A: Fundamentals of Life

- Definition of Life
- Logic of Molecular Biology
- History of Biology
- Becoming alive
- Soup of Life
- Selection: before and in life
- Three faces of Entropy
- Death and equilibrium
- Missing non-equilibrium
- Structure of Origin of Life
- Modes of non-equilibrium
- Examples of evolution

`

B: Physics for Chemistry

Polymerization
- Theory of polymerization
- P. by fast cooling
- P. by stacking with 3’-5’-Ph.
- Activation groups
- P. on clay
- P. by thermophoresis
- Phase transitions with DNA
- Sedimentation of DNA
- Drying and its problems
- Elegance of air interface

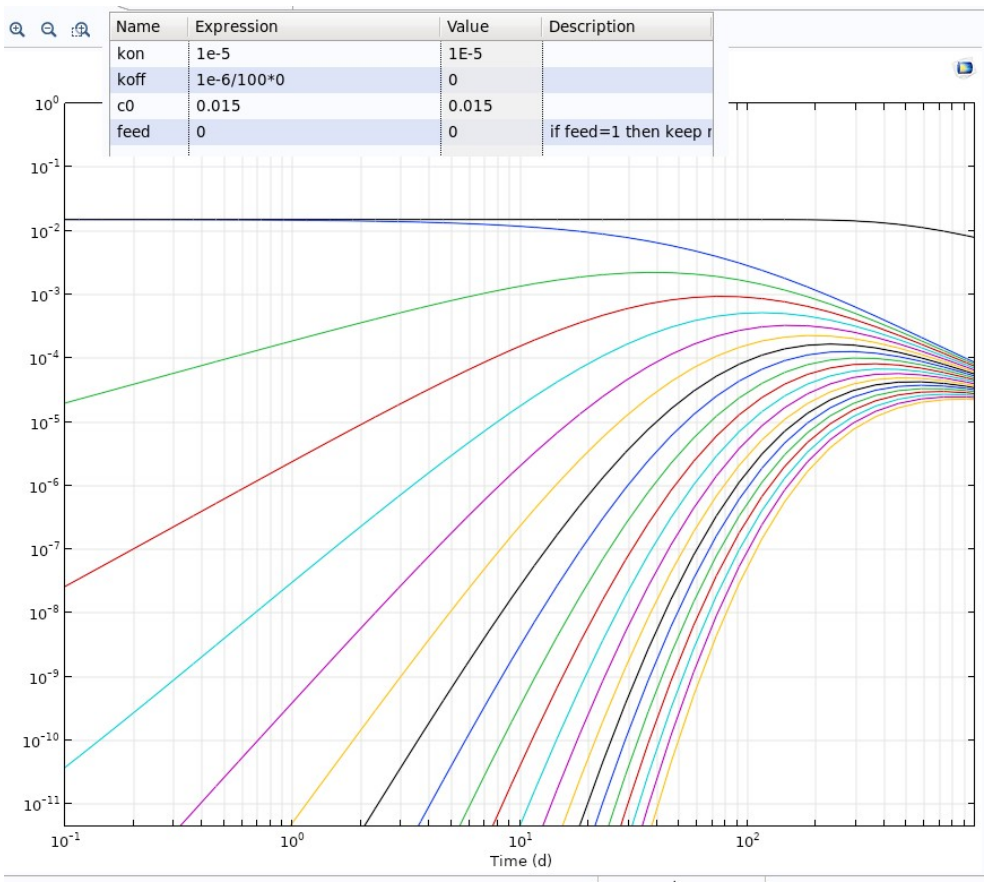
Replication
- Templated polymerization
- Ligation
- Strand separation problem
- PCR in convection
- Ribo-PCR in convection

C: Evolution Machines

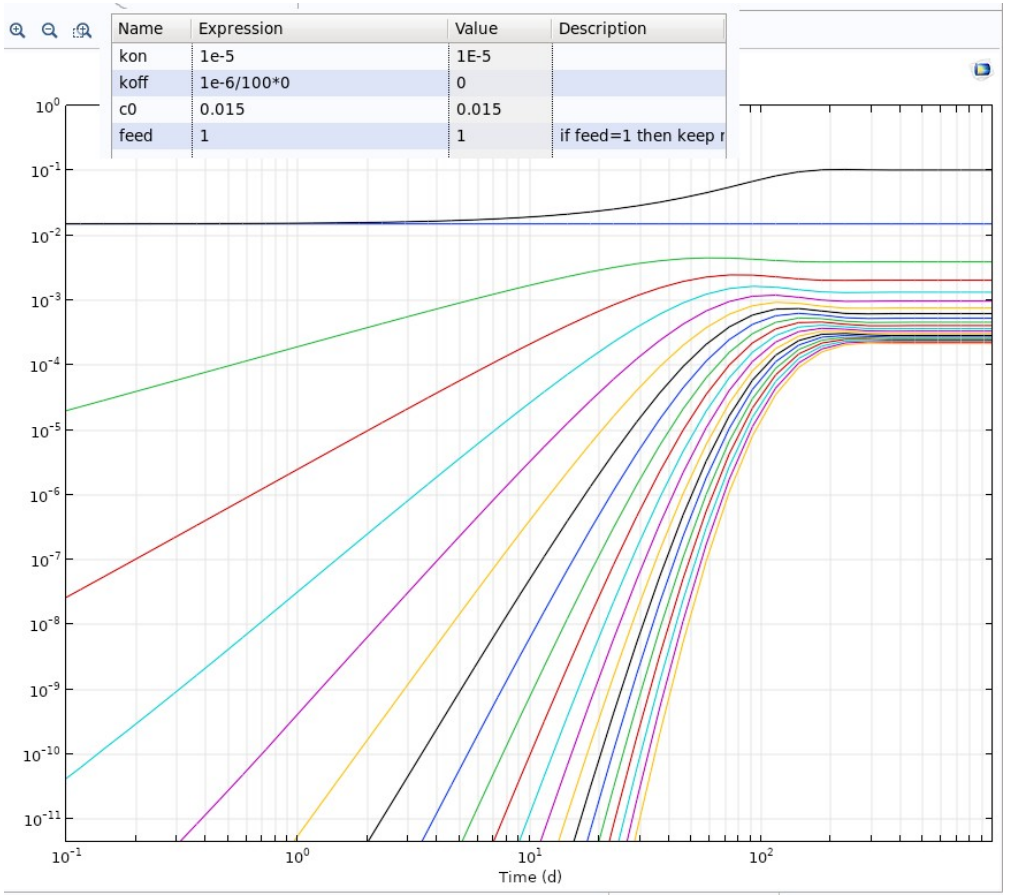
Replication with accumulation
- Case of Ribo-PCR
- Spiegelman problem
- Case of trapped PCR
- Trapped PCR with flow
- Feeding problem
- Replication with heated tRNA
- Replication in driven Fog

Rebustness of evolution
- Error threshold
- Instability of four bases
- Hypercycles with ligation
- Spont. Symmetry breaking
- Spont. sequence selection
- Cooperation within cells

Theory of polymerization

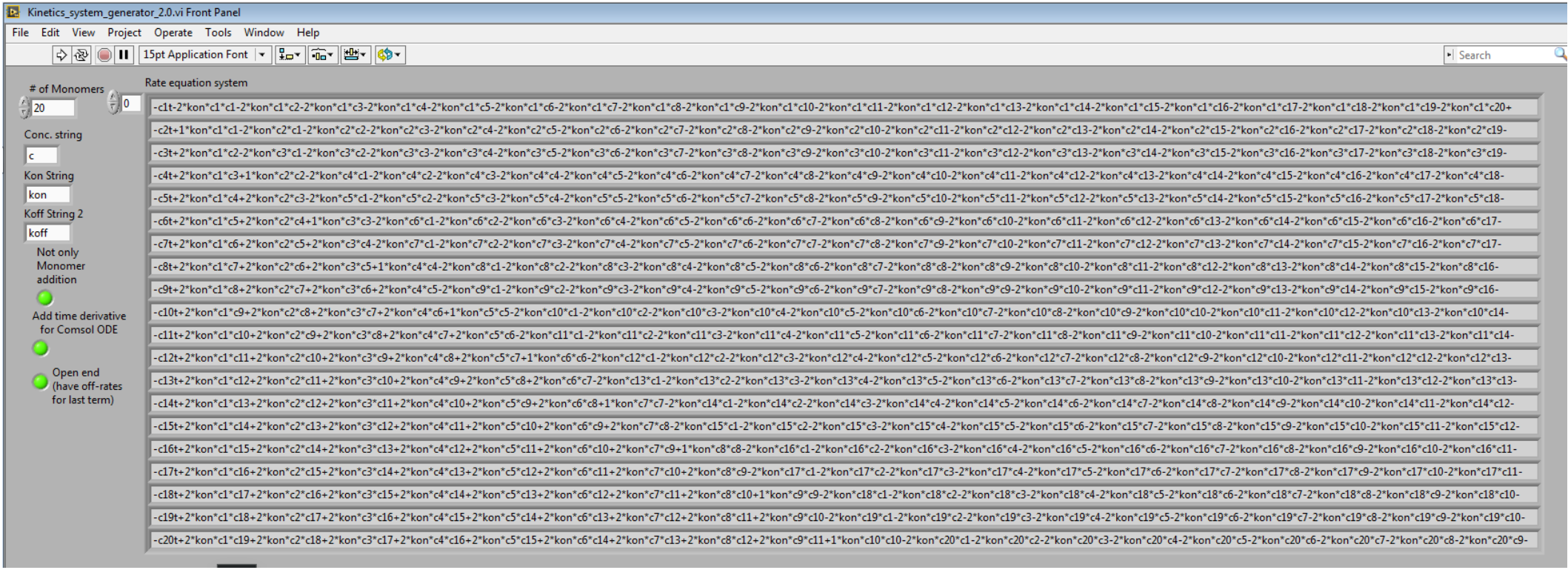


Comsol no feeding of monomers



Comsol with feeding of monomers

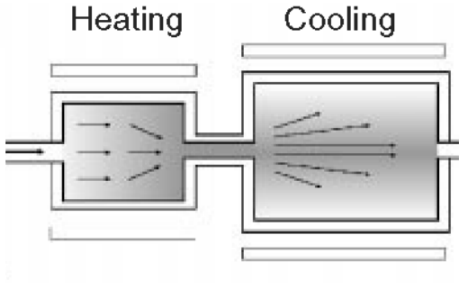
Theory of polymerization

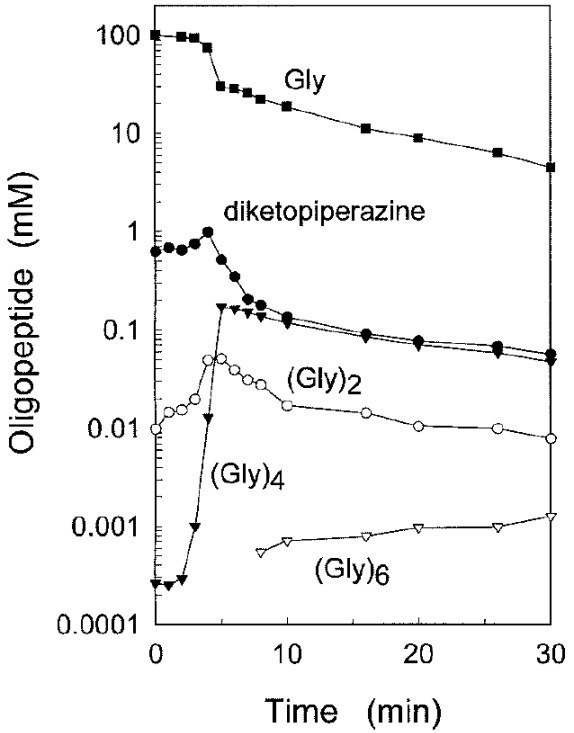


Creating kinetic terms with a LabView program

Esoteric?
Protein Polymerization
by fast cooling

Matsuno: Polymerisation by fast cooling





Koichiro Matsuno, Science 283, 831 (1999)

Polymerization on clay
Needs ion washing: Correct mechanism?

Ferris: Clay-based polymerisation

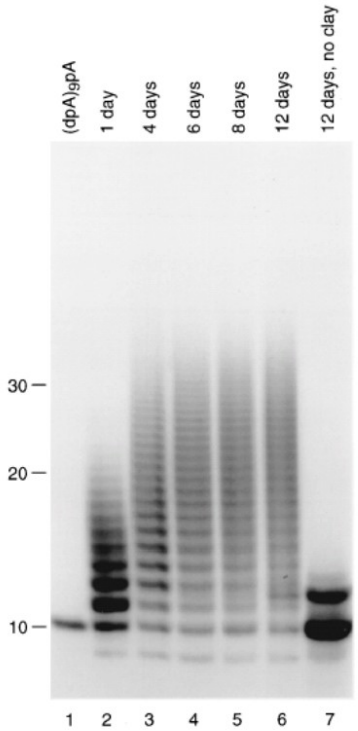
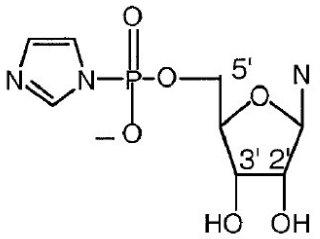


Figure 2. Gel electrophoresis of the elongation of ^{32}pdA(pdA)$_8$pA with ImpA in microcentrifuge tubes. Lane 1, ^{32}pdA(pdA)$_8$pA; lanes 2–6 elongation in the presence of montmorillonite; lane 7, elongation in the absence of montmorillonite.



On the **surface of negative charged montmorillonite** clay, energy rich nucleotide-primers can undergo efficient polymerization. One can reach **30-50-mers within some days**. Surfaces are therefore interesting places for catalysis of prebiotic reactions since they can enhance the concentration of the molecules. Problem is the removal of the polymerized species from the surface and replication priming.

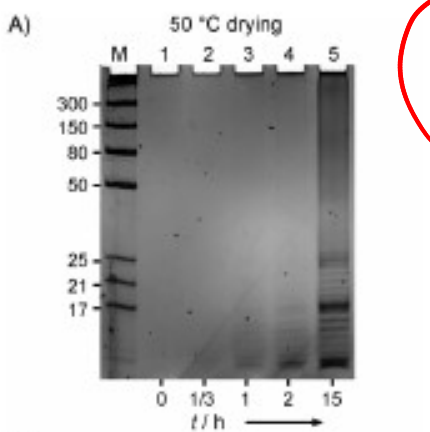
James P. Ferris: Origins of Life and Evolution of the Biosphere **32:** 311–332, 2002.

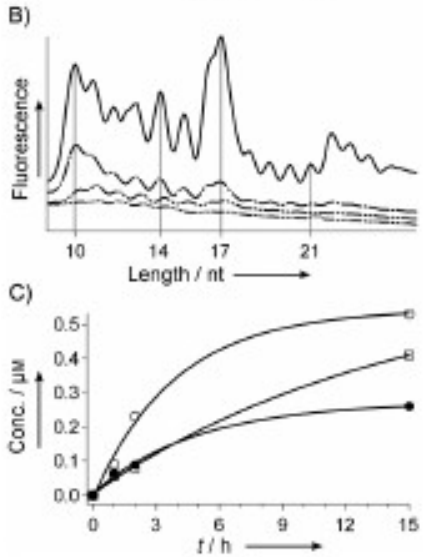
Polymerization by drying of 3’-5’ cyclic G-Nucleotide

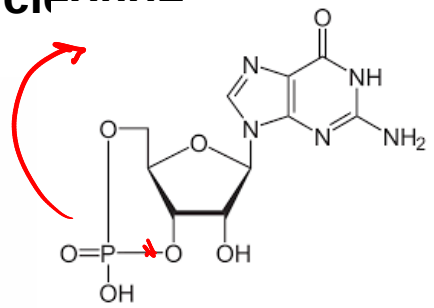
DOI: 10.1002/cbic.201300773

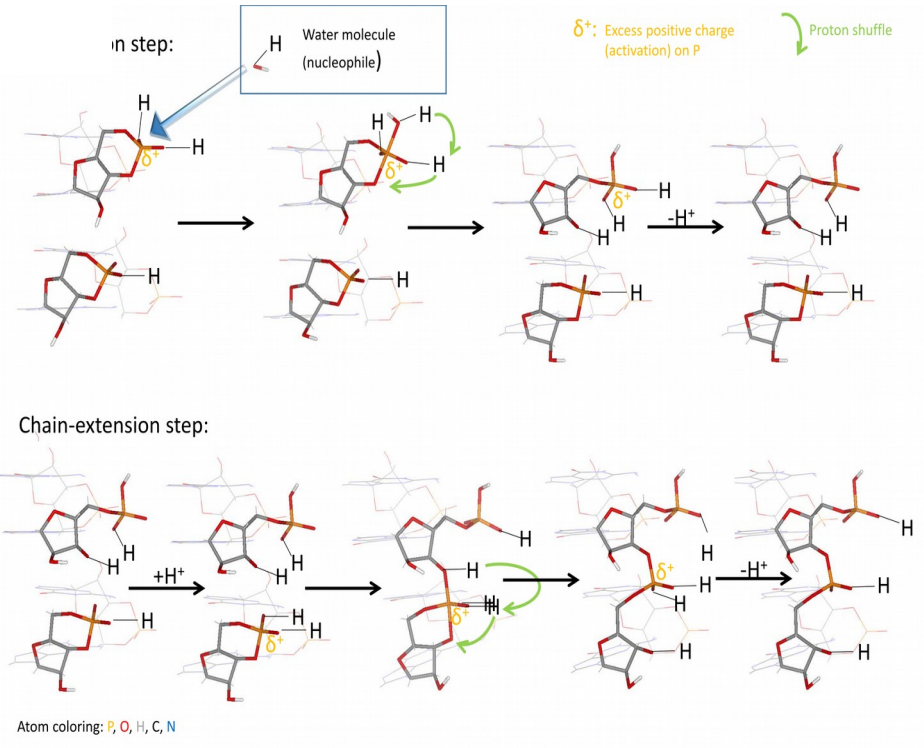
Dry Polymerization of 3′,5′-Cyclic GMP to Long Strands of RNA

Matthias Morasch,[a] Christof B. Mast,[a] Johannes K. Langer,[a] Pierre Schilcher,[b] and Dieter Braun*[a]









See papers by di Mauro and Judith Sponer

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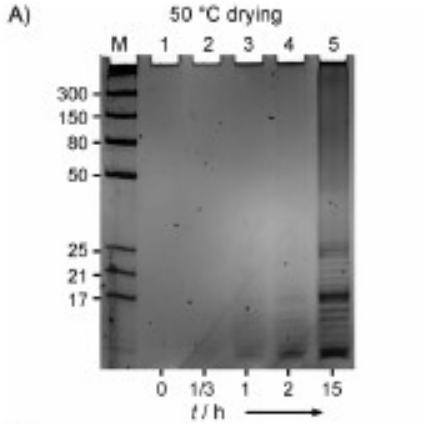
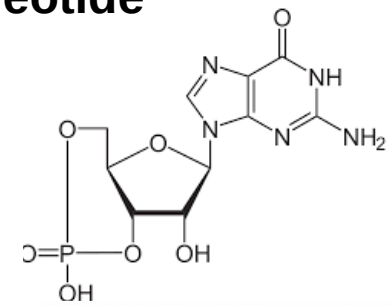
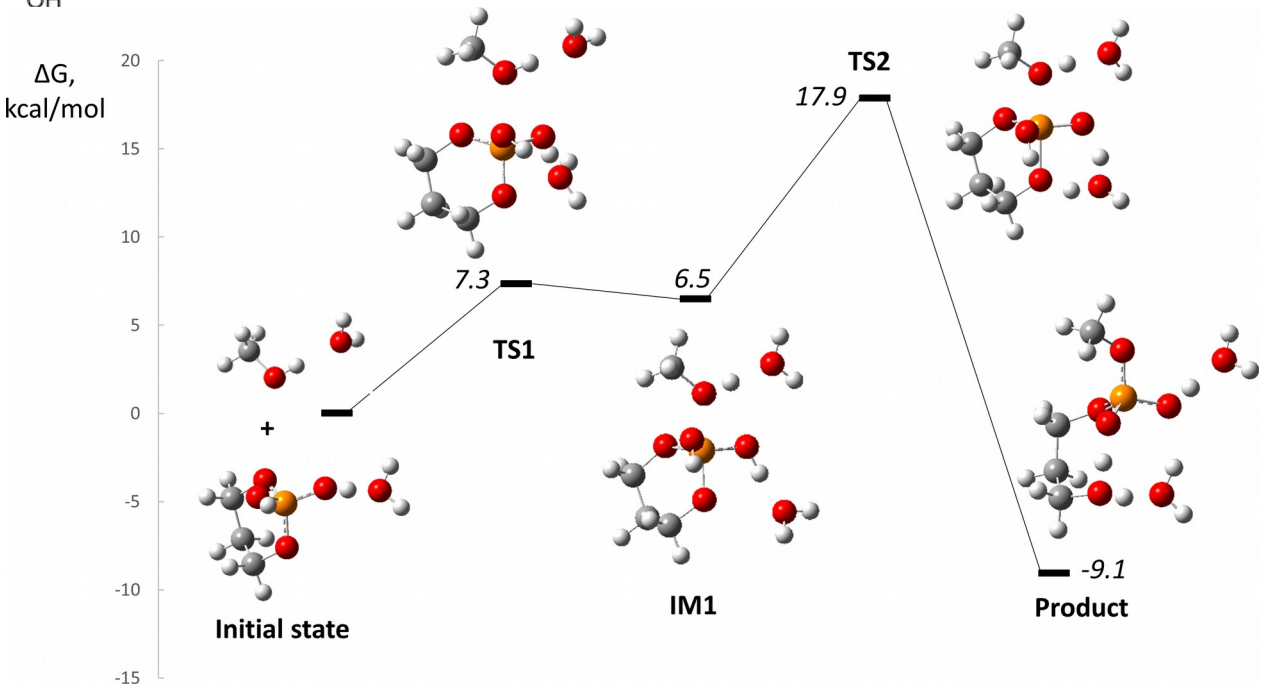






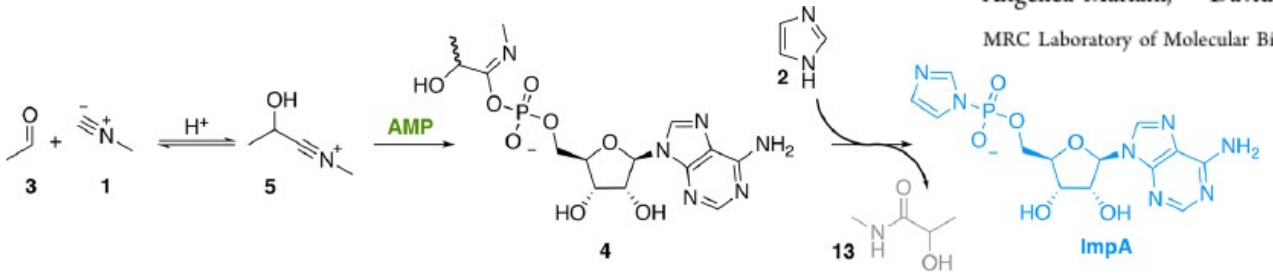
See papers by di Mauro and Judith Sponer

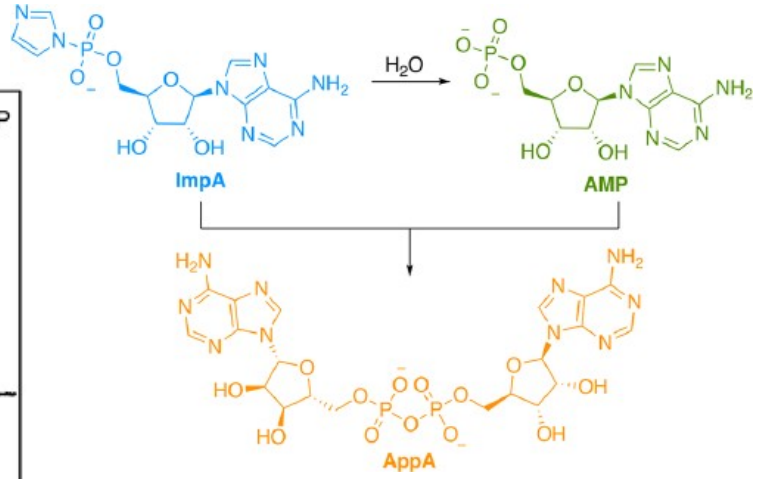
Activation group: in situ possible?

