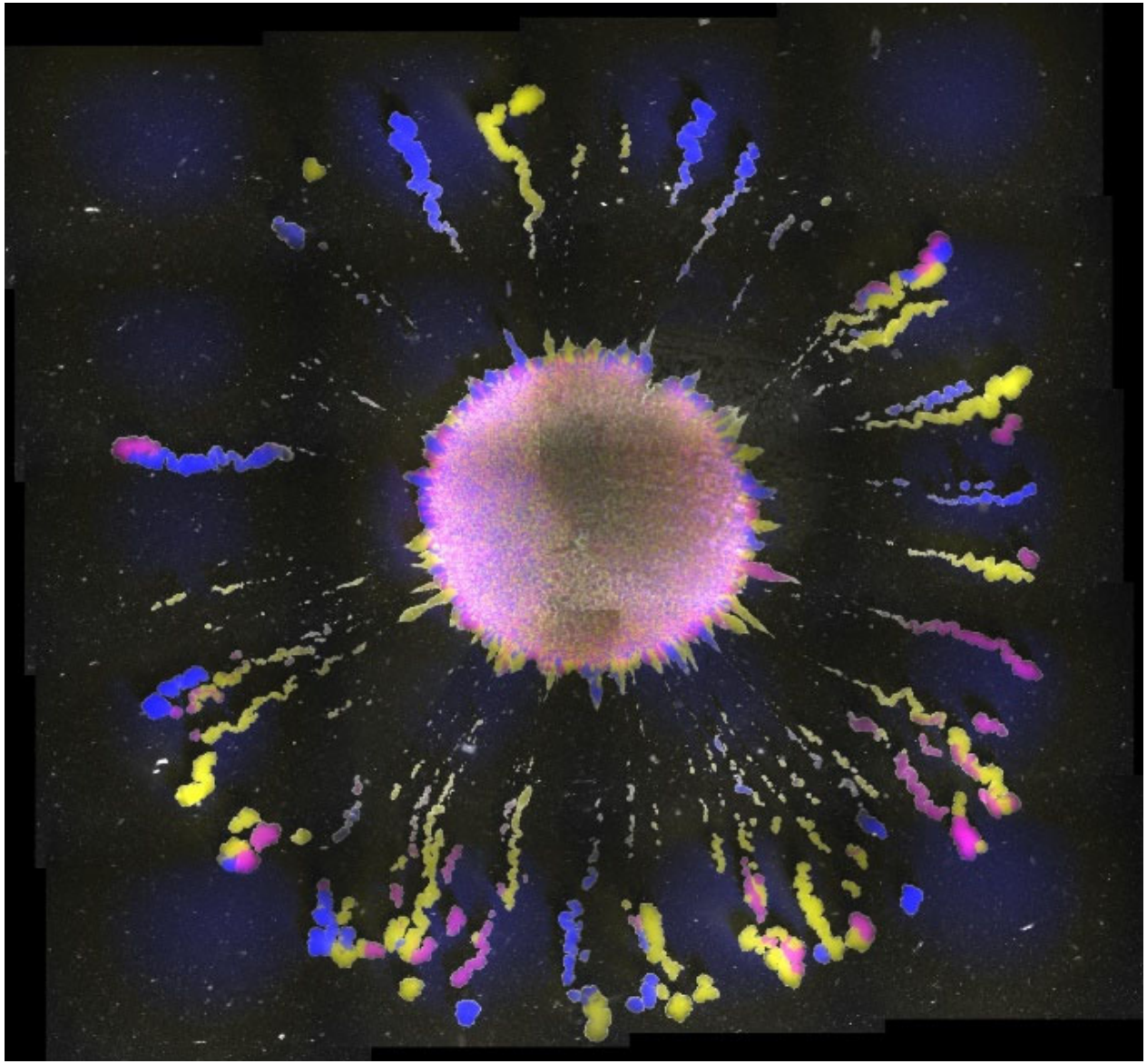


Liquid-like fingering instabilities

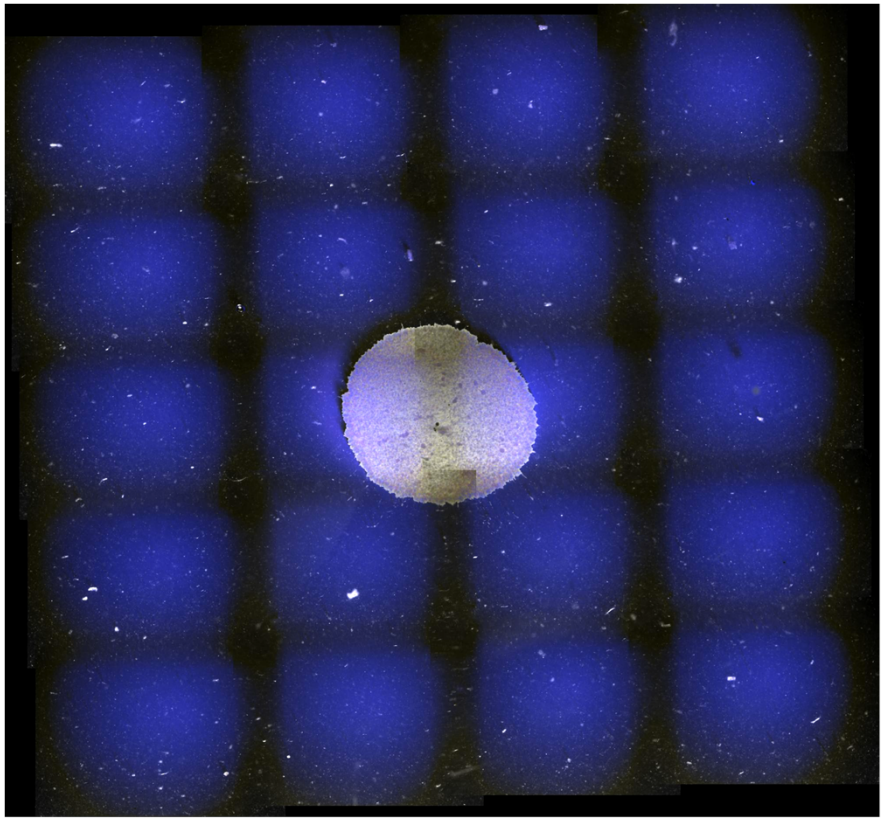
Dynamics of a single finger: Rayleigh-Plateau type instability with growth?

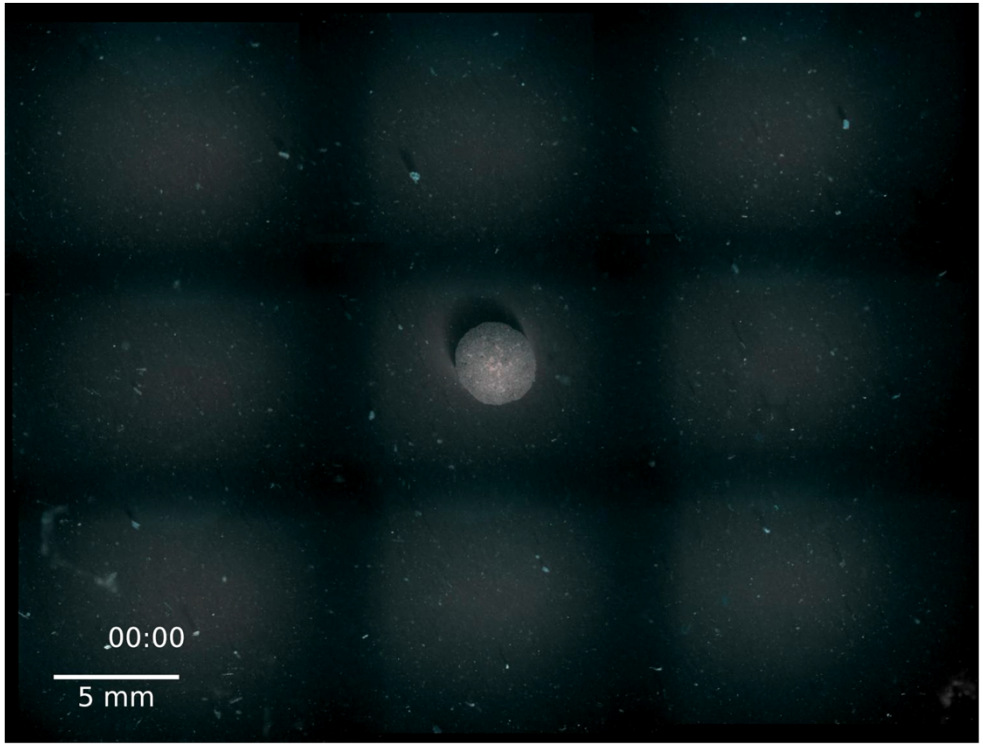


Three colors: genetic demixing among *three* different genotypes



- Anomalous expansion of neutral S. *cerevisiae* strains on a liquid substrate (driven by a submerged vortex ring!)
  S. Atis, B. Weinstein, A. Murray, drn