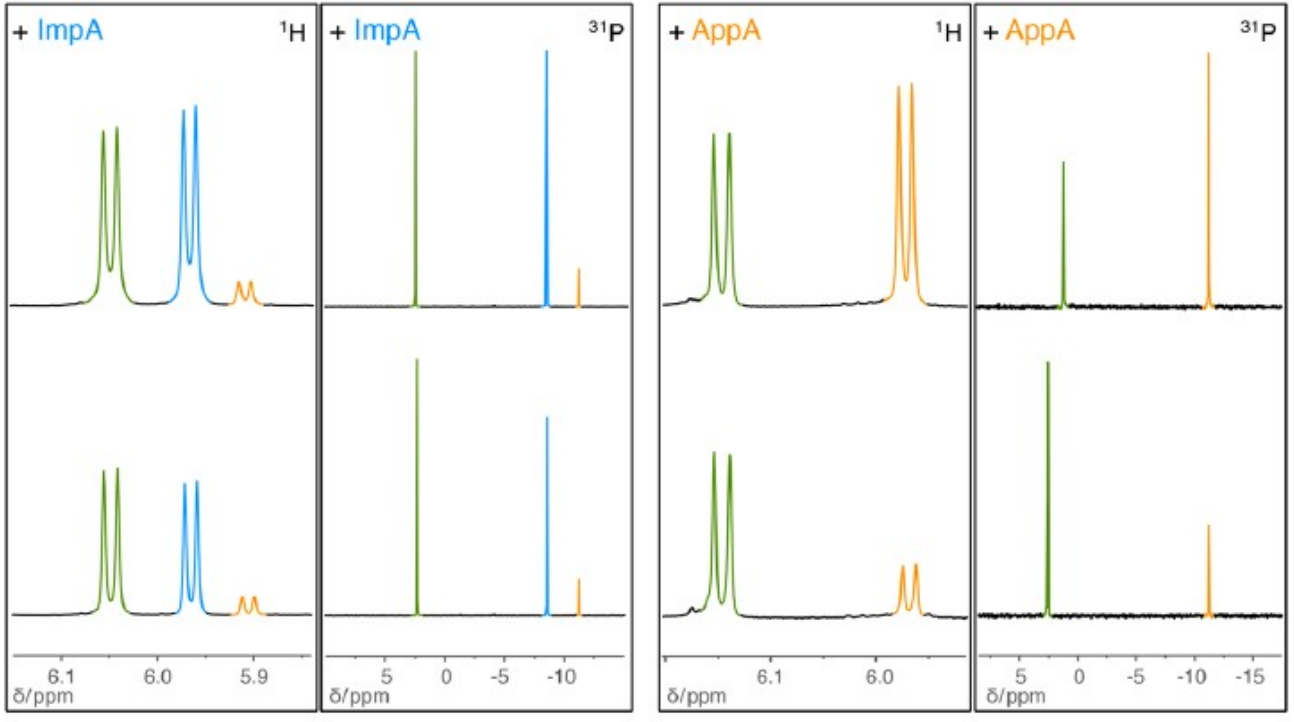
A Light-Releasable Potentially Prebiotic Nucleotide Activating Agent

Angelica Mariani,[†] David A. Russell,[†] Thomas Javelle, and John D. Sutherland[*]

MRC Laboratory of Molecular Biology, Francis Crick Avenue, Cambridge Biomedical Campus, Cambridge CB2 0QH, U.K.





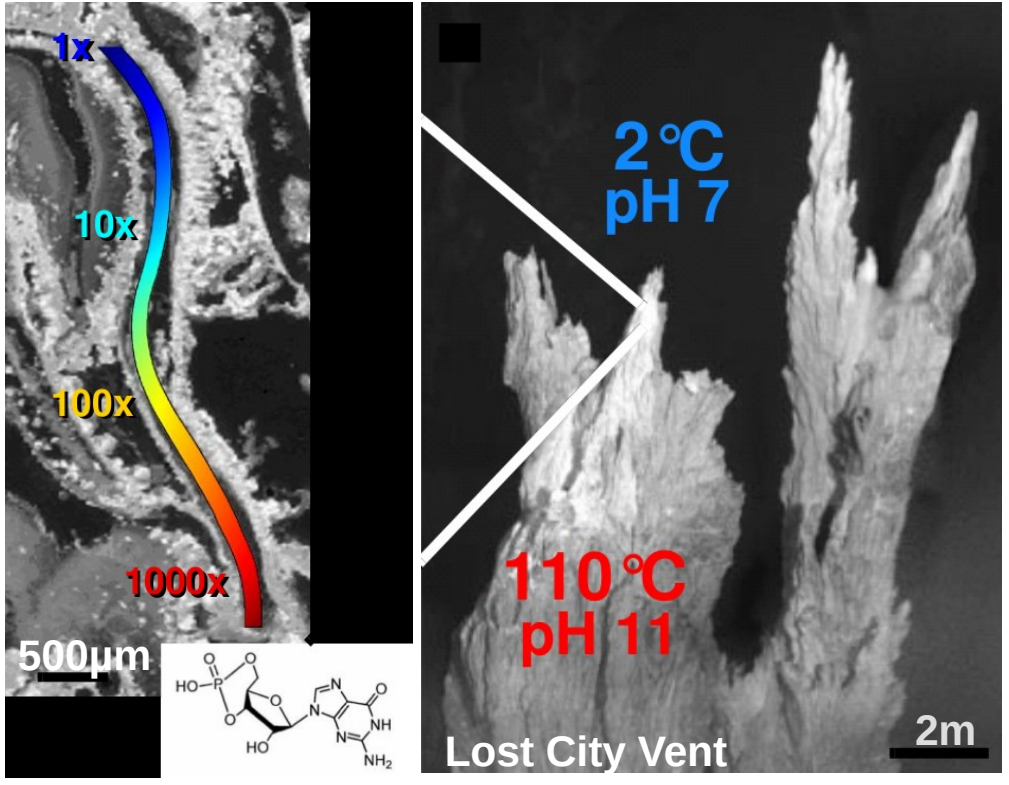


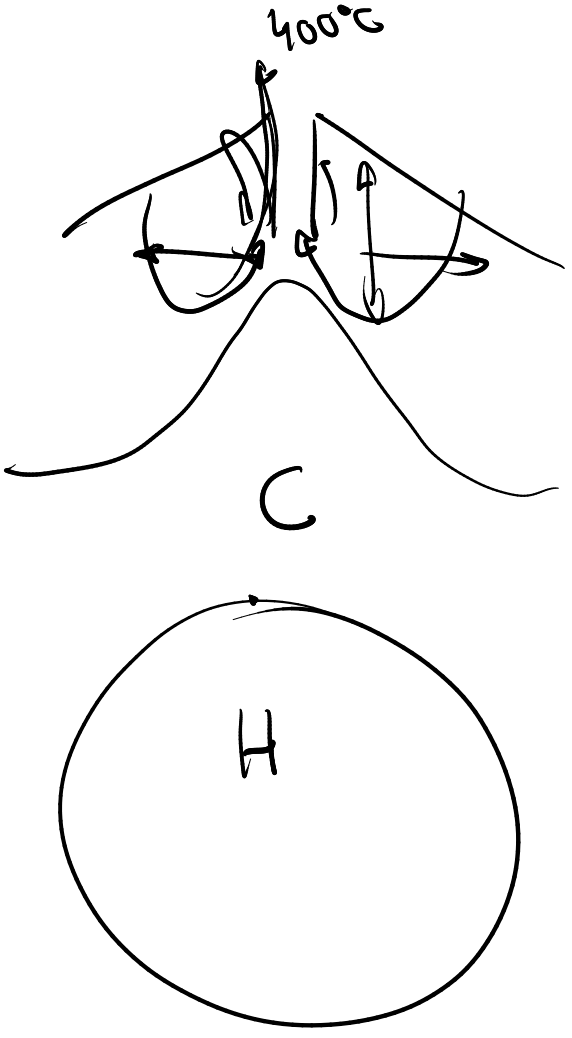
Accumulation by temperature gradients

Hot Vapor Settings

Accumulation by temperature gradients

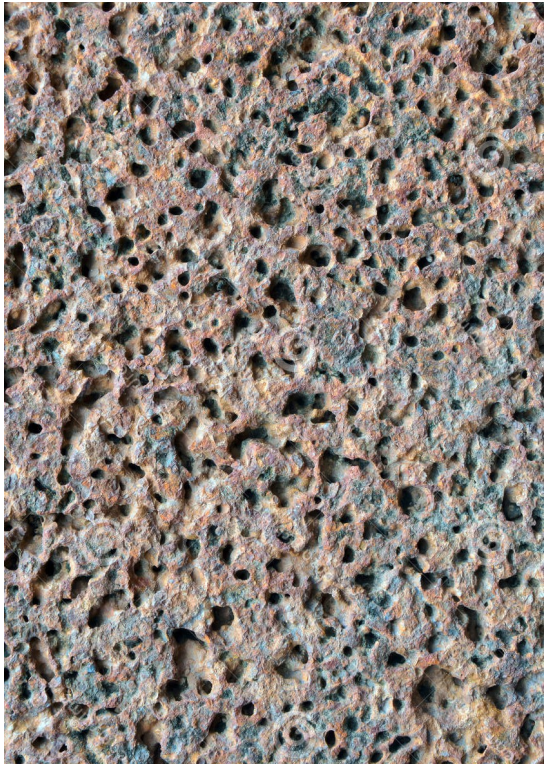
Hydrothermal Settings

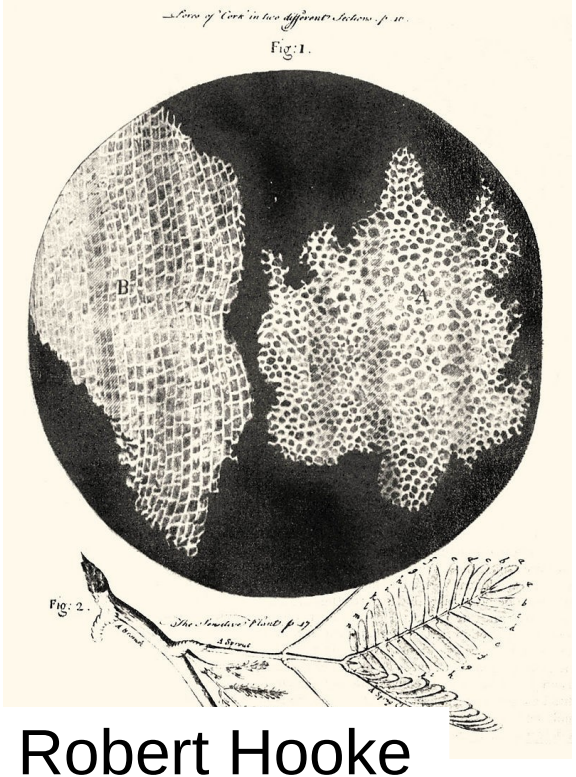




Accumulation by temperature gradients

Cells defined by Pores of Rock





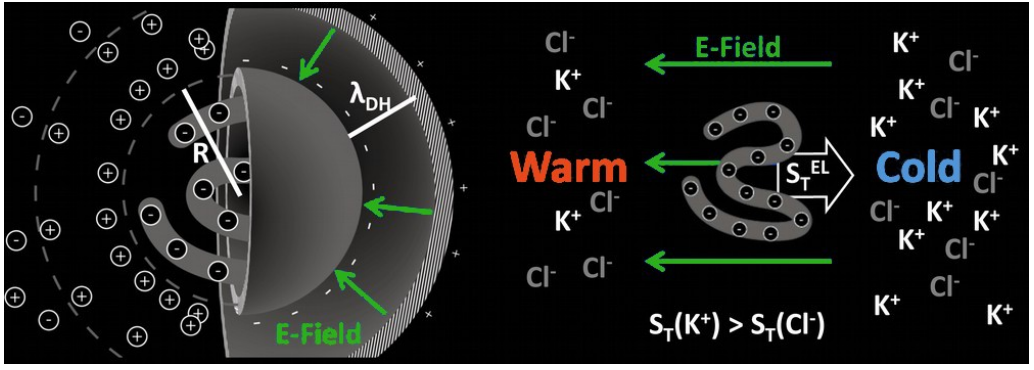
Robert Hooke

Accumulation by temperature gradients

Thermophoresis

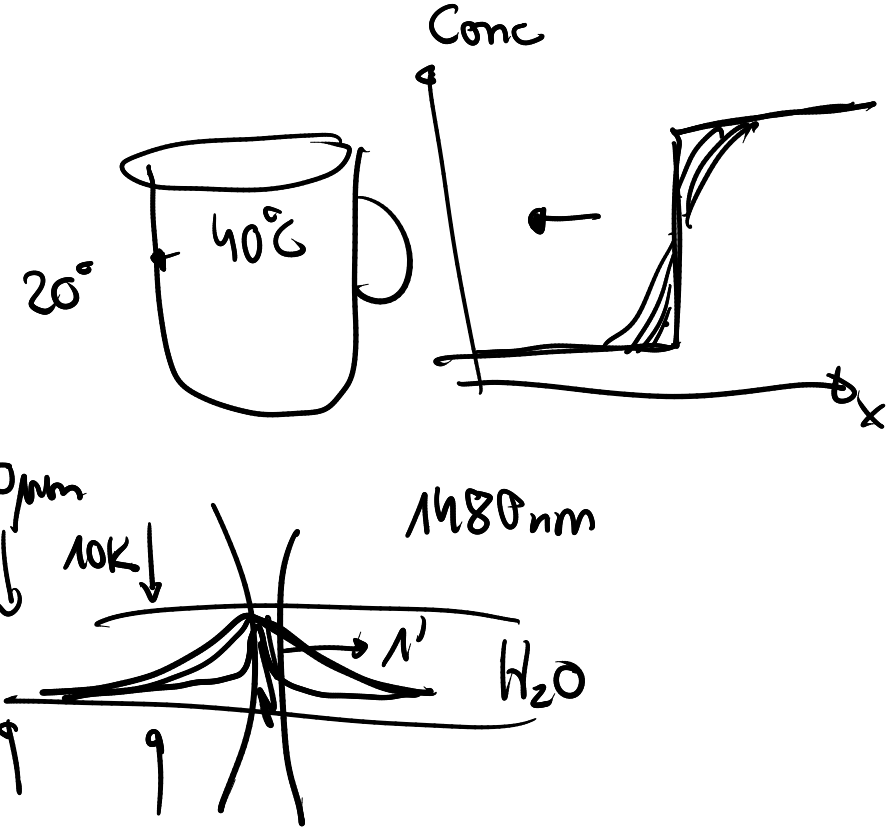
Local E-Field

Global E-Field



Duhr and Braun, PNAS 103, 19678 (2006)
Reichl, Herzog, Götz, and Braun, PRL 112, 198101 (2014)

$$S_T^{CM}\frac{R}{Z_{\text{eff}}^2}=\frac{e^2R/\lambda_{DH}}{16\pi k_BT^2\varepsilon_r\varepsilon_0(1+R/\lambda_{DH})^2}\times\left(1-\frac{\partial\ln\rho(T)}{\partial\ln T}-\frac{\partial\ln\varepsilon_r(T)}{\partial\ln T}\left(1+\frac{2\lambda_{DH}}{R}\right)\right)$$



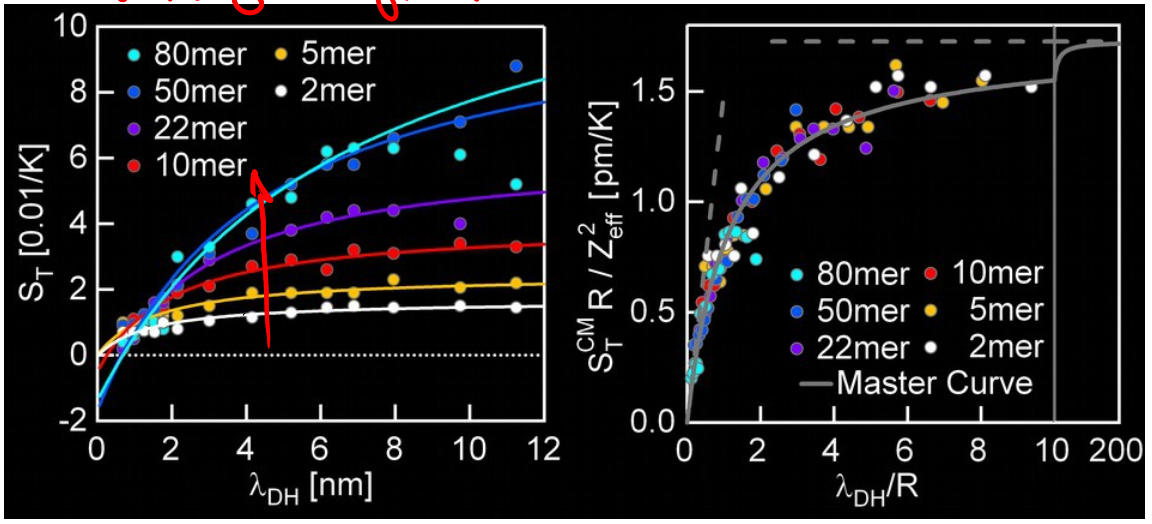
=> NanoTemper

Accumulation by temperature gradients

Thermophoresis

Warm → **Cold**

↓ Physiological concentrat



high Salt low Salt

$$S_T^{CM}\frac{R}{Z_{eff}^2}=\frac{e^2 R/\lambda_{DH}}{16\pi k_B T^2 \varepsilon_r \varepsilon_0 (1+R/\lambda_{DH})^2}\times\left(1-\frac{\partial \ln \rho(T)}{\partial \ln T}-\frac{\partial \ln \varepsilon_r(T)}{\partial \ln T}\left(1+\frac{2\lambda_{DH}}{R}\right)\right)$$

Diff. coeff. Gradient of T

$$\vec{v}\cdot c = j = \frac{\#}{s\cdot A} = -D\nabla c - cD_T\nabla T$$

$$\doteq 0$$

$$\Rightarrow c = c_0 \exp\left(-\frac{D_T}{D}\cdot\Delta T\right)$$

$$c(T) = c_0 \exp\left(-\frac{D_T}{D}(T-T_0)\right)$$

$S_T = \frac{D_T}{D}$

$T(x,y)$

c_0

T_0

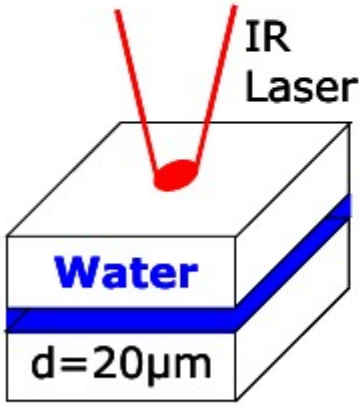
$c(x,y)$

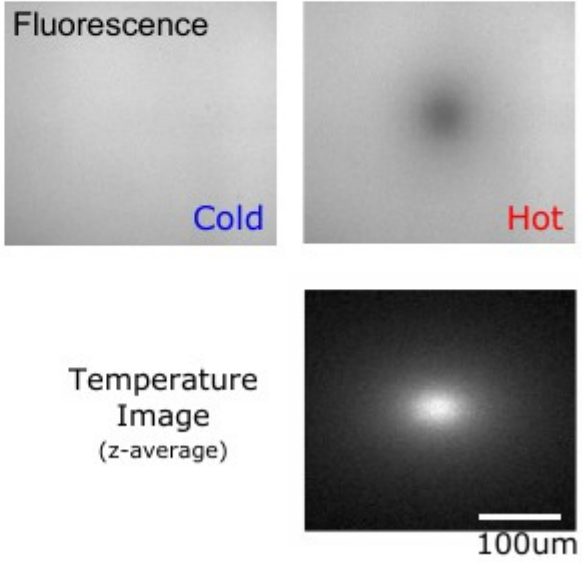
Accumulation by temperature gradients

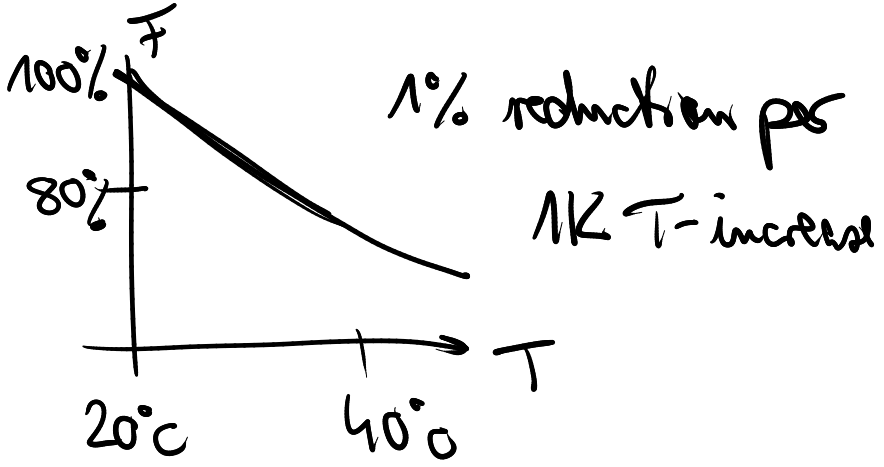
Thermophoresis of DNA

Warm → **Cold**

$v = -D_T \nabla T$ $\quad j = -D\nabla c - D_T c \nabla T$

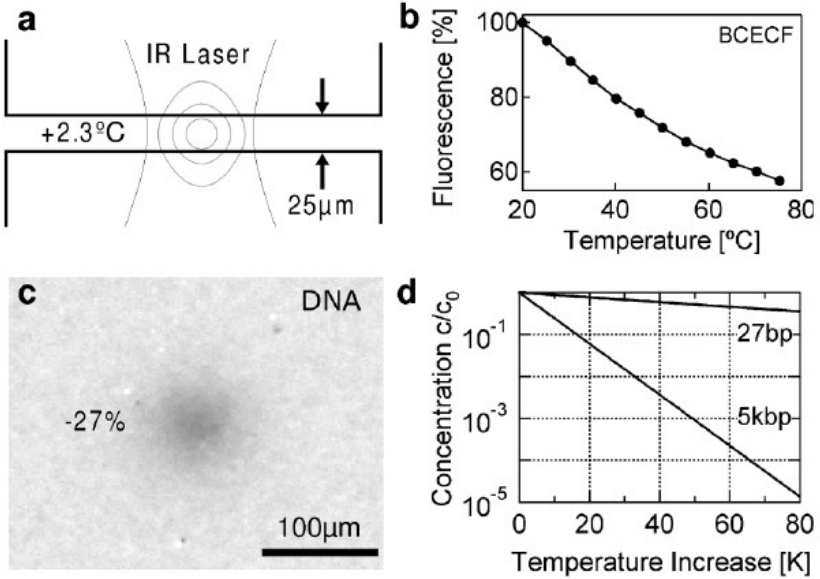


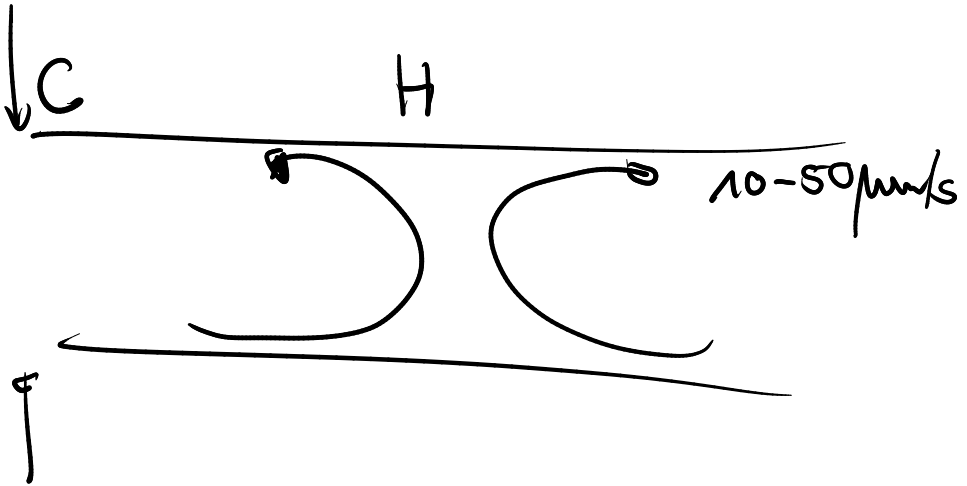




Trapping of DNA by Thermophoretic Depletion and Convection

Dieter Braun* and Albert Libchaber
Center for Studies in Physics and Biology, Rockefeller University, New York, New York 10021
(Received 2 May 2002; published 14 October 2002)





Accumulation by temperature gradients

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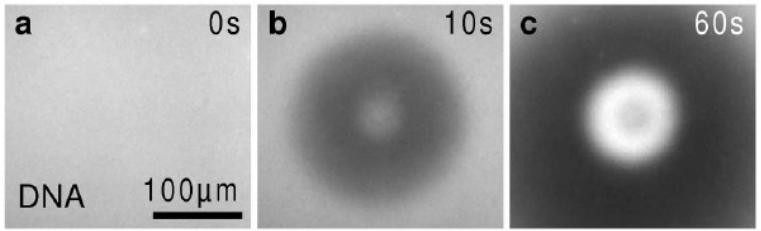
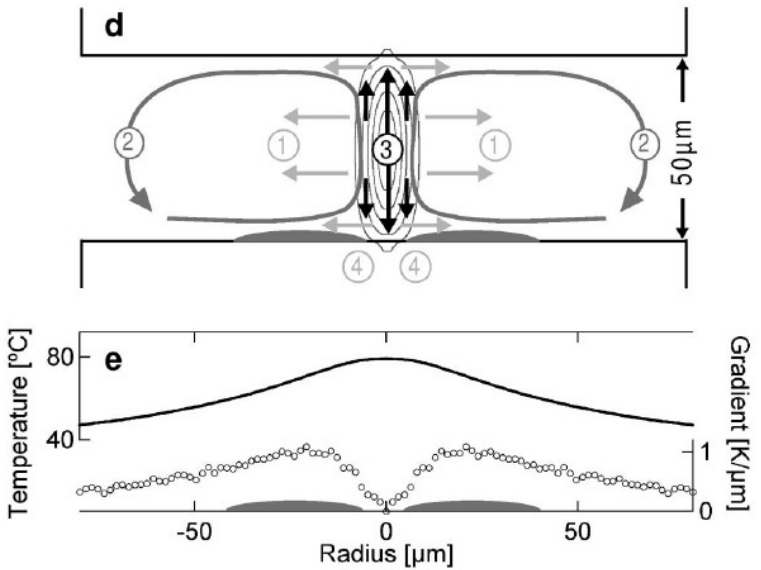
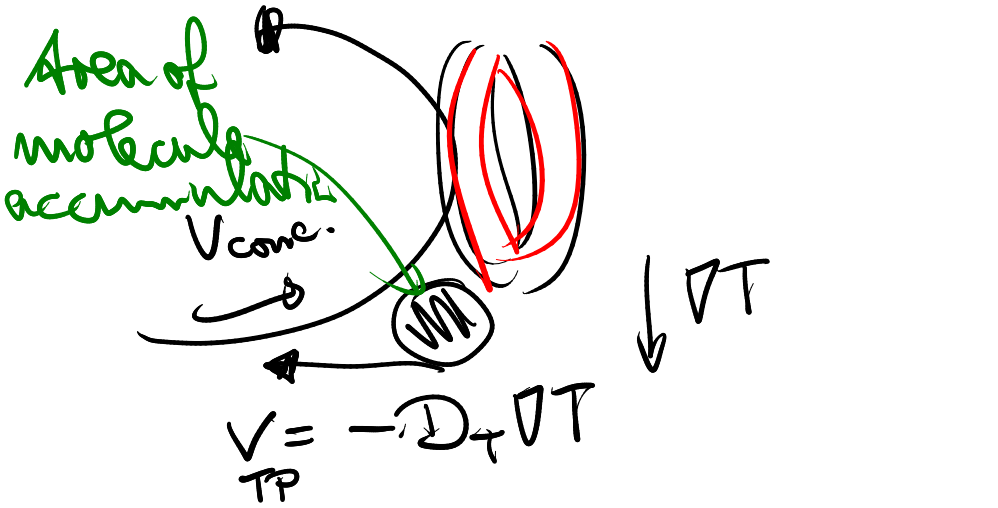
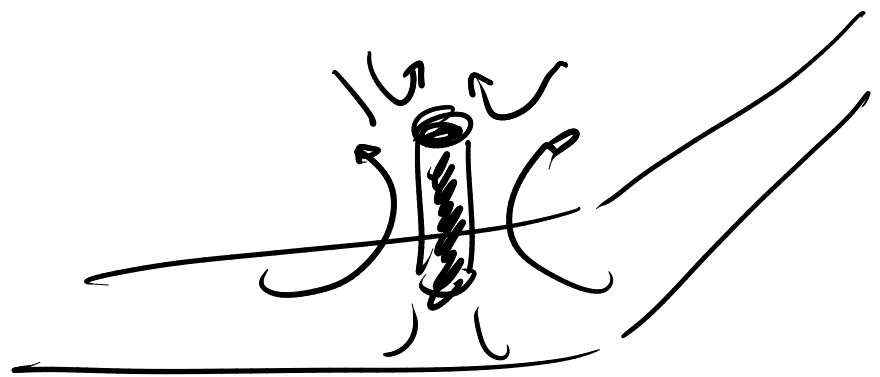


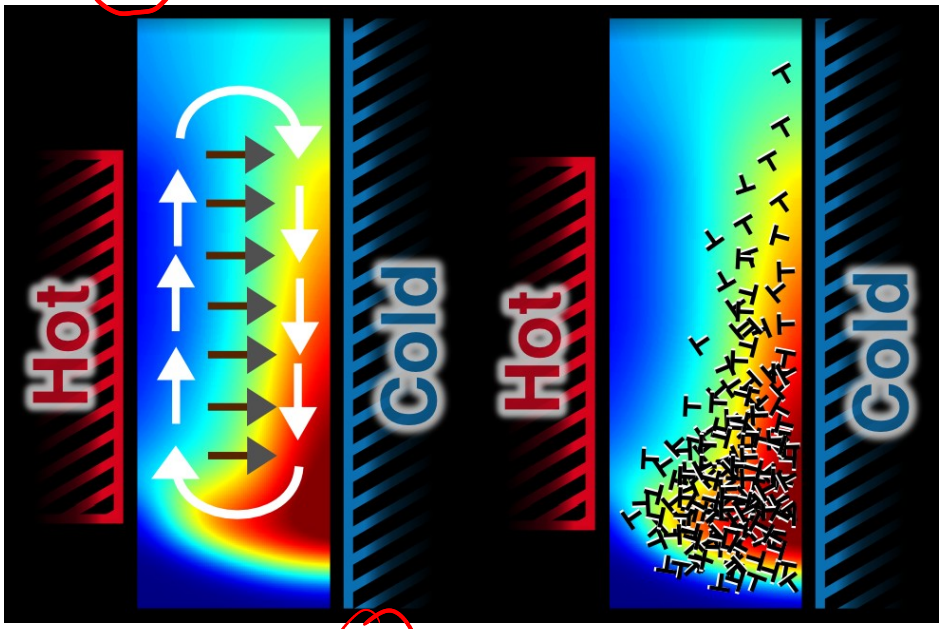






Accumulation by temperature gradients

Accumulation by heat flow

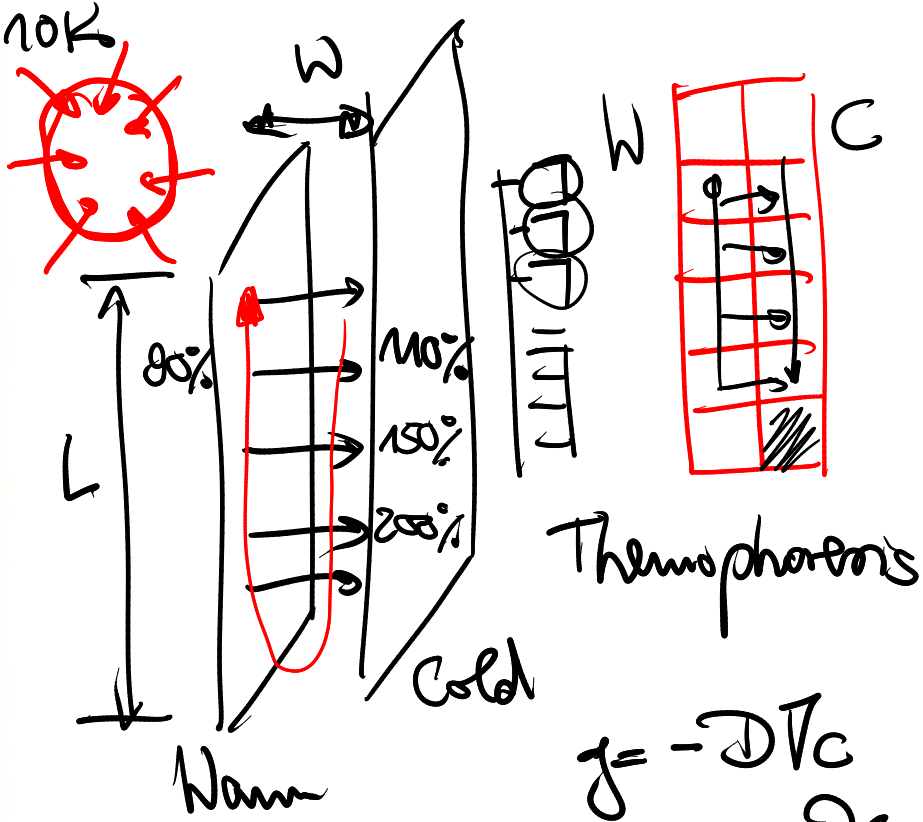


Convection
Thermophoresis

PRL 2002, PNAS 2007, NanoLetters 2009, PRL 2010, APL 2015, PCCP 2016

$$\frac{c}{c_0} = \exp\left(+0.4 \frac{D_T}{D} \cdot \Delta T \cdot \frac{L}{D}\right)$$

150µm



$$j = -D\nabla c$$

$$= -D\frac{\partial c}{\partial x}$$

$$j = -D\frac{\Delta c}{\Delta x}$$

1.5mm

1.5 — 100x

1.5 — 10x

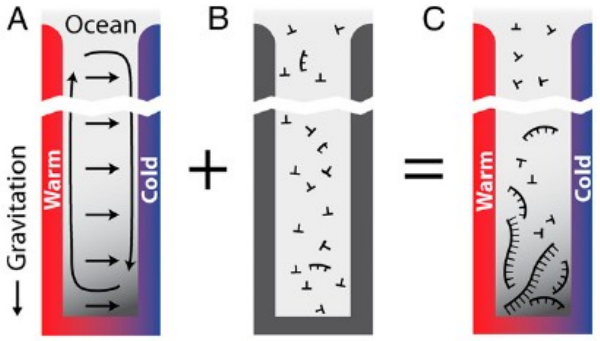
10x

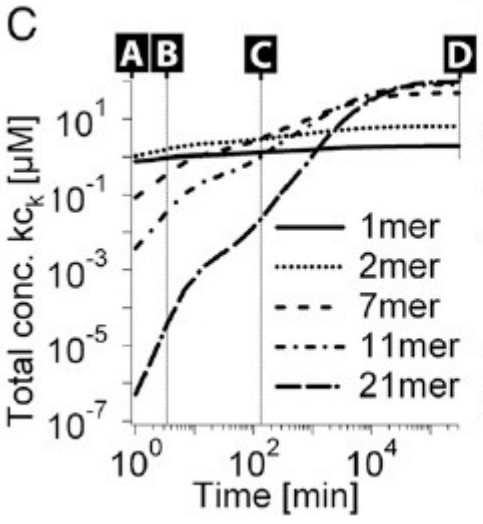
Simulation with Comsol

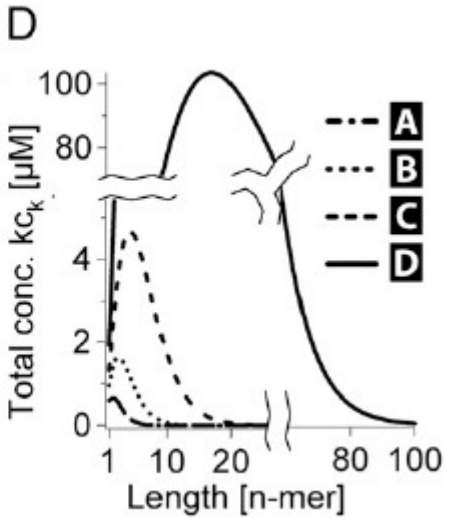
Accumulation and Polymerization

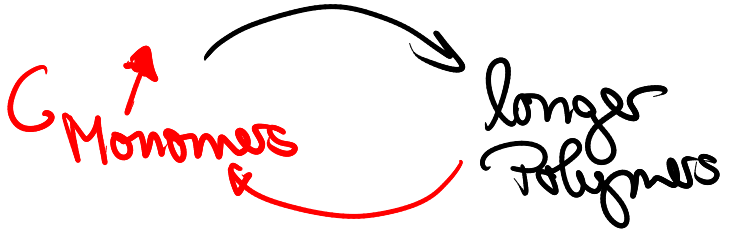
Escalation of polymerization in a thermal gradient

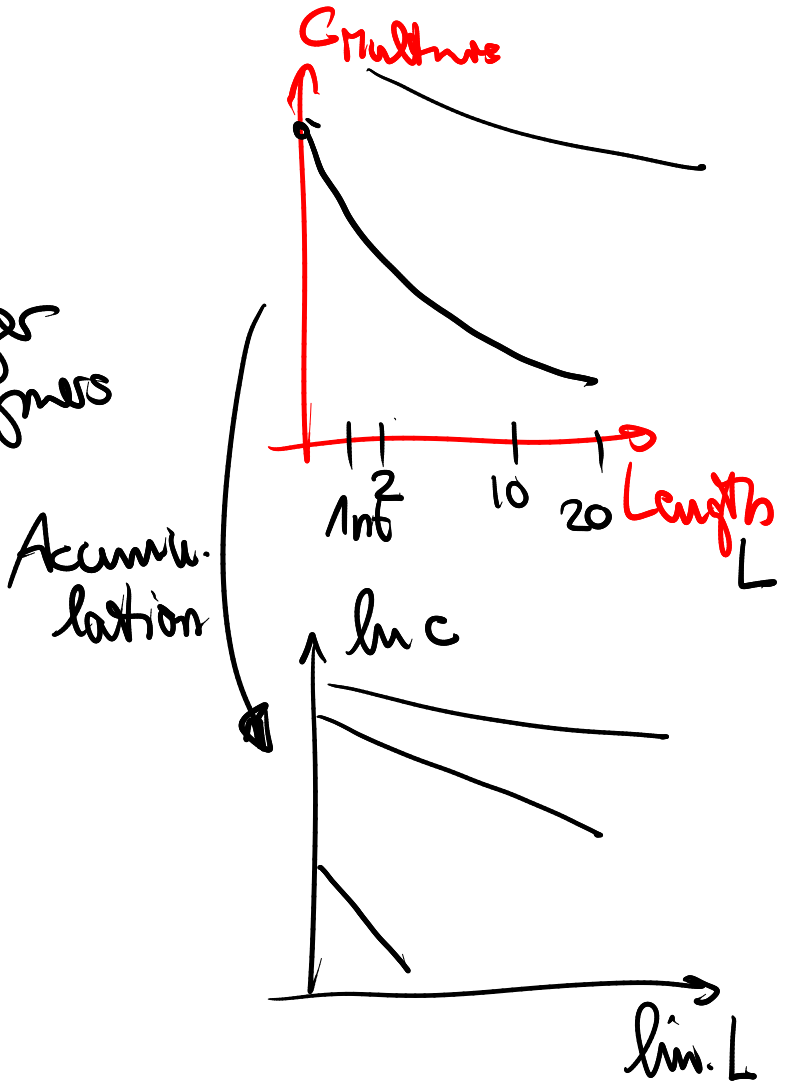
Christof B. Mast[a,1], Severin Schink[b,1], Ulrich Gerland[b], and Dieter Braun[a,2]