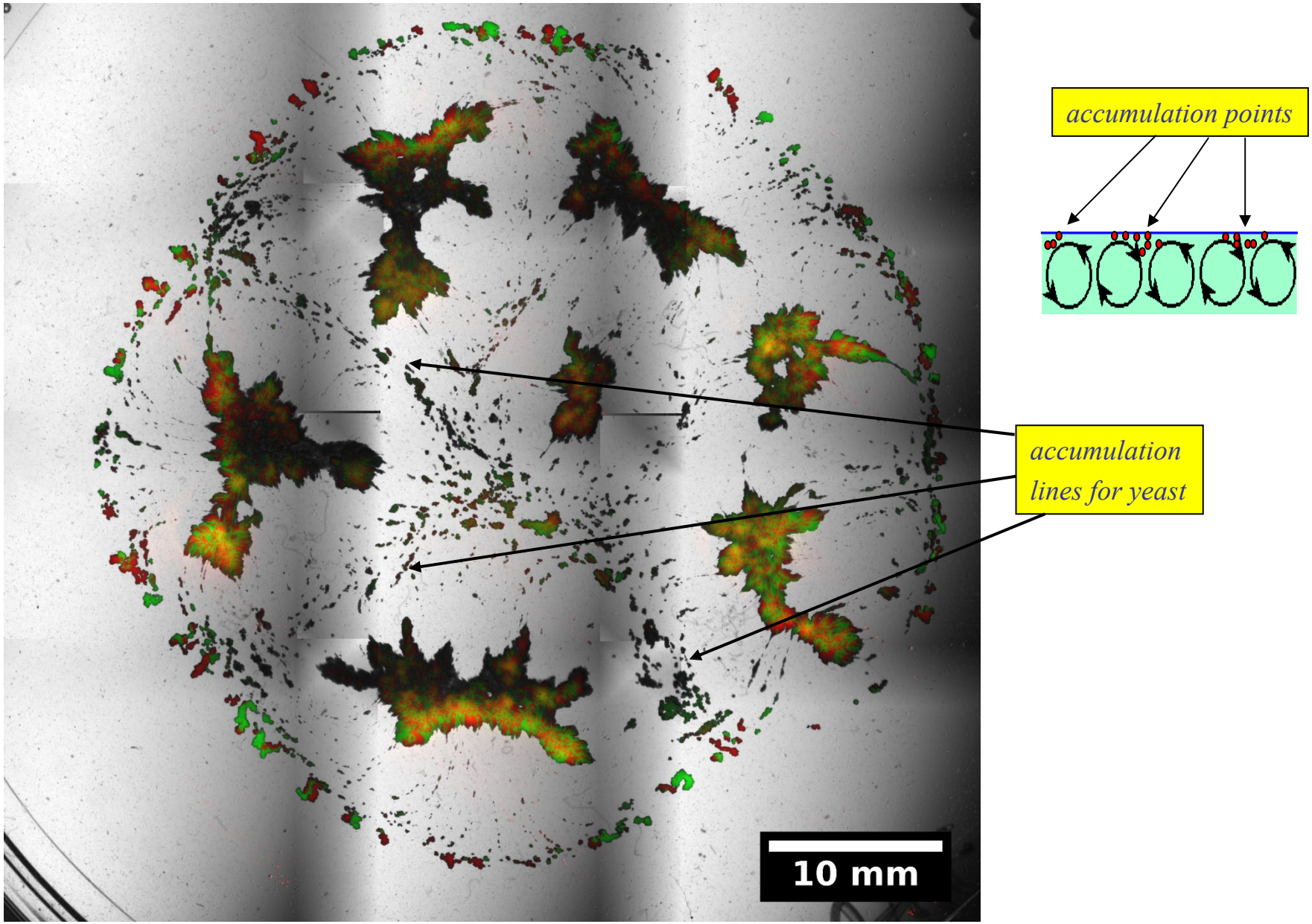




•*Range expansion floating on a high viscosity substrate → fingering with population genetics*

• *Range expansion floating on a lower viscosity substrate → fracture with population genetics*

At lower viscosities, submerged vortex rings fracture the colony – like plate tectonics & continental drift ! ….



Entry #V0020

ROCKET YEAST

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Thank you!

http://streetanatomy.com