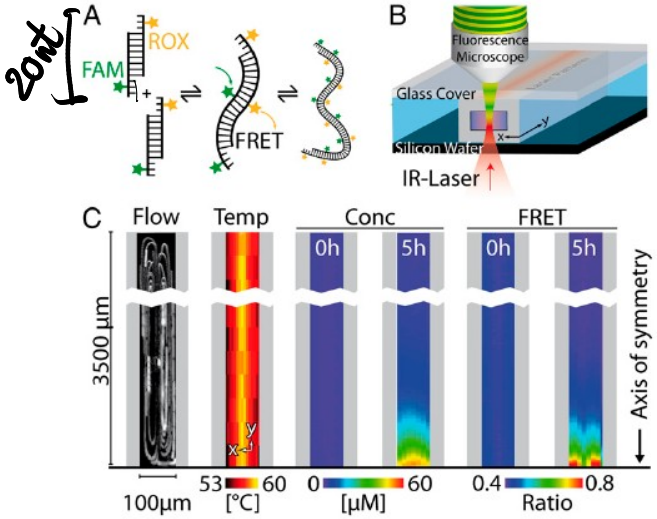


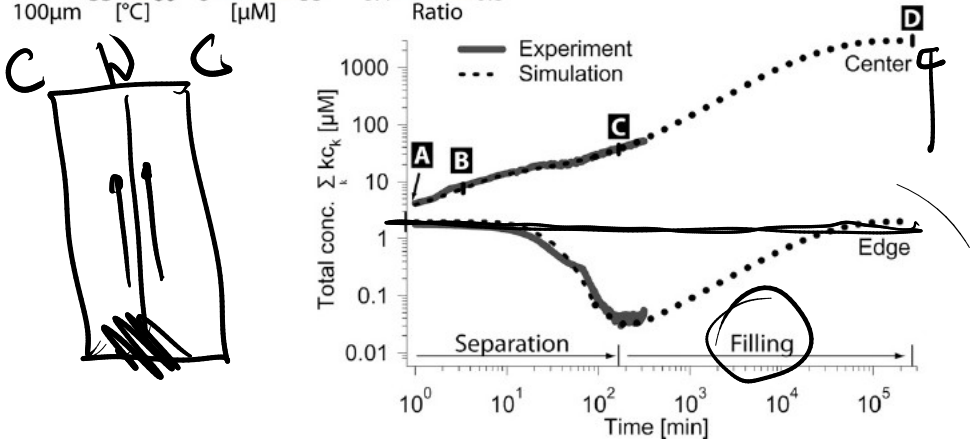


Accumulation and Polymerization

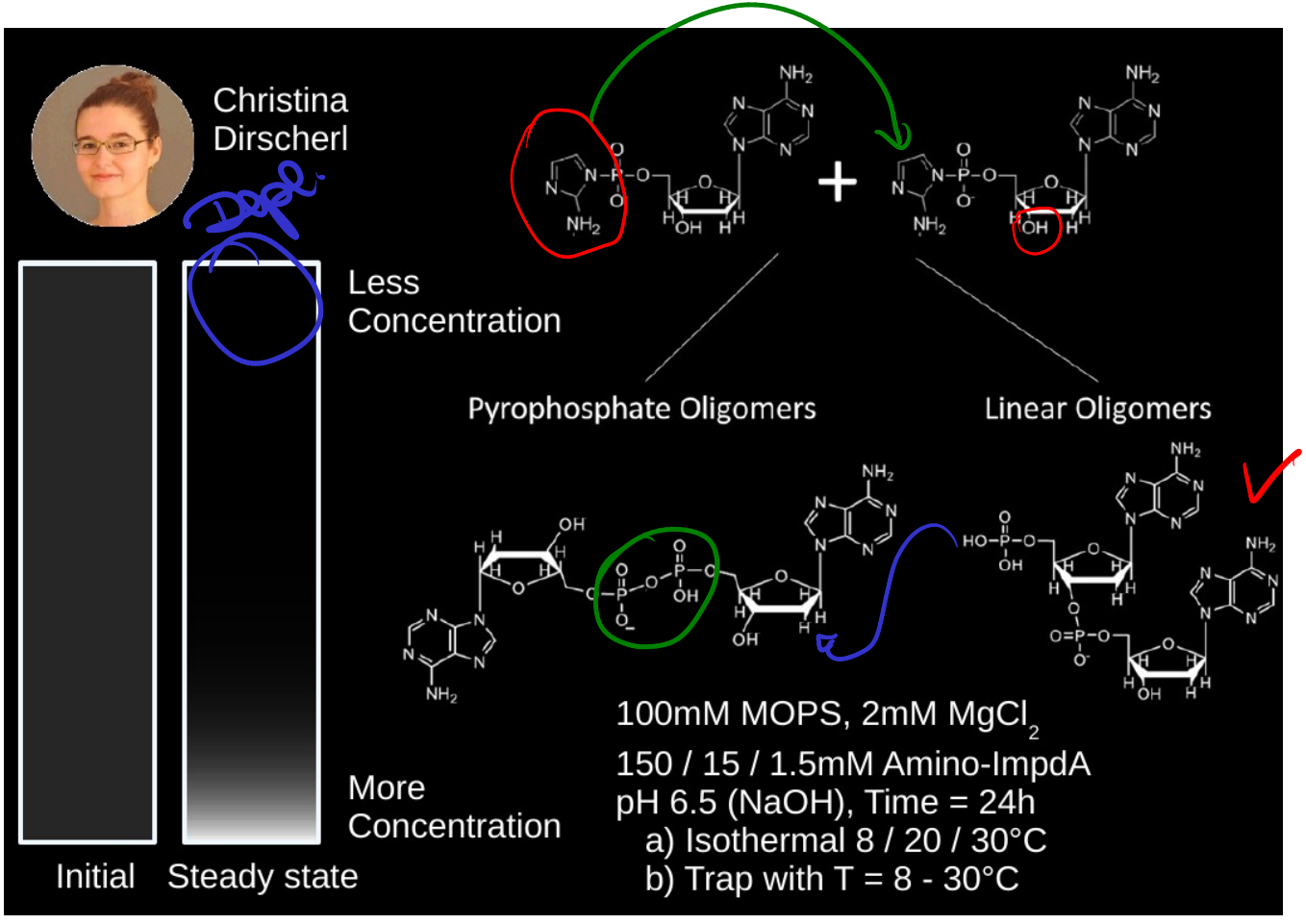
Escalation of polymerization in a thermal gradient

Christof B. Mast[a,1], Severin Schink[b,1], Ulrich Gerland[b], and Dieter Braun[a,2]

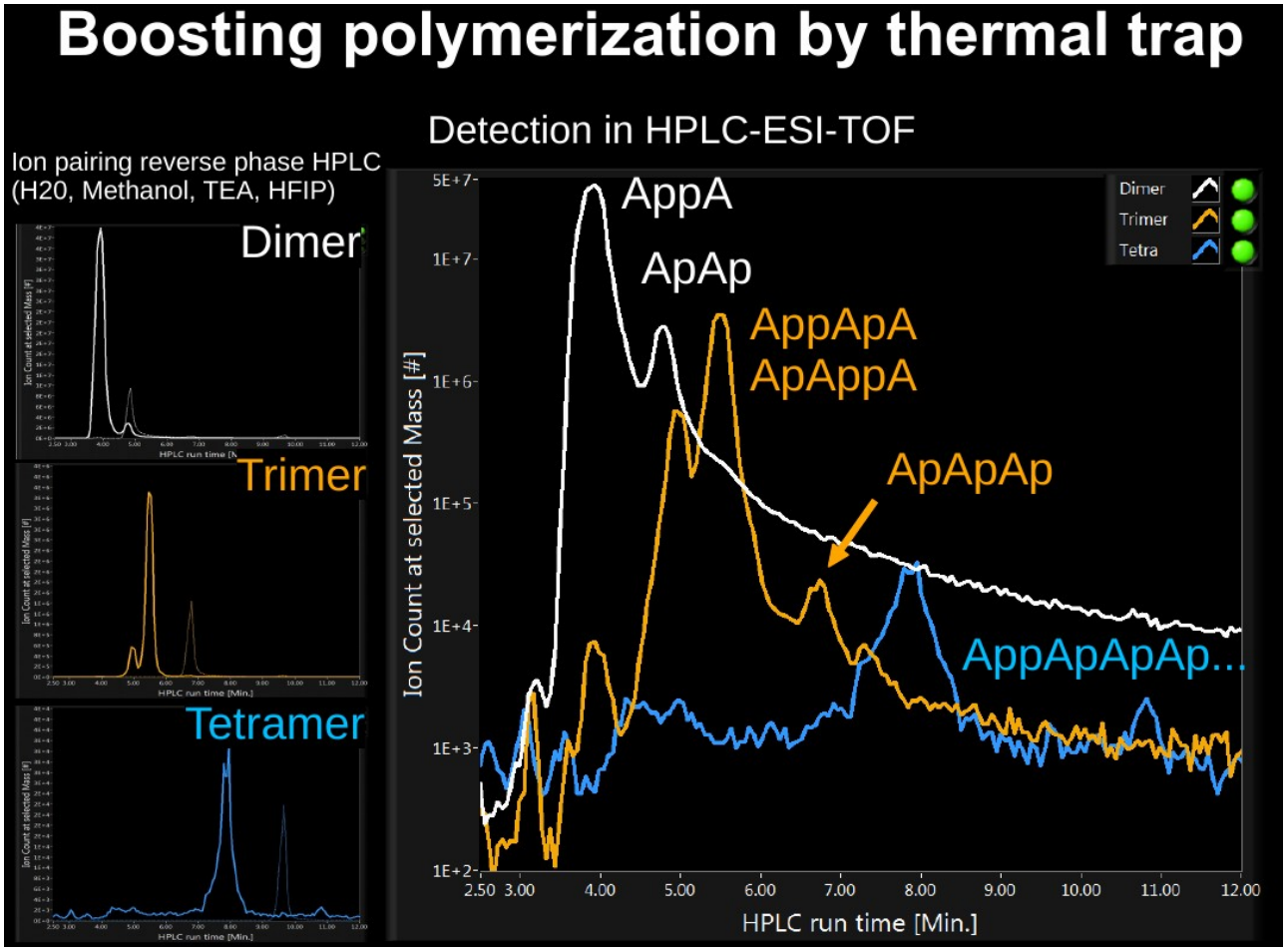


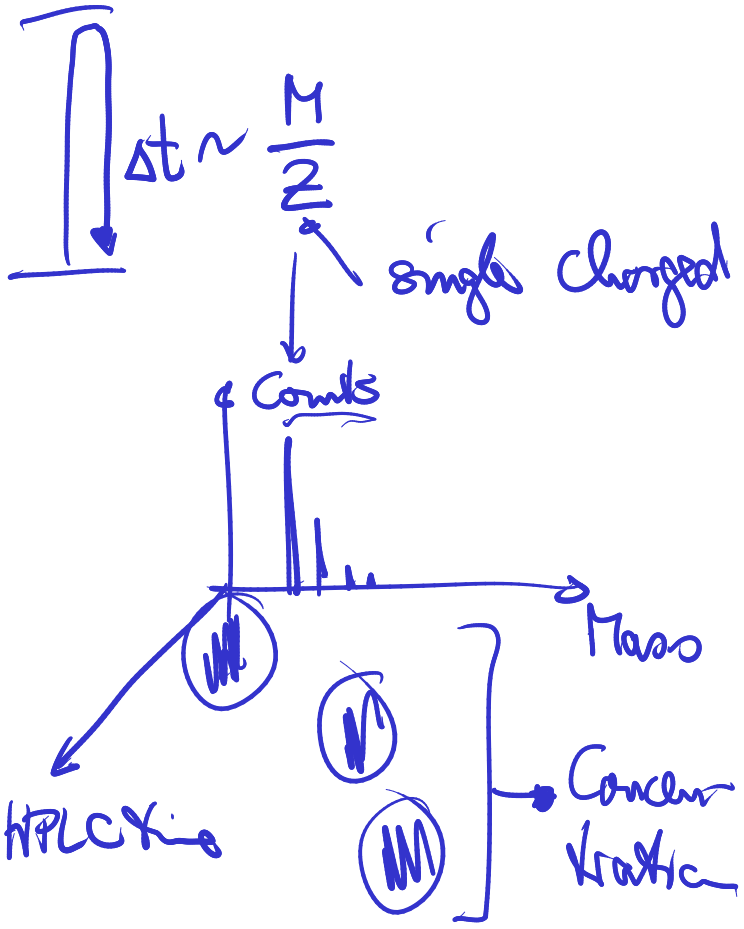


Accumulation and Polymerization

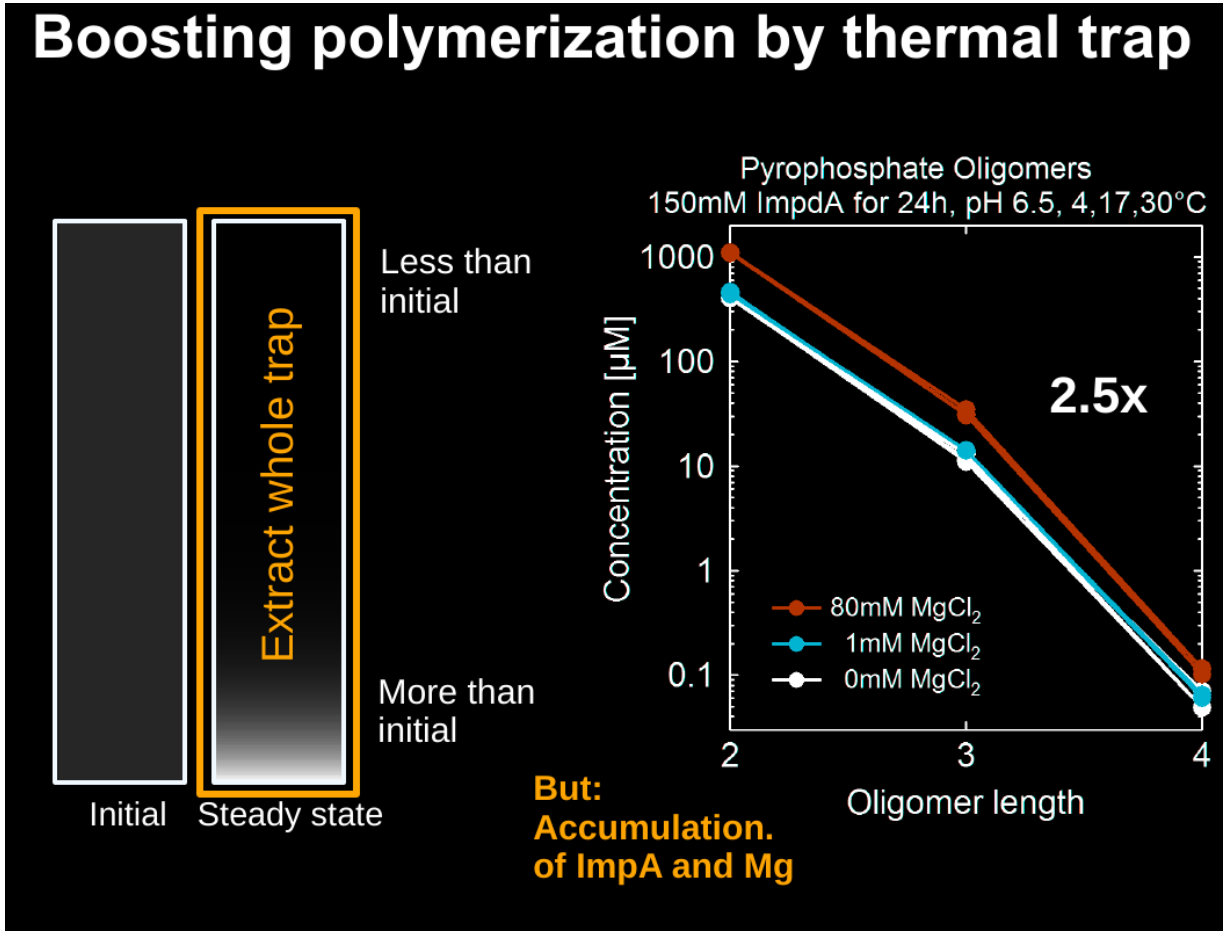


Accumulation and Polymerization

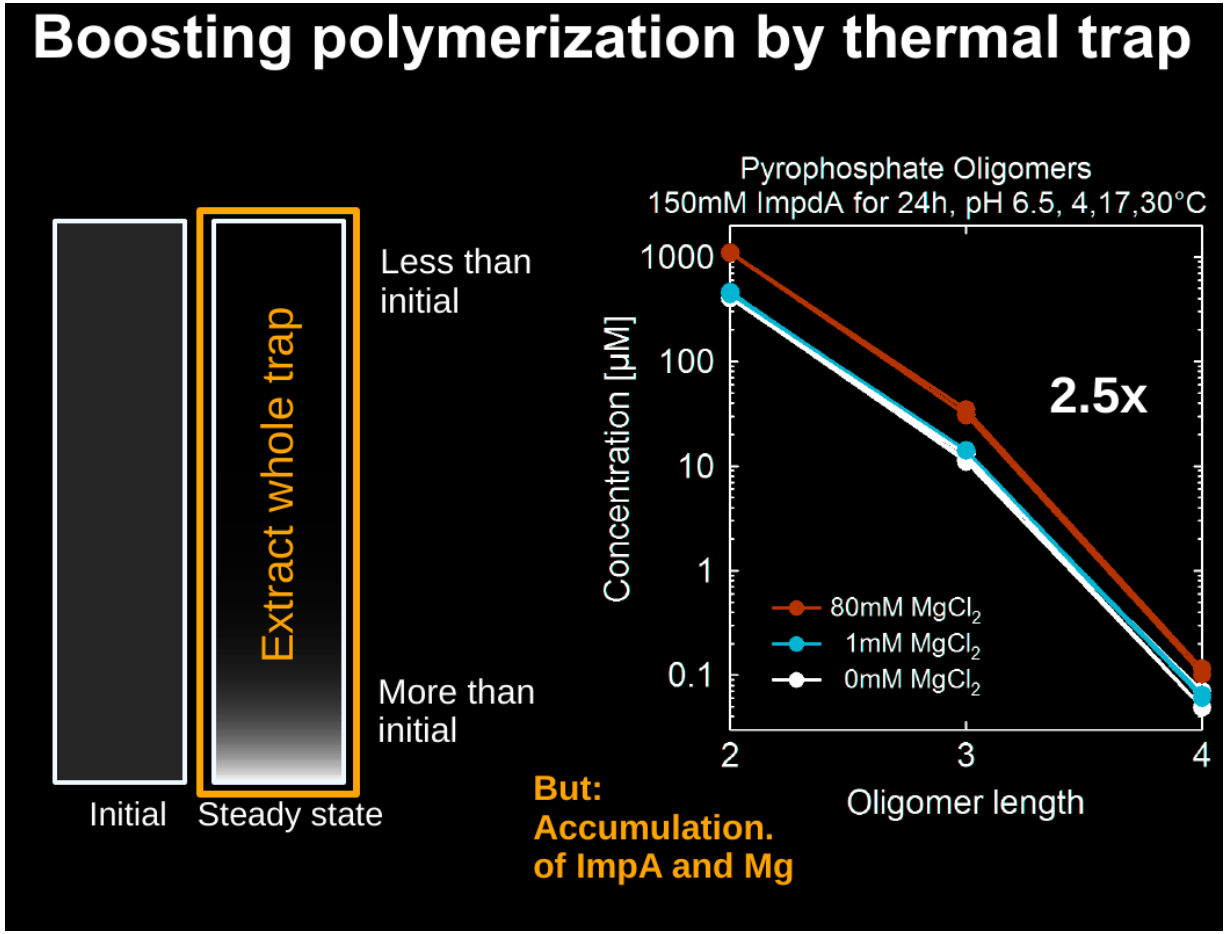


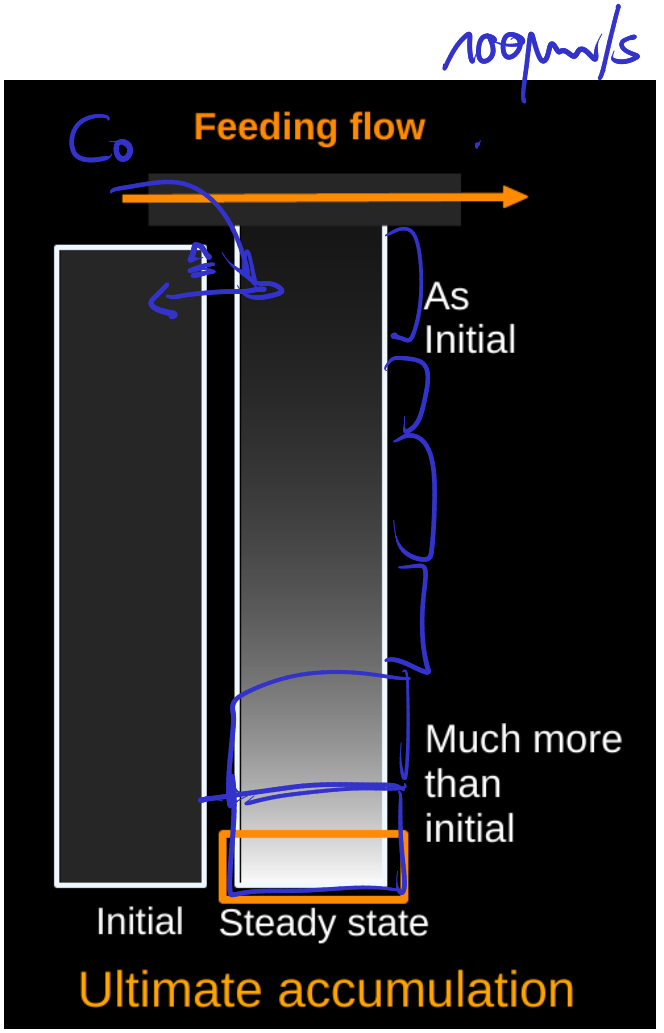


Accumulation and Polymerization

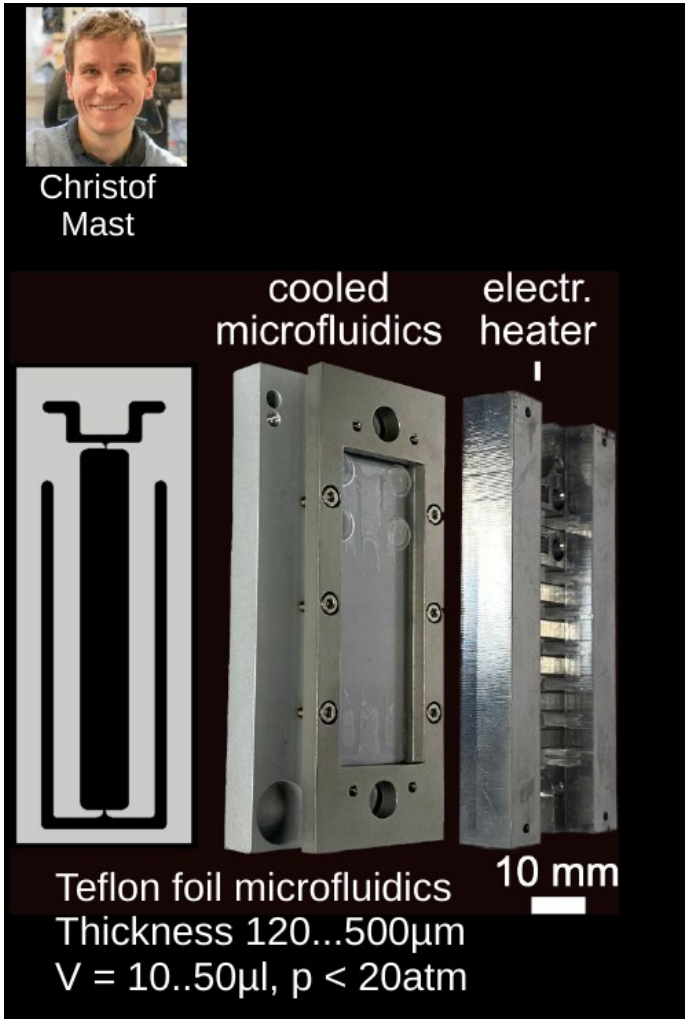


Accumulation and Polymerization

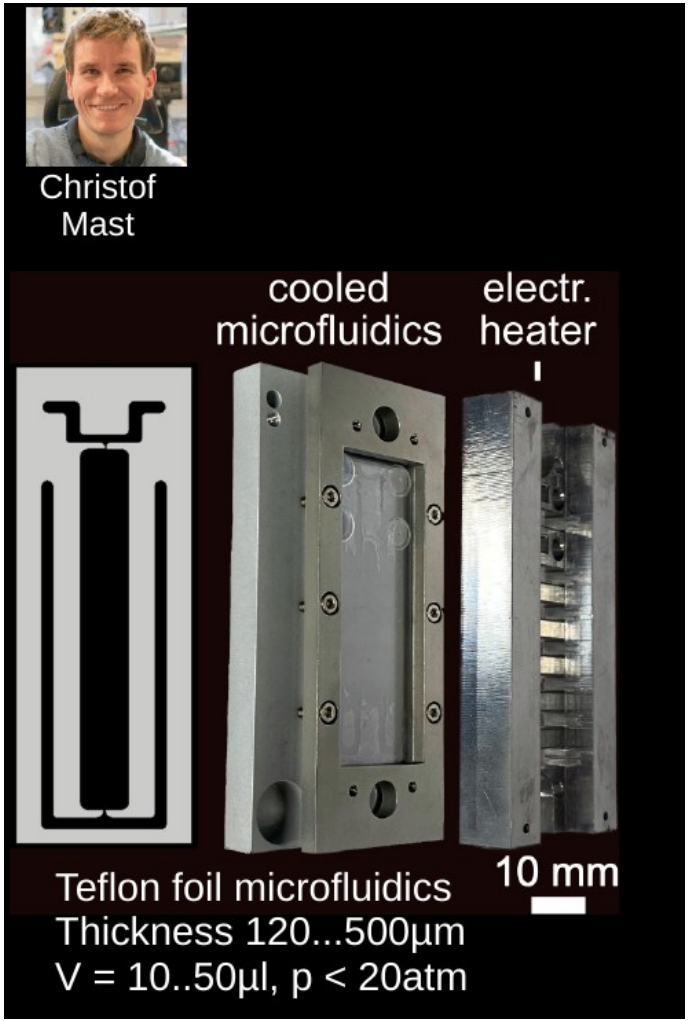


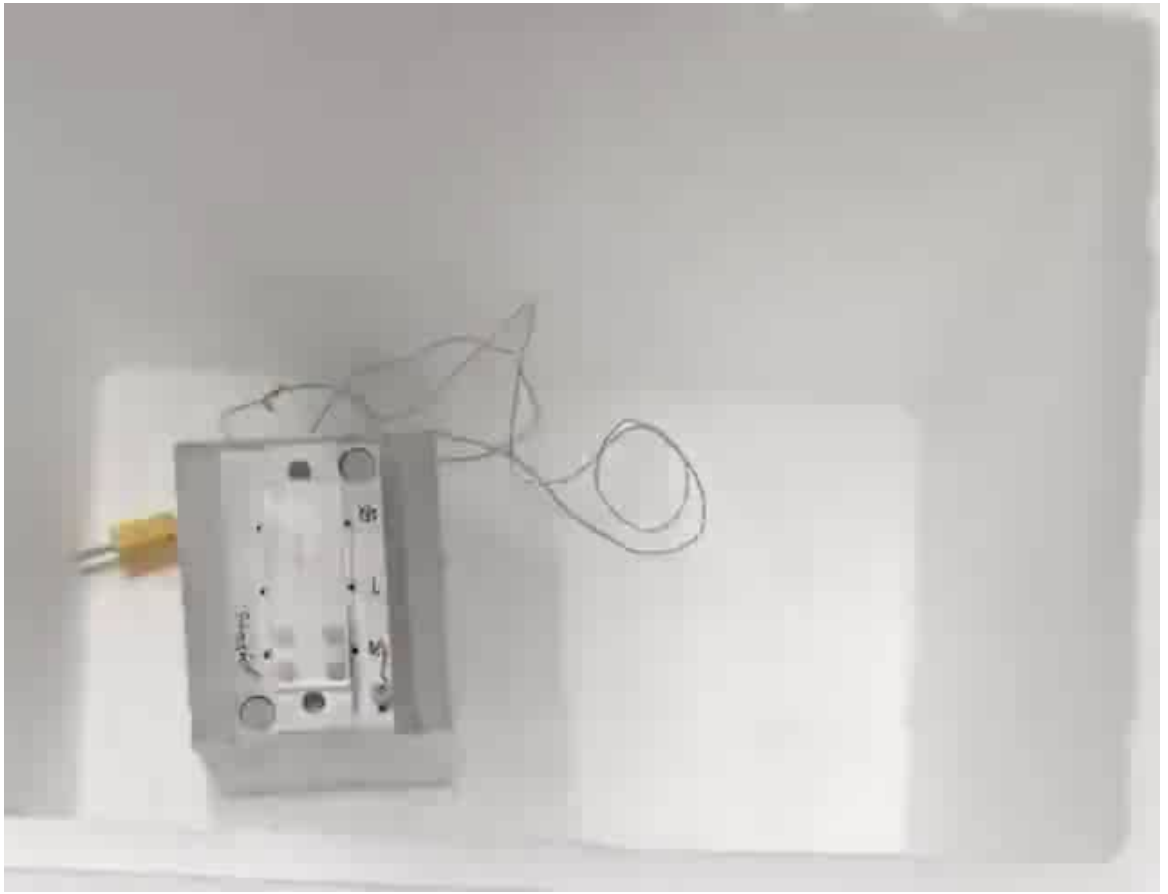


Accumulation and Polymerization

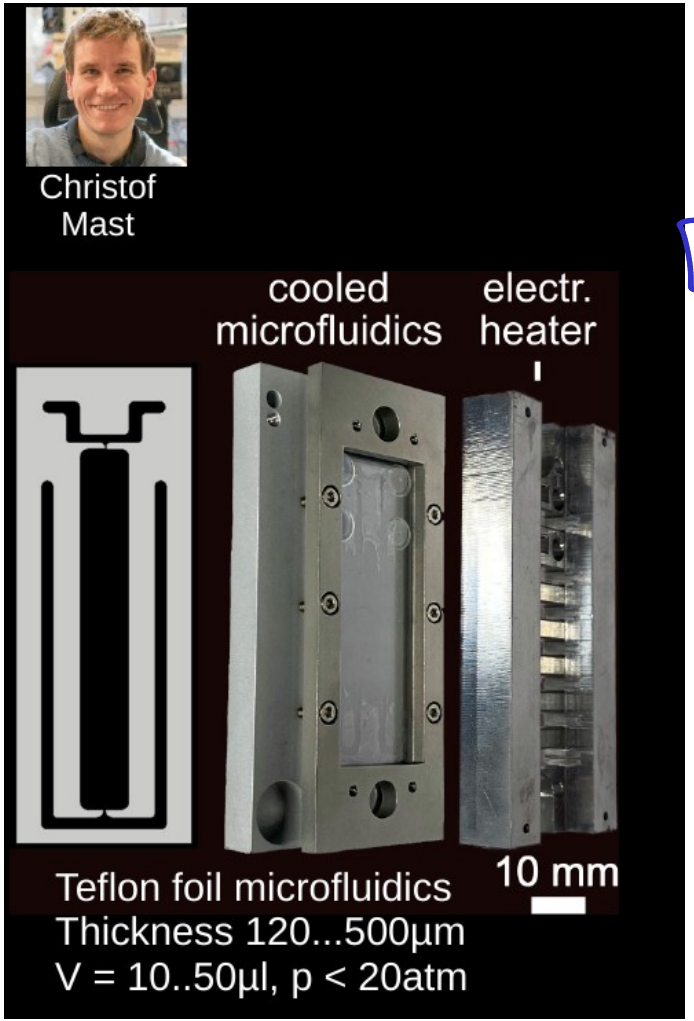


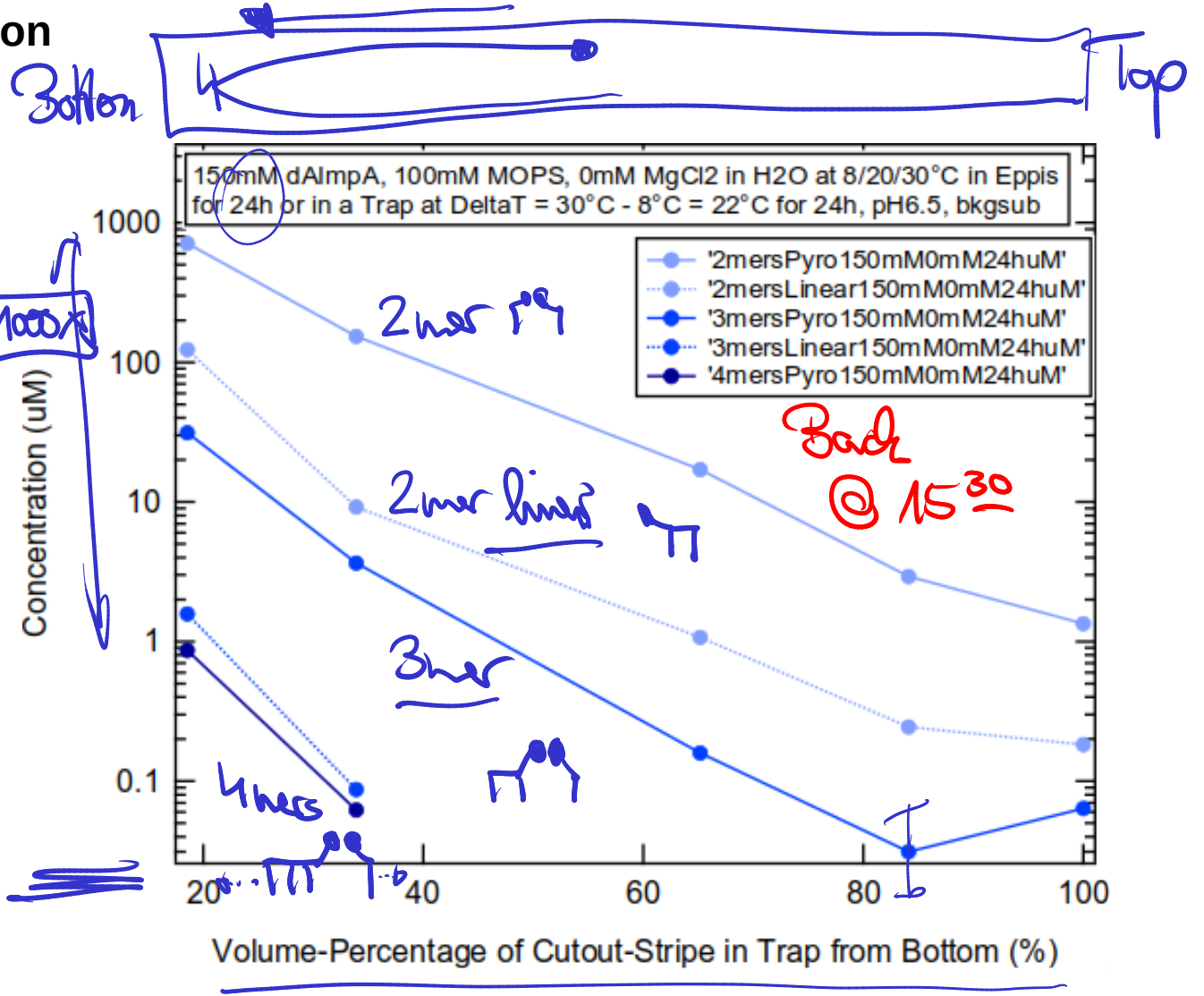
Accumulation and Polymerization





Accumulation and Polymerization





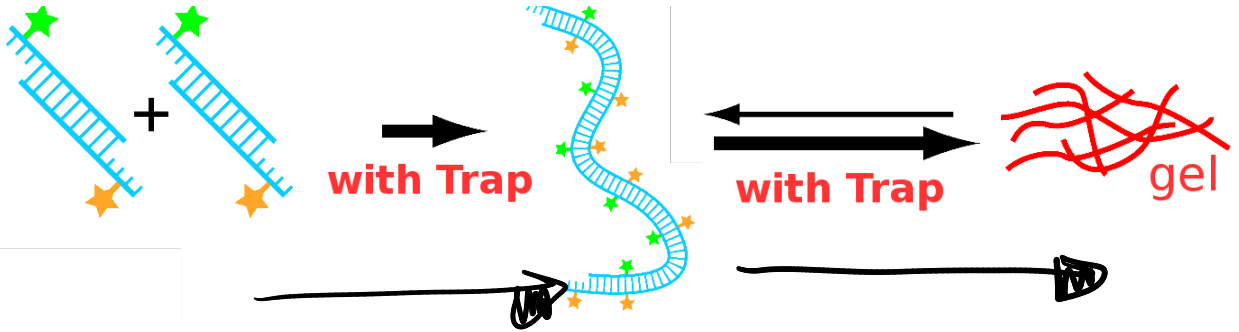
Accumulation and Polymerization leads to gels

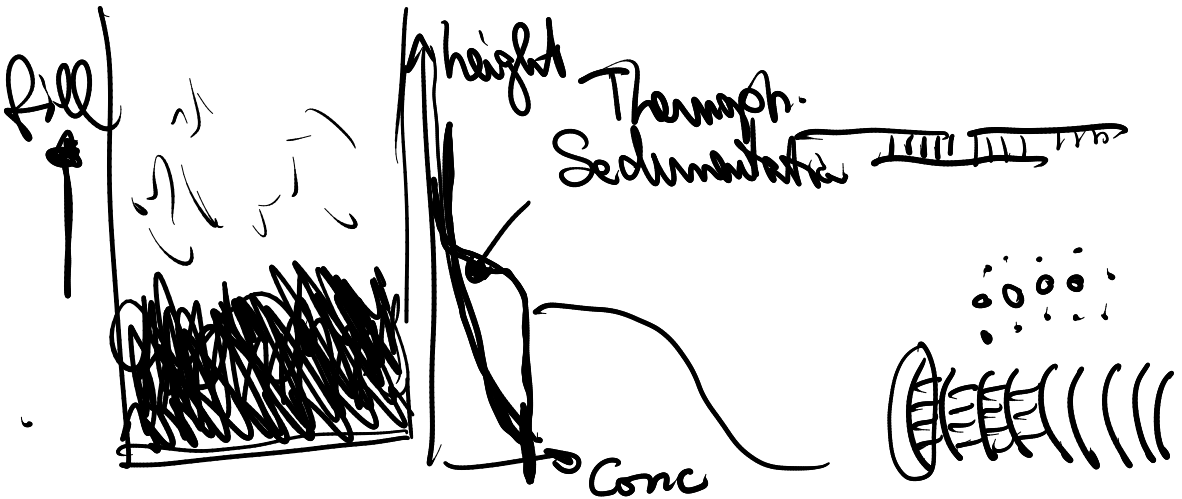
DNA Hydrogels Hot Paper

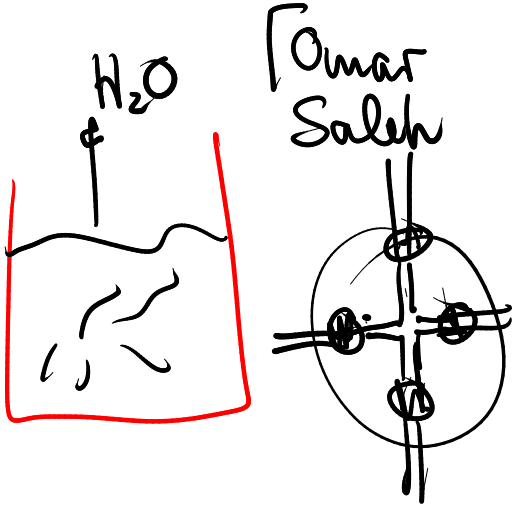
International Edition: DOI: 10.1002/anie.201601886
German Edition: DOI: 10.1002/ange.201601886

Heat-Flow-Driven Oligonucleotide Gelation Separates Single-Base Differences

*Matthias Morasch, Dieter Braun, and Christof B. Mast**







2D, 3D: Phase transition

1D: Cannot undergo Phase transition

Accumulation and Polymerization leads to gels

DNA Hydrogels Hot Paper

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Heat-Flow-Driven Oligonucleotide Gelation Separates Single-Base Differences

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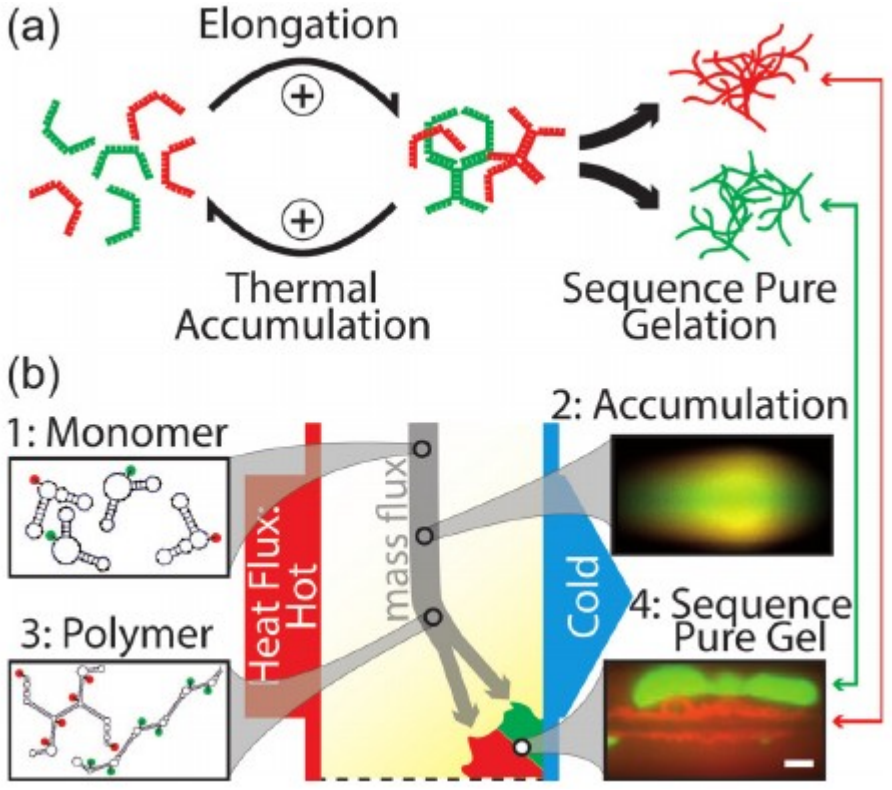
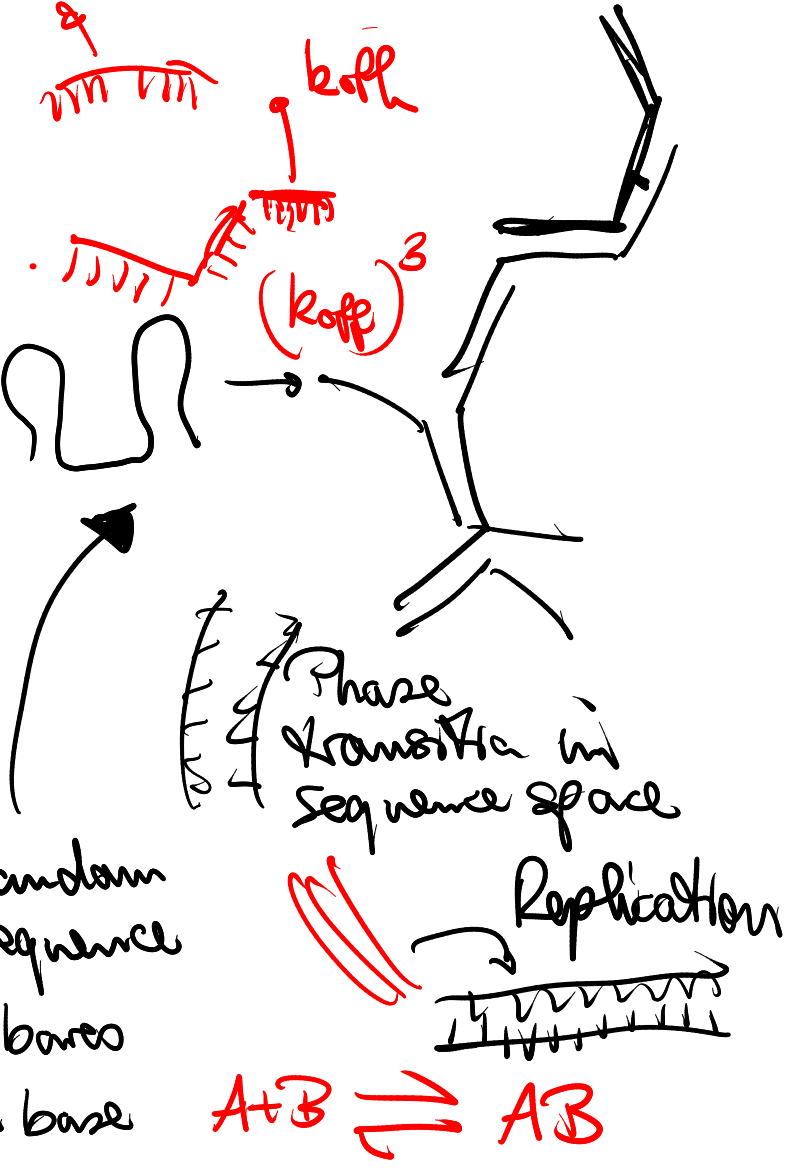
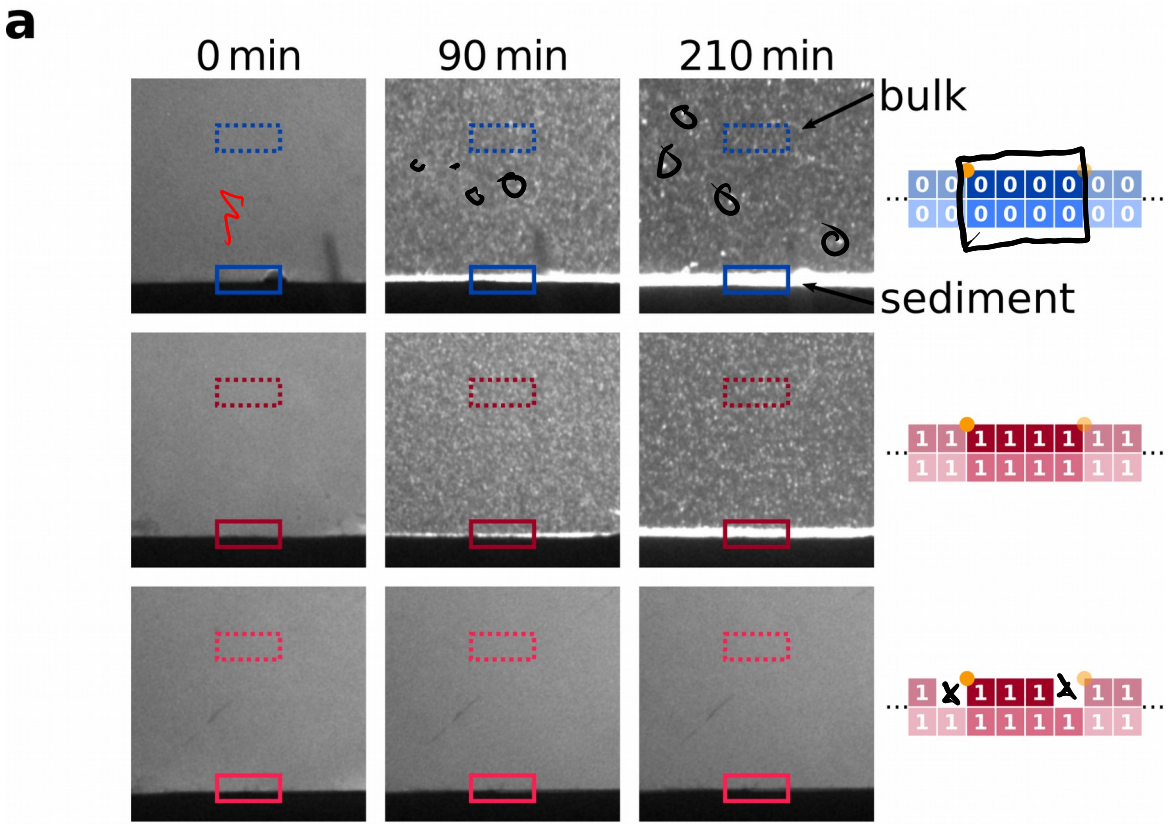
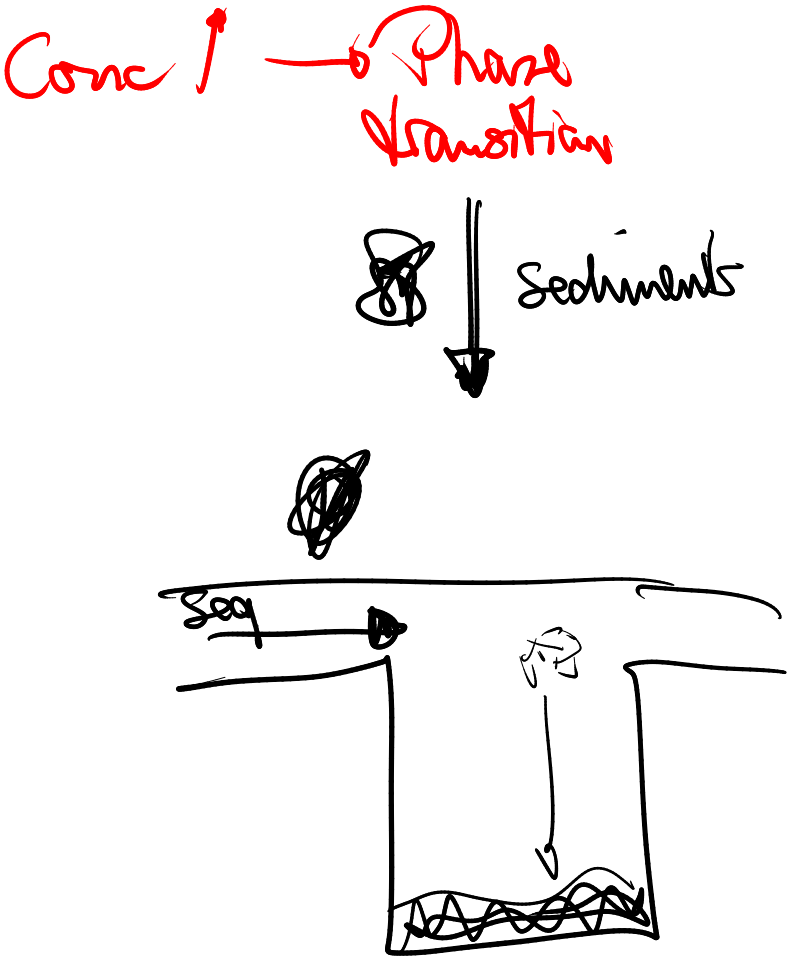


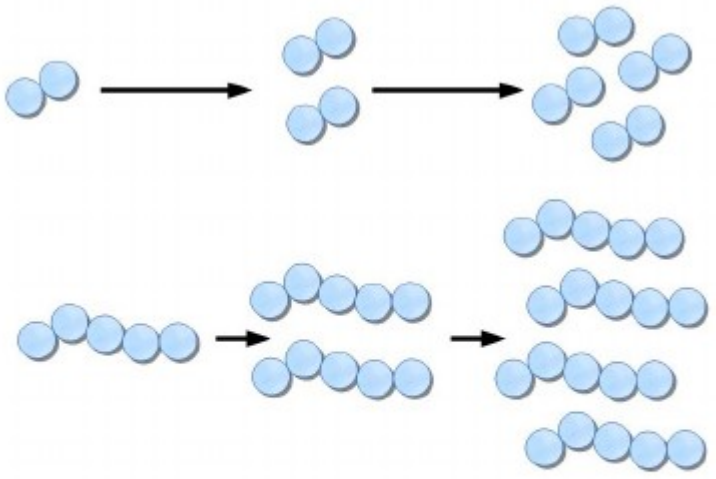


Gelation and sedimentation





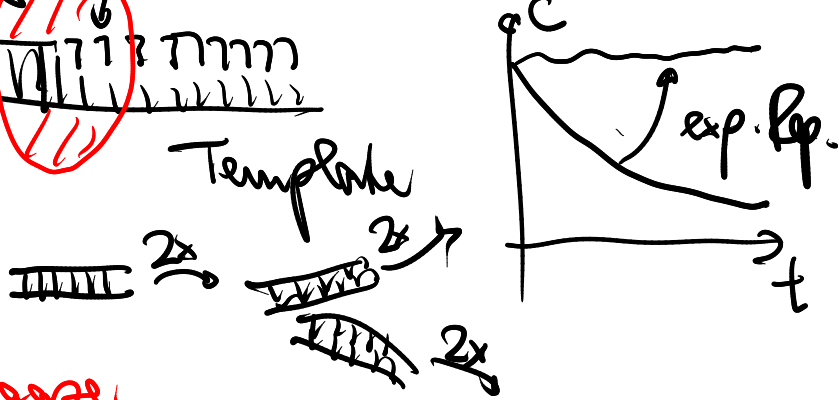
Replication driven by temperature gradients



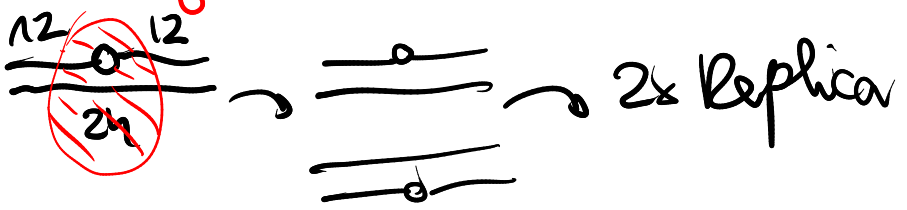
Replication
by Convection

Base by base | 50 nt/s (PCR) | 2-AL: 1nt/h

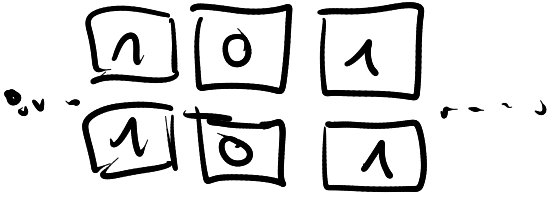
Primer — Helicase — activate Nucleotides



Ligase

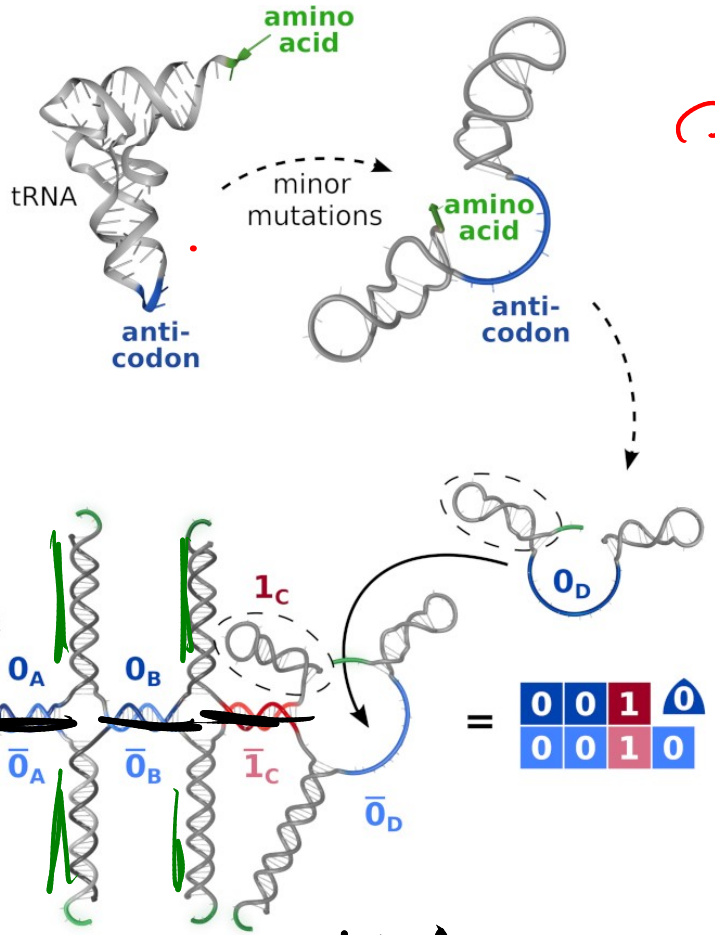


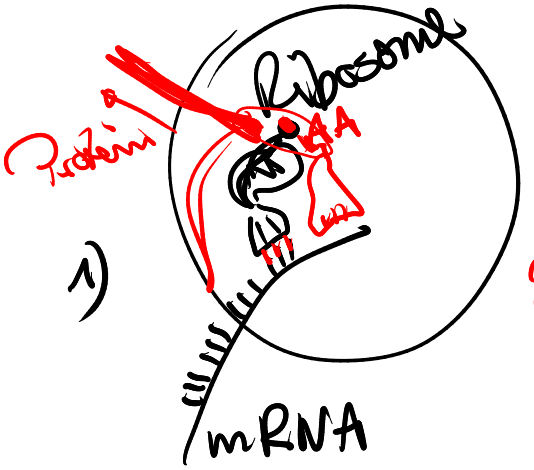
2x Replica

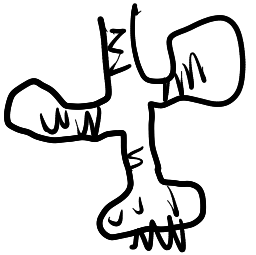


Metasequence

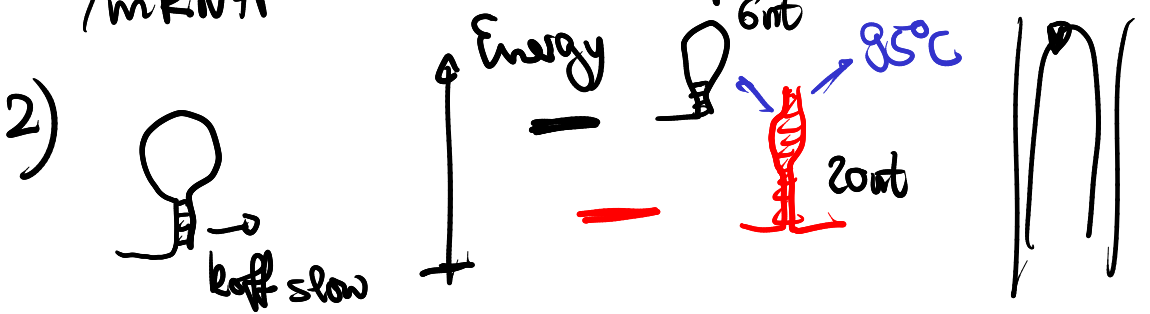
Replication driven by temperature gradients

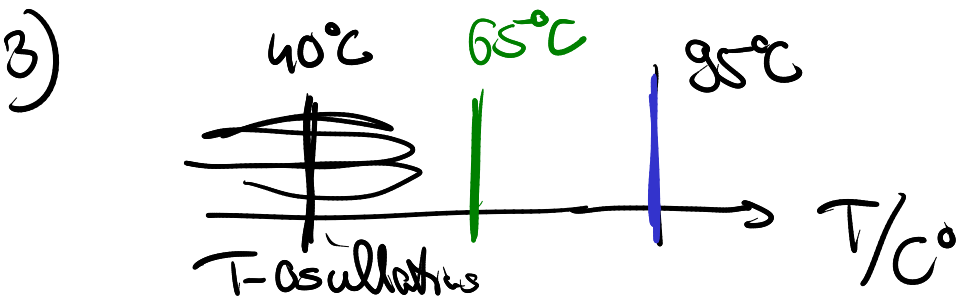




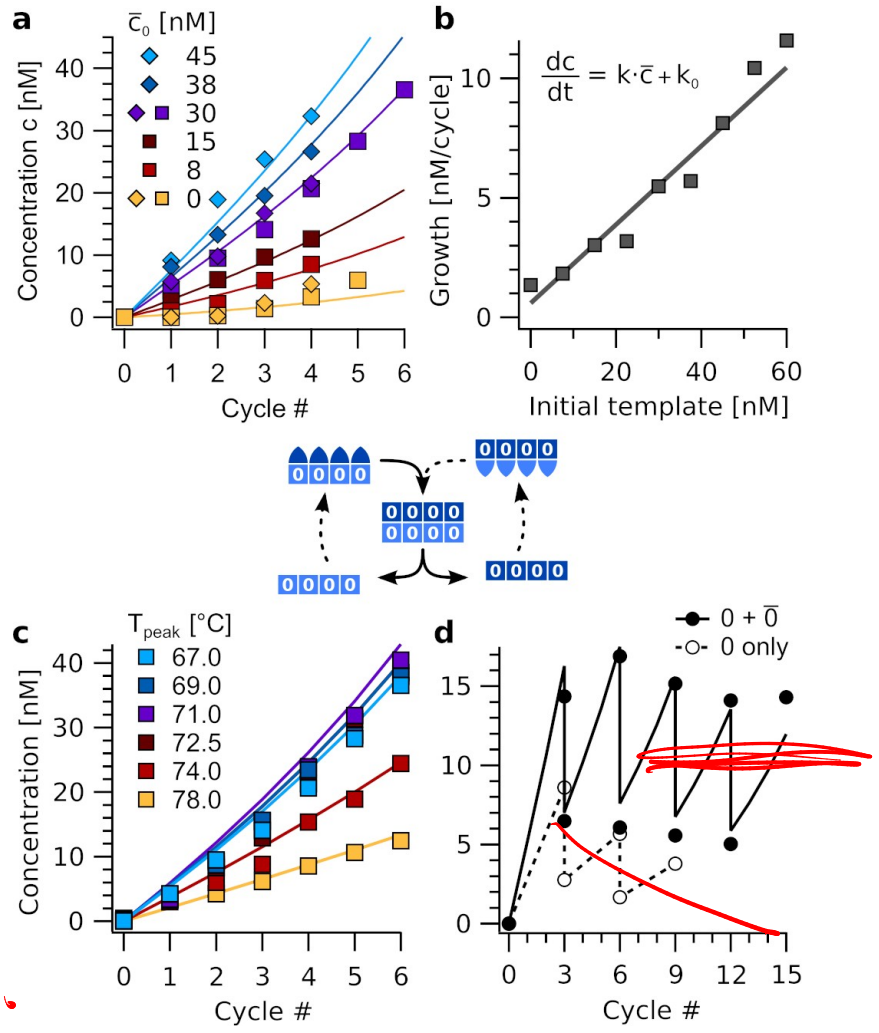


20 tRNA : useful for replication?





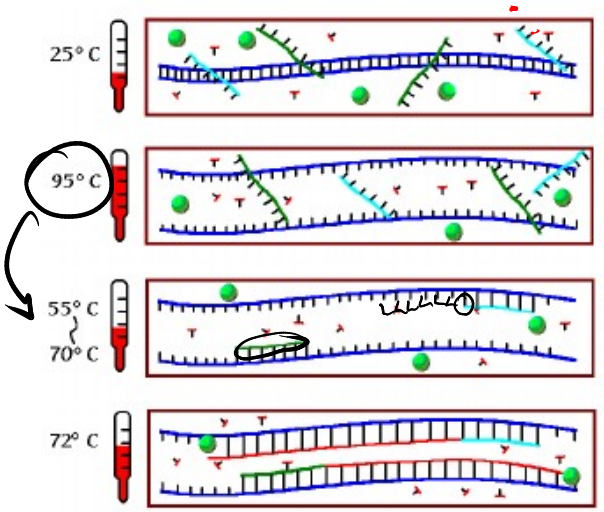
Replication driven by temperature gradients



Replication driven by temperature gradients

Polymerase Chain Reaction (PCR)

Taq Polymerase

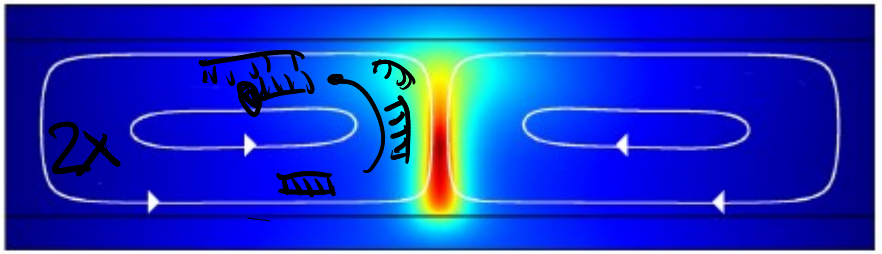


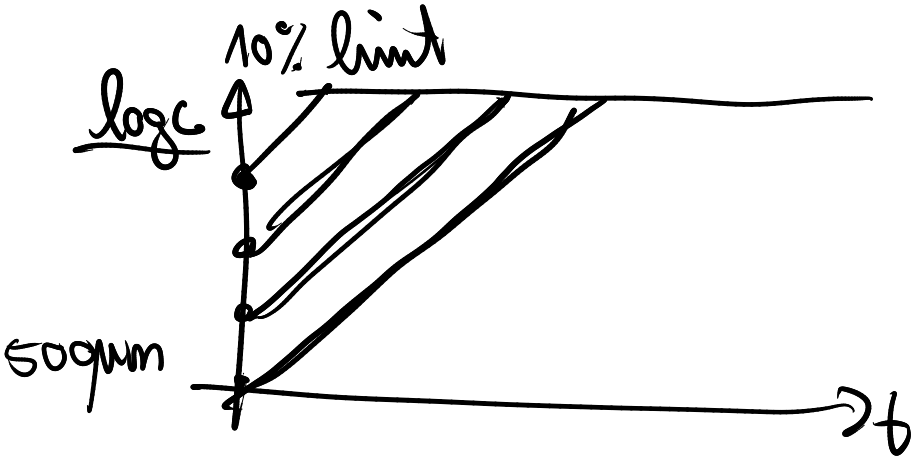
Protein is Thermostable:

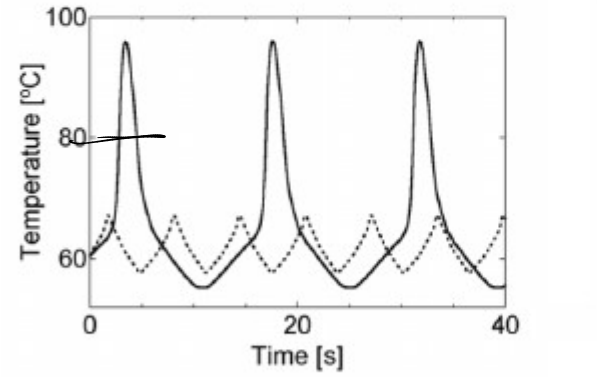
- 30 Min @ 95°C
- 50 wt/s

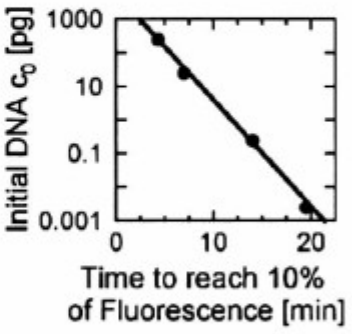
Replication driven by temperature gradients

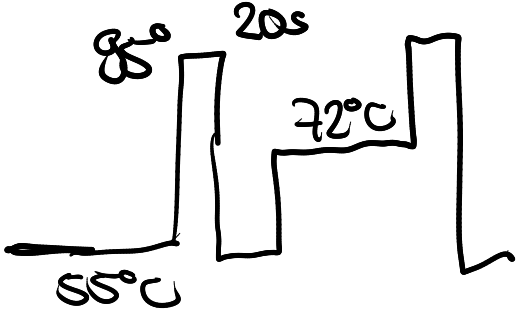
Replication by Convection (PCR)

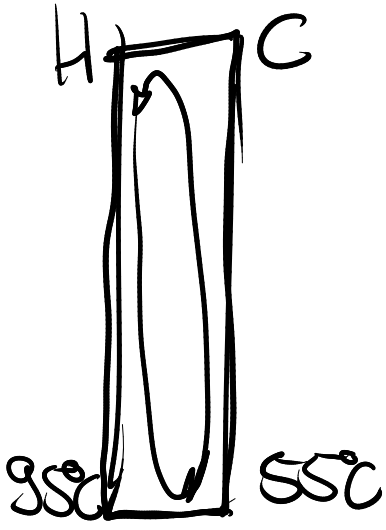












Length independent Replication
(80-2000 base pairs)

Braun, Goddard & Libchaber, PRL 91, 158103 (2003)

Replication only by RNA

to be submitted to PRL

A Thermal Habitat for RNA Amplification and Accumulation

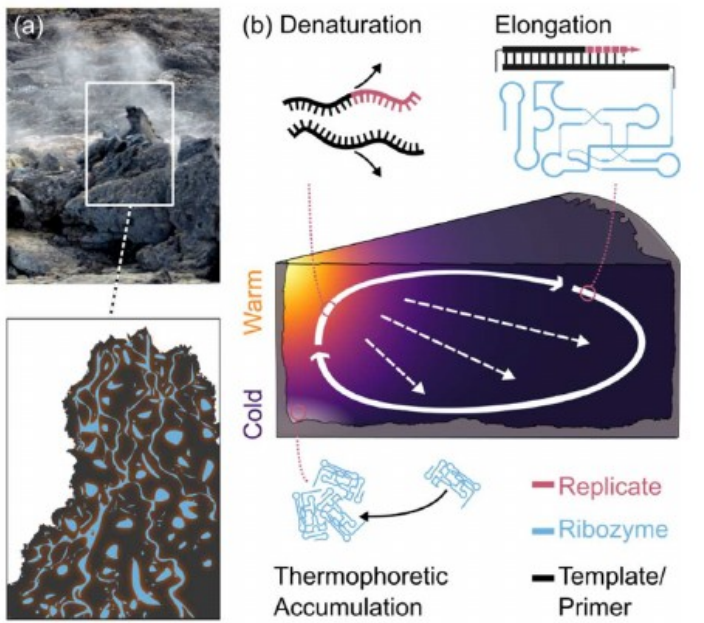
Lorenz M. R. Keil[a#], Annalena Salditt[a#], David P. Horning[b#], Christof B. Mast[a], Gerald F. Joyce[b] & Dieter Braun[a*]

Affiliations: [a]Systems Biophysics, Physics Department, Center for Nanoscience, Ludwig-Maximilians-Universität München, 80799 Munich, Germany

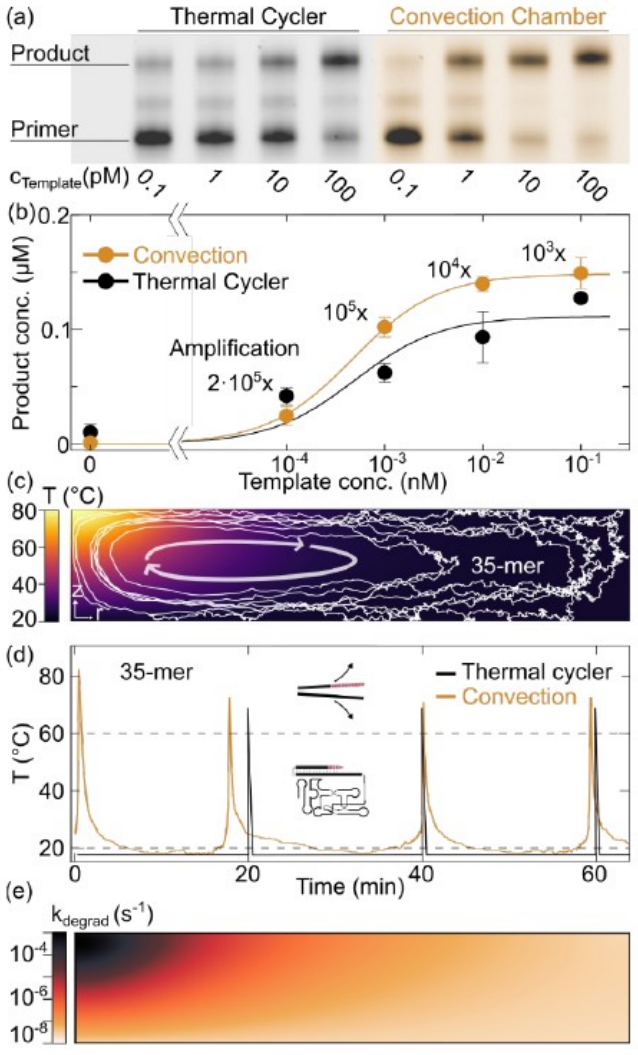
[b]The Salk Institute, 10010 N. Torrey Pines Road, La Jolla, CA 92037

* Corresponding author. Email: dieter.braun@lmu.de; Phone: +49-89-2180-1484

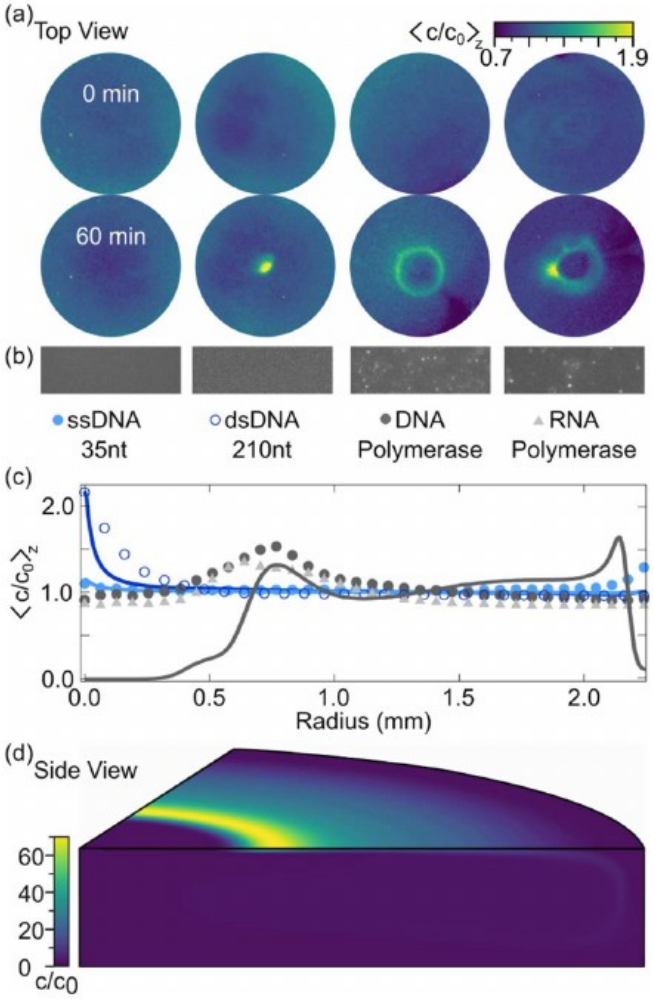
# Contributed equally

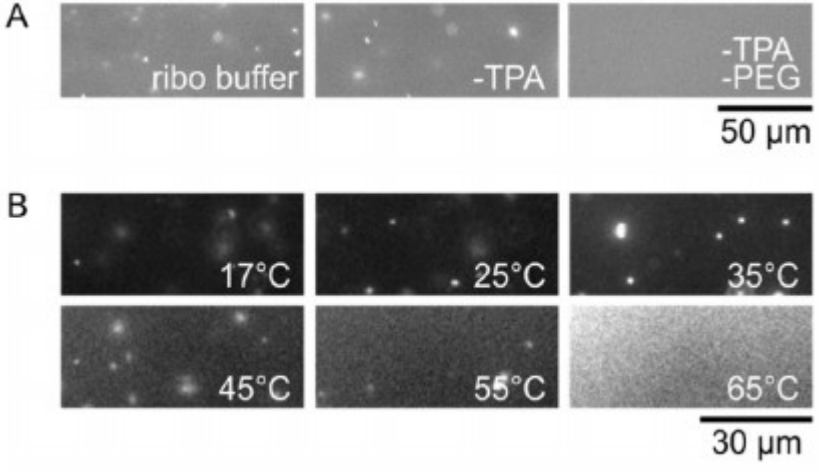


Replication only by RNA

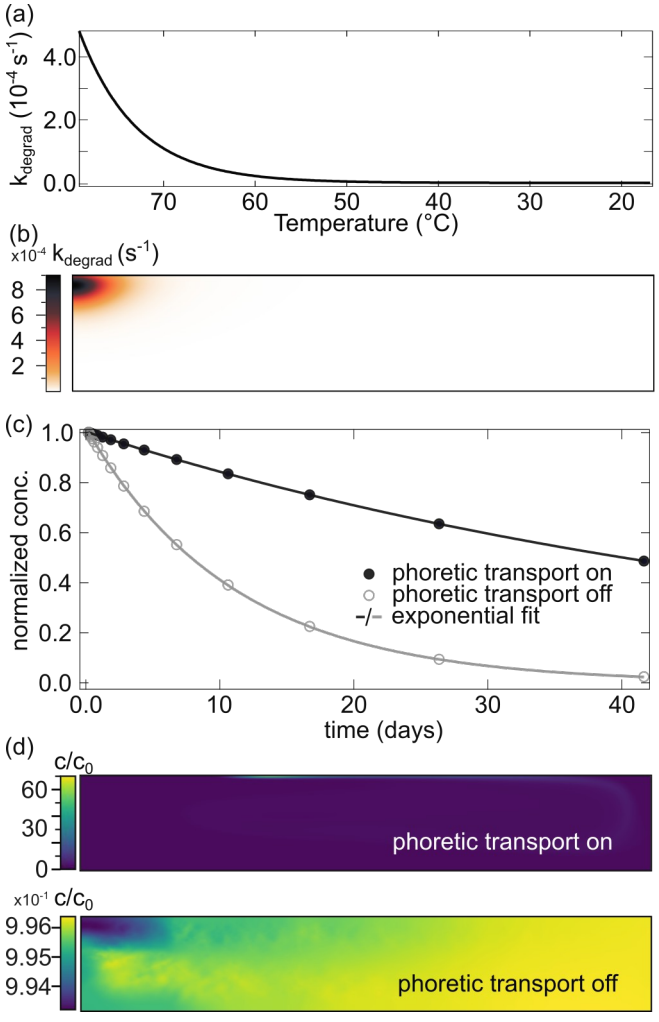


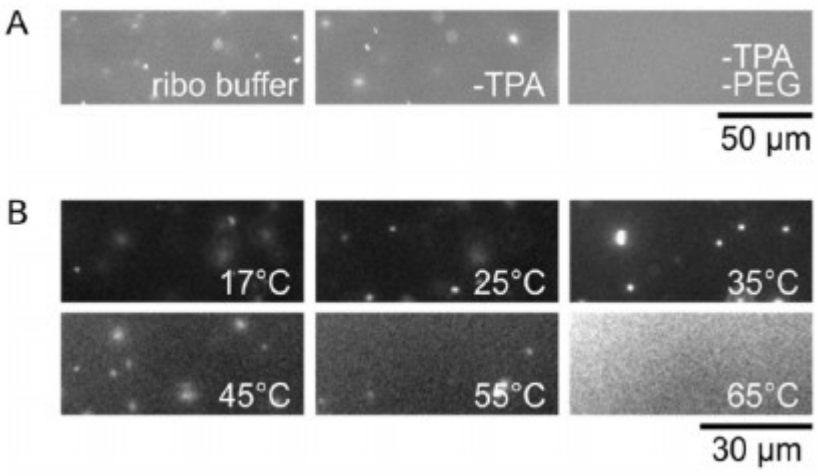
Replication only by RNA



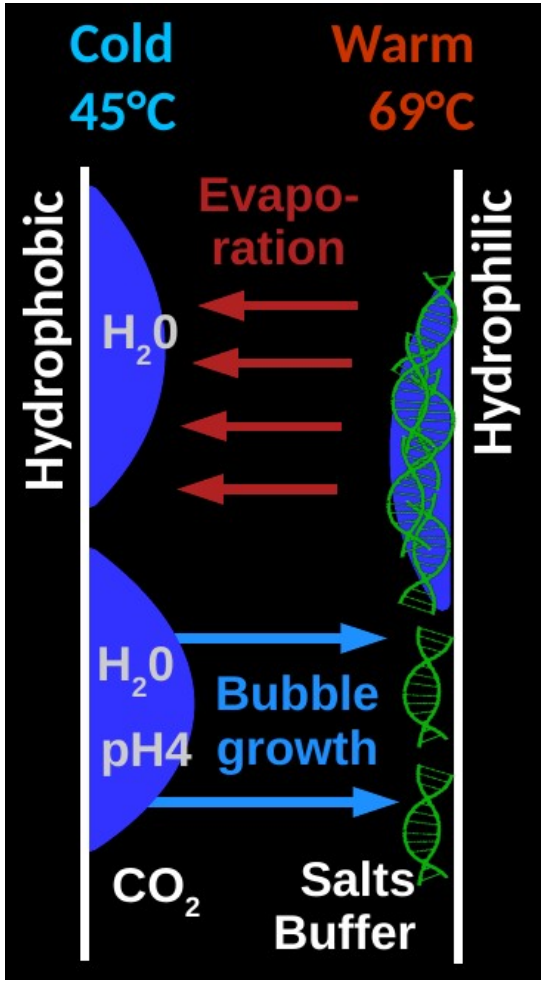


Protection by accumulation

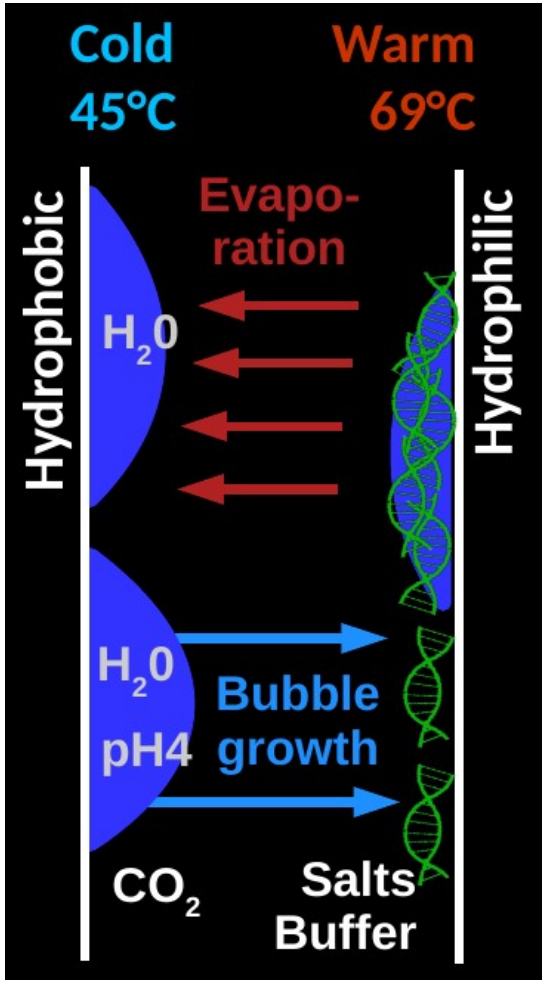


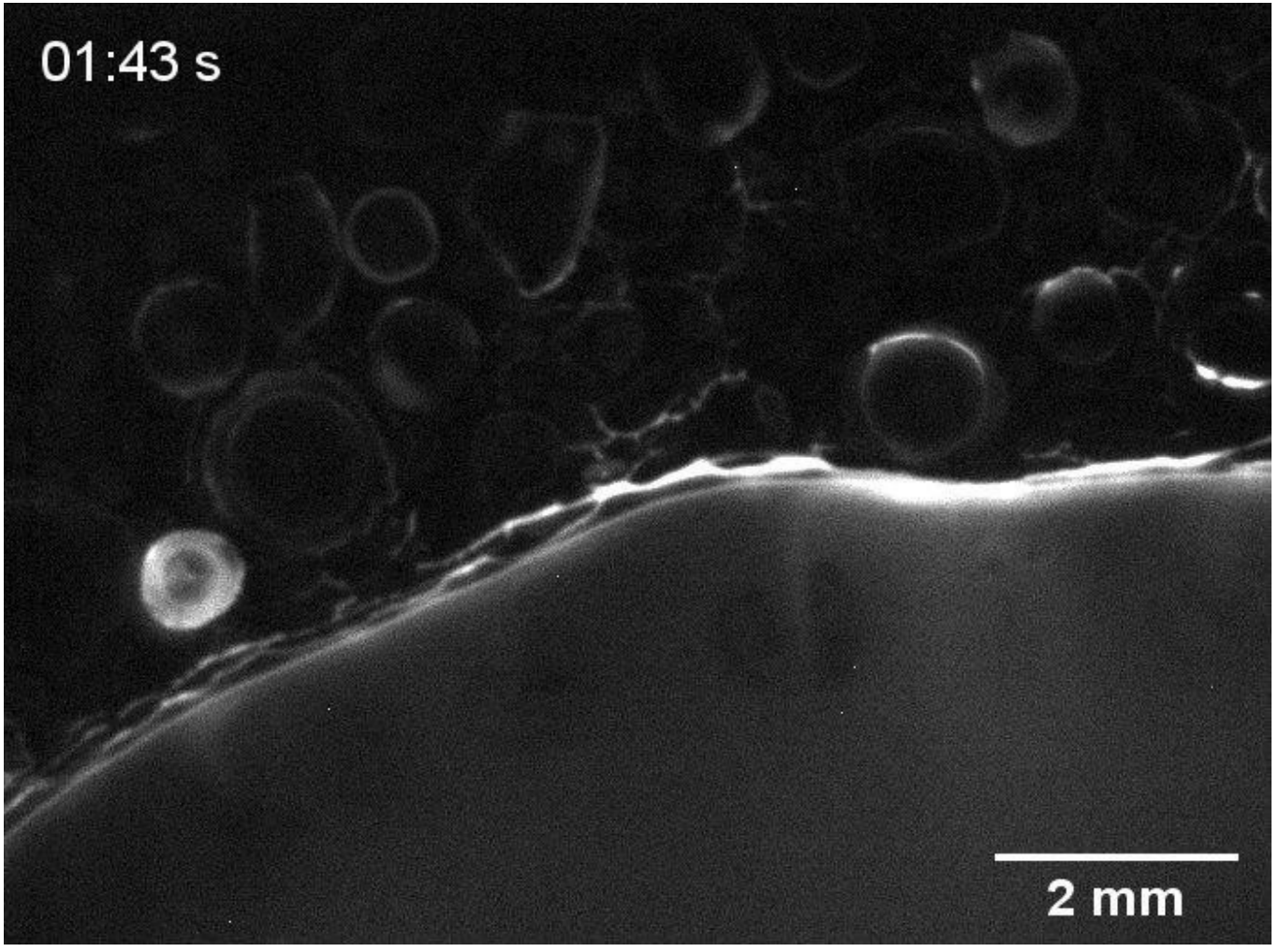


Fog PCR

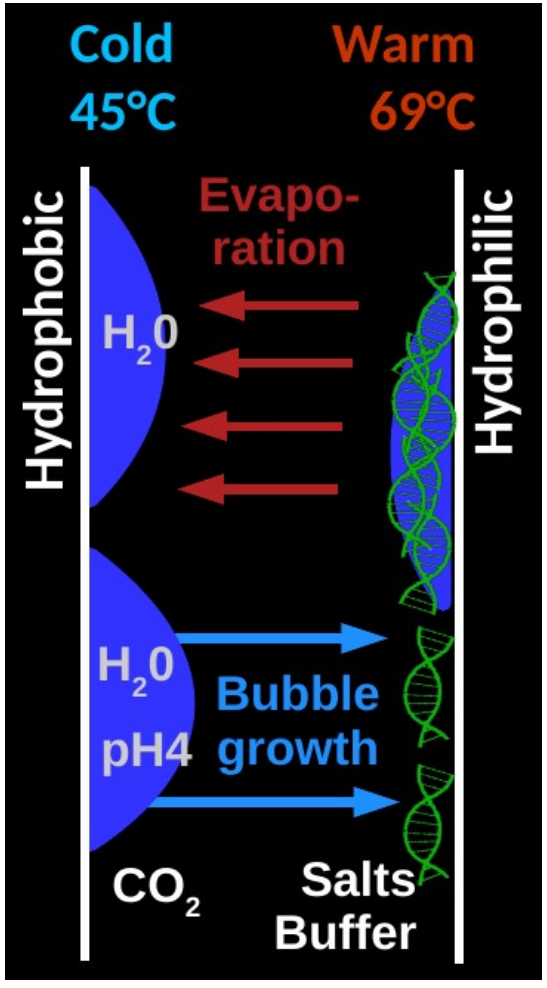

Cold
45°C
Warm
69°C
Hydrophobic
Hydrophilic
Evapo-
ration
H_20
H_20
pH4
Bubble
growth
CO_2
Salts
Buffer

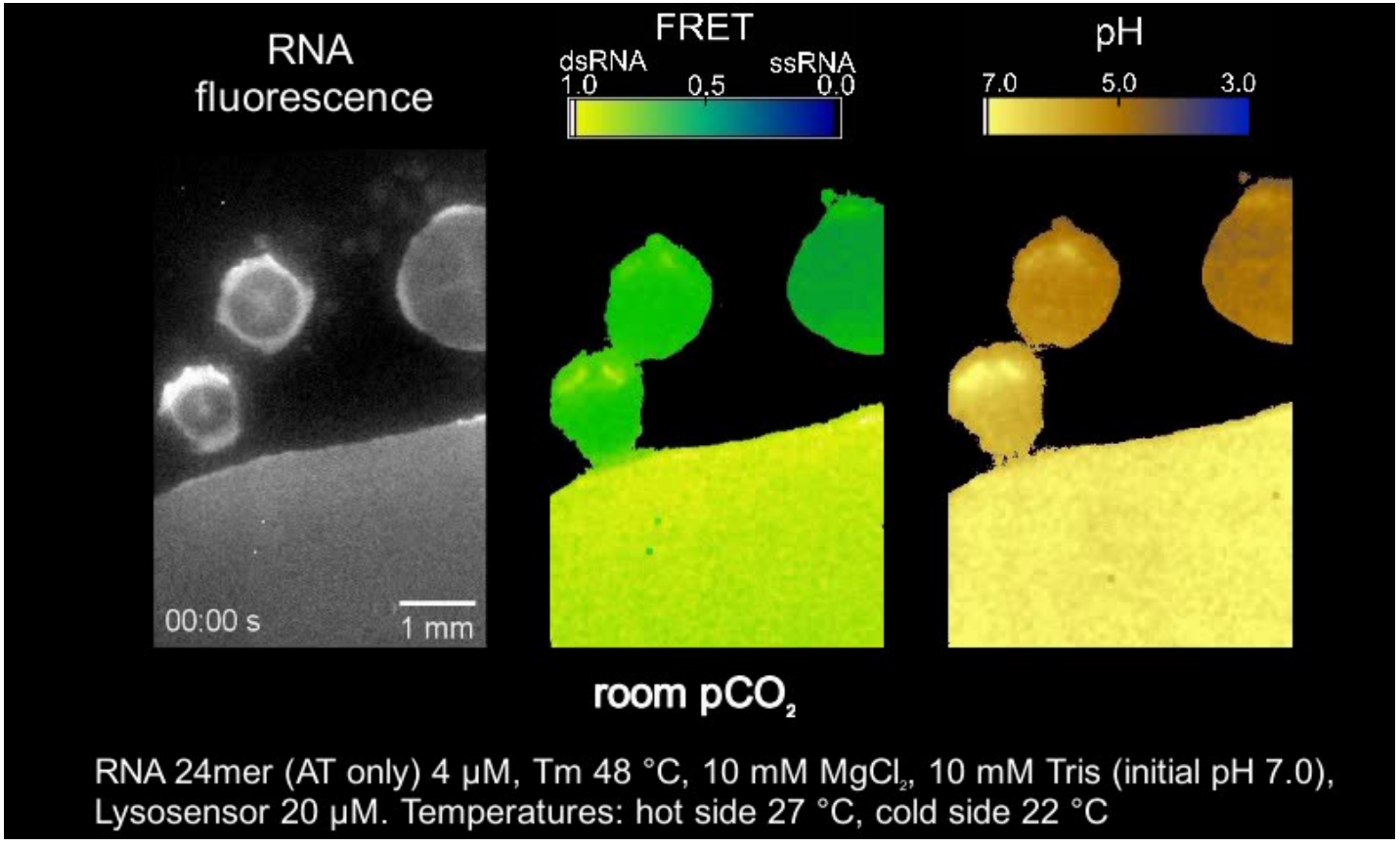
Fog PCR


Cold
45°C
Warm
69°C
Hydrophobic
Hydrophilic
Evapo-
ration
H_20
H_20
pH4
Bubble
growth
CO_2
Salts
Buffer

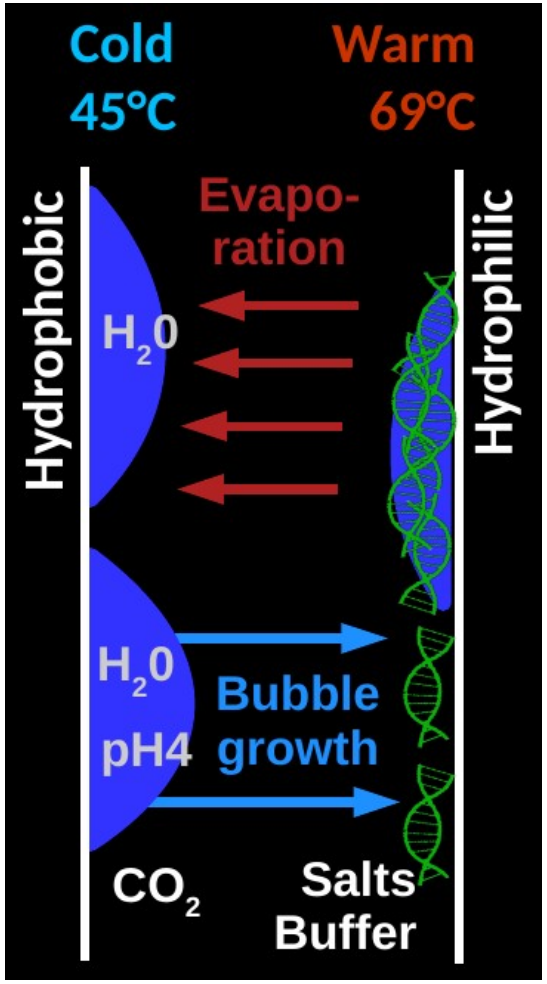

01:43 s
2 mm

Fog PCR

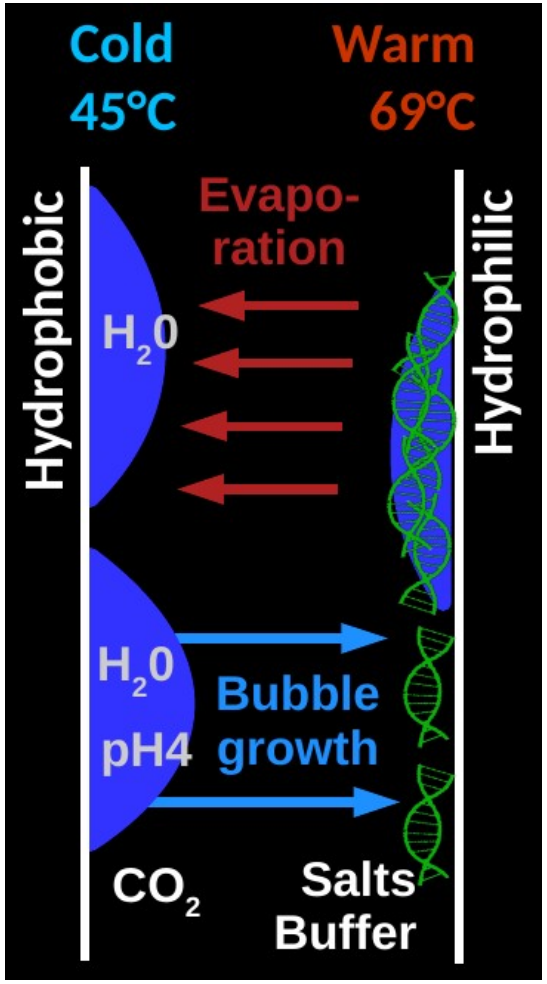

Cold
45°C
Warm
69°C
Hydrophobic
Hydrophilic
Evapo-
ration
H_2O
H_2O
pH4
Bubble
growth
CO_2
Salts
Buffer

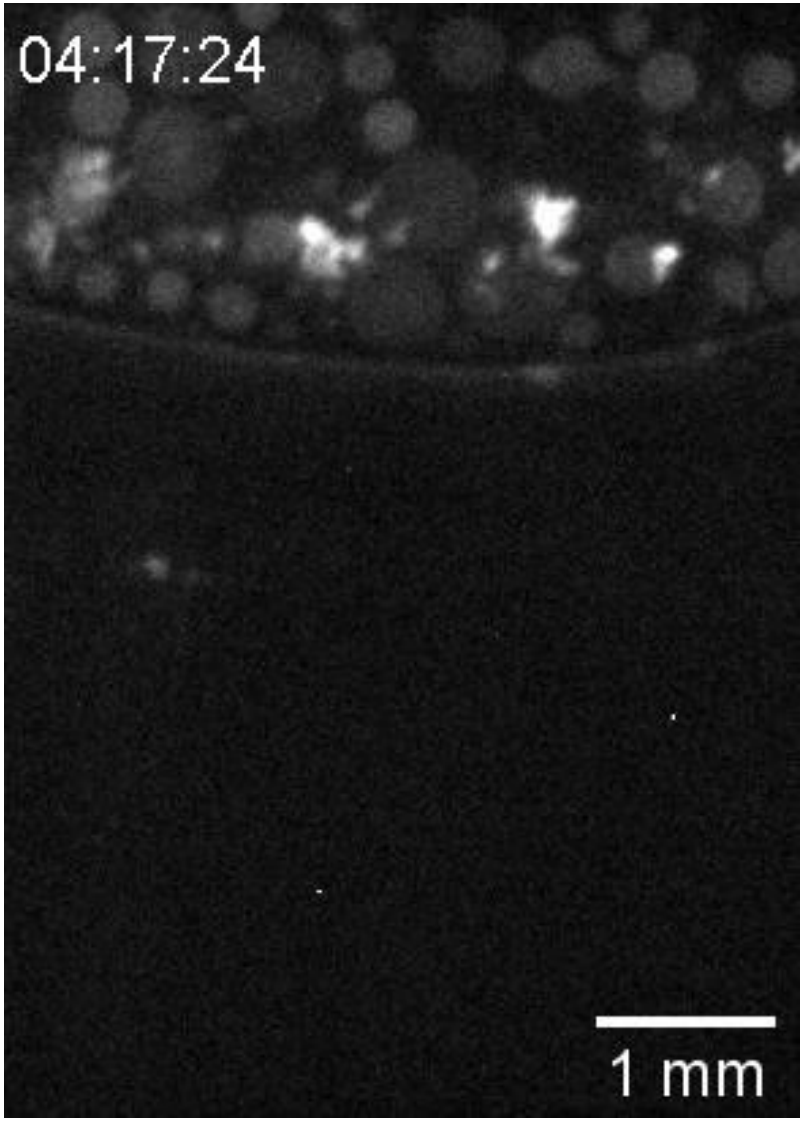

RNA
fluorescence
FRET
dsRNA
ssRNA
1.0
0.5
0.0
pH
7.0
5.0
3.0
00:00 s
1 mm
room pCO_2
RNA 24mer (AT only) 4 µM, Tm 48 °C, 10 mM $MgCl_2$, 10 mM Tris (initial pH 7.0),
Lysosensor 20 µM. Temperatures: hot side 27 °C, cold side 22 °C

Fog PCR


Cold
45°C
Warm
69°C
Hydrophobic
Hydrophilic
Evapo-
ration
H_20
H_20
pH4
Bubble
growth
CO_2
Salts
Buffer

Fog PCR

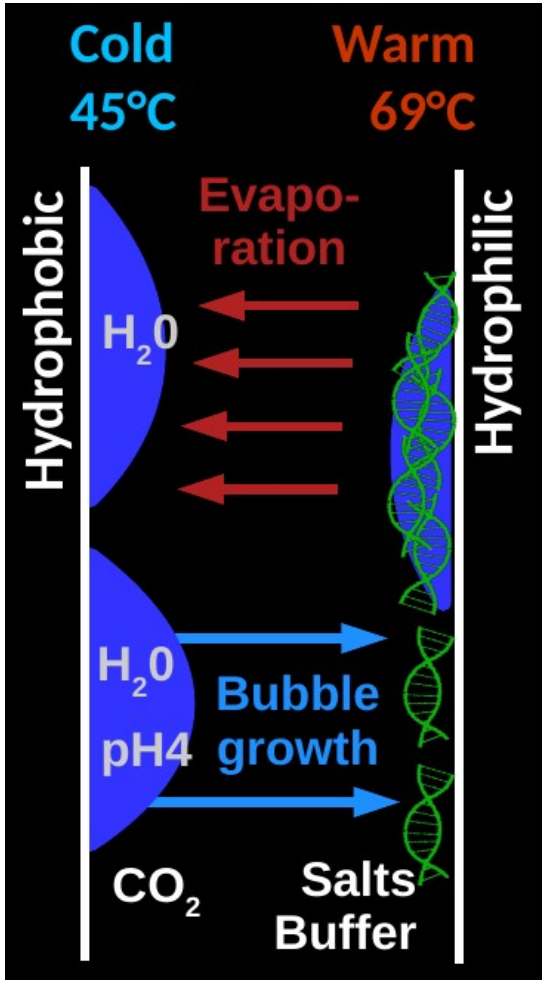


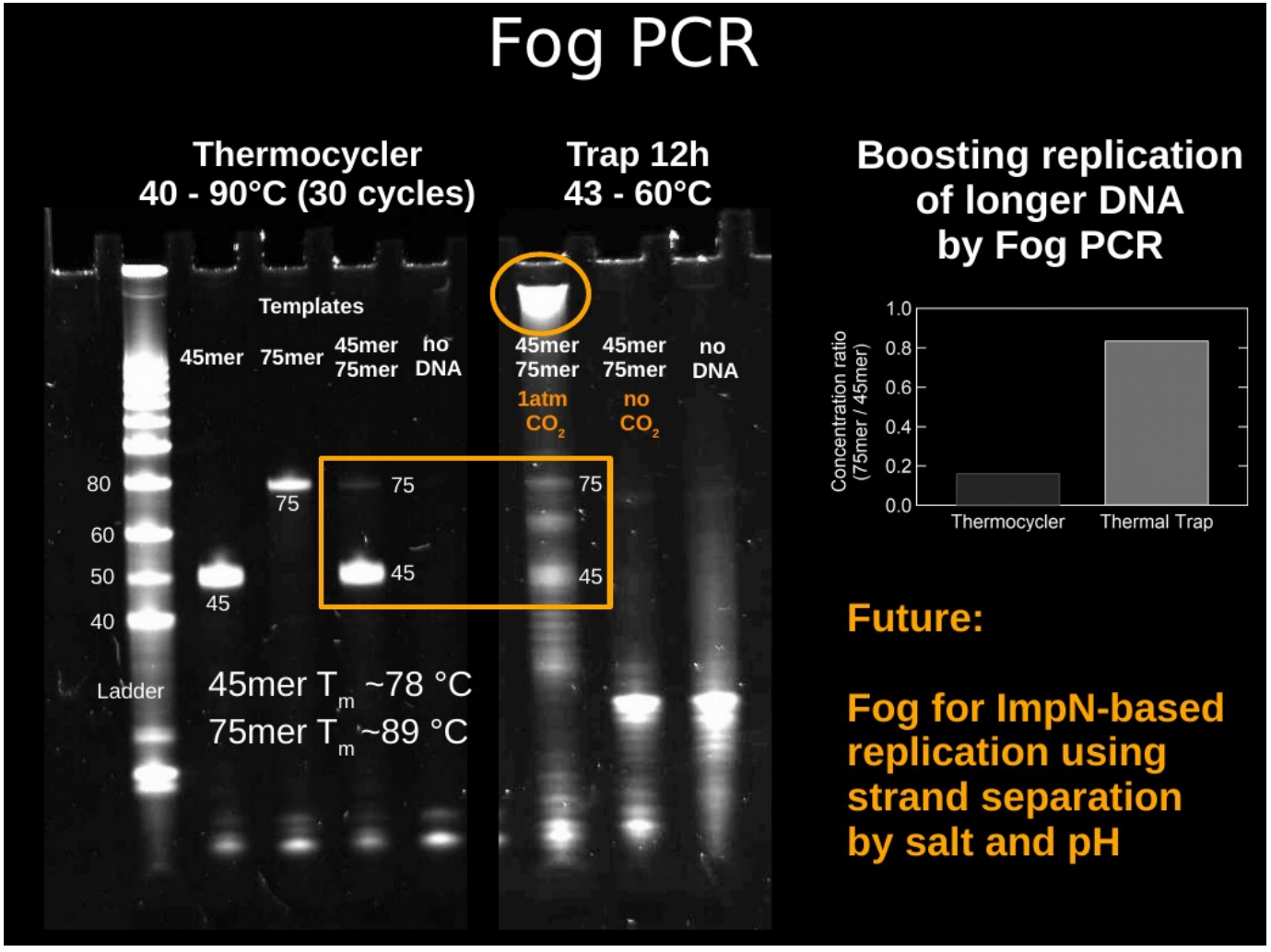


Alan
Ianeselli

T gradient:
45 °C - 69 °C
51mer T_m = 83 °C
1 bar CO_2
1 nM template DNA
0.5 µM primers
Taq polymerase
1.5 mM $MgCl_2$
0.1% BSA
2x SYBR Green

Fog PCR

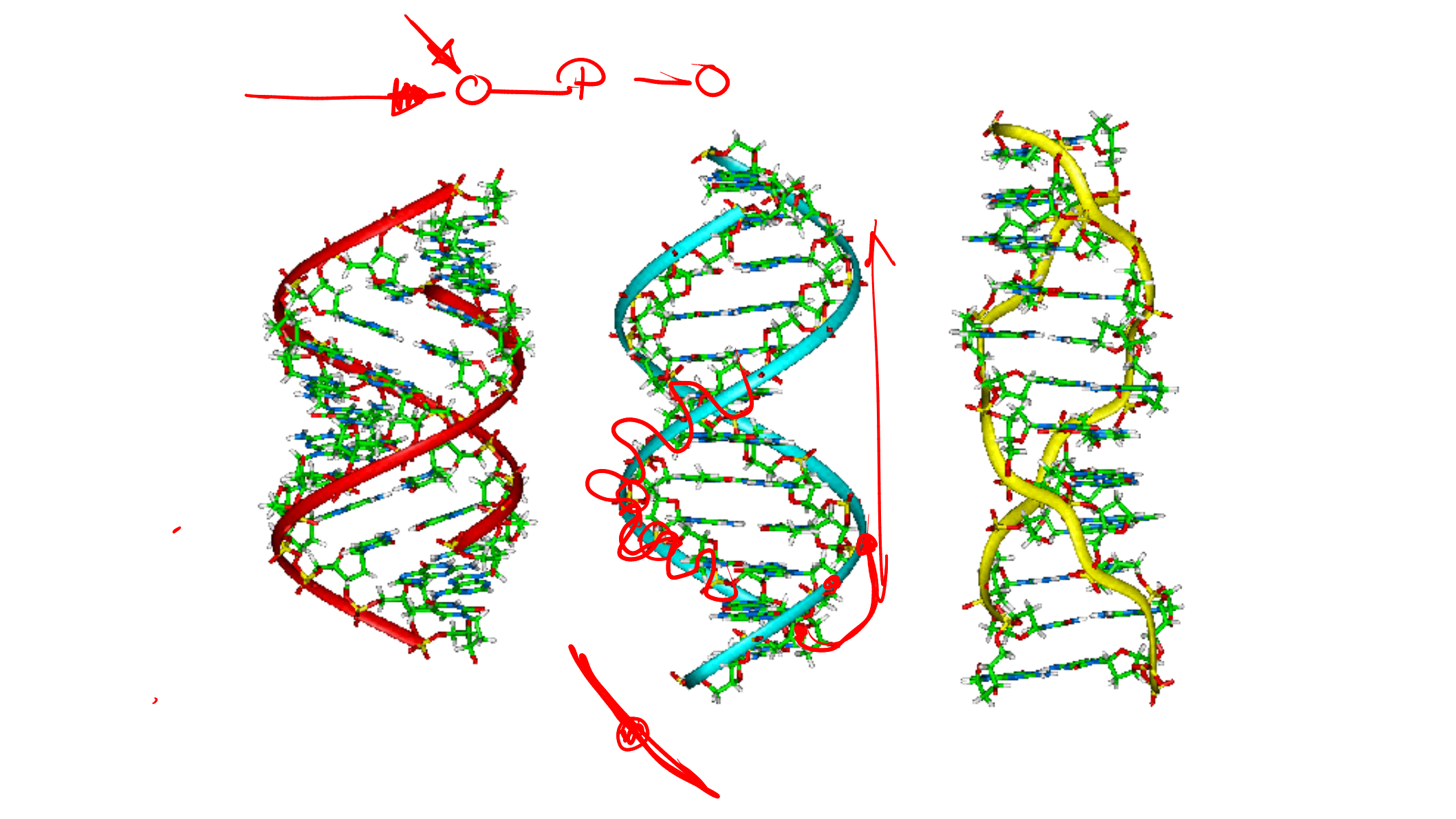

Cold
45°C
Warm
69°C
Hydrophobic
Hydrophilic
Evapo-
ration
H_2O
H_2O
pH4
Bubble
growth
CO_2
Salts
Buffer


Fog PCR
Thermocycler
40 - 90°C (30 cycles)
Trap 12h
43 - 60°C
Templates
45mer
75mer
45mer
75mer
no
DNA
45mer
75mer
1atm
CO_2
45mer
75mer
no
CO_2
no
DNA
80
60
50
40
Ladder
45
75
75
45
75
45
45mer T_m ~78 °C
75mer T_m ~89 °C
Boosting replication
of longer DNA
by Fog PCR
Concentration ratio
(75mer / 45mer)
1.0
0.8
0.6
0.4
0.2
0.0
Thermocycler
Thermal Trap
Future:
Fog for ImpN-based
replication using
strand separation
by salt and pH

Polymerization boost by Thermophoretic Trap

- Accumulation PRL 2002
- Click together the accumulation in comsol
- Sidepoint: NanoTemper
- PNAS paper accumulation
- Szostak vesicle formation paper
- PNAS polymerization
- Simons update polymerization
- Gel formation Angewandte
- Gel formation and sedimentation (tRNA)

Replication
- tRNA-based replication
- Convection PCR
- Ribo-PCR
- NatChem2015: replication and selection
- Alan results
- Water-Air interface Natchem 2018
- Overview over non-equilibrium (rep from last).



a