Self-organization and phoretic motions for the origin of life

Yusuke T. Maeda [1,2]

[1] Assistant Professor, The Hakubi center, Kyoto University
[2] PRESTO, Japan Science and Technology Agency

Self-organization

Equilibrium system

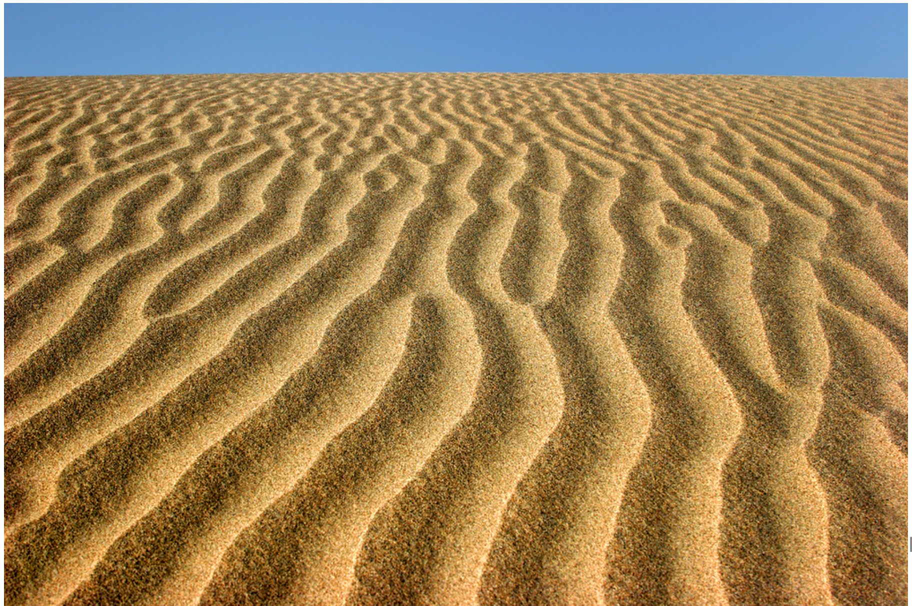
・Second law of thermodynamics tells
entropy in a closed and isolated system never decreases.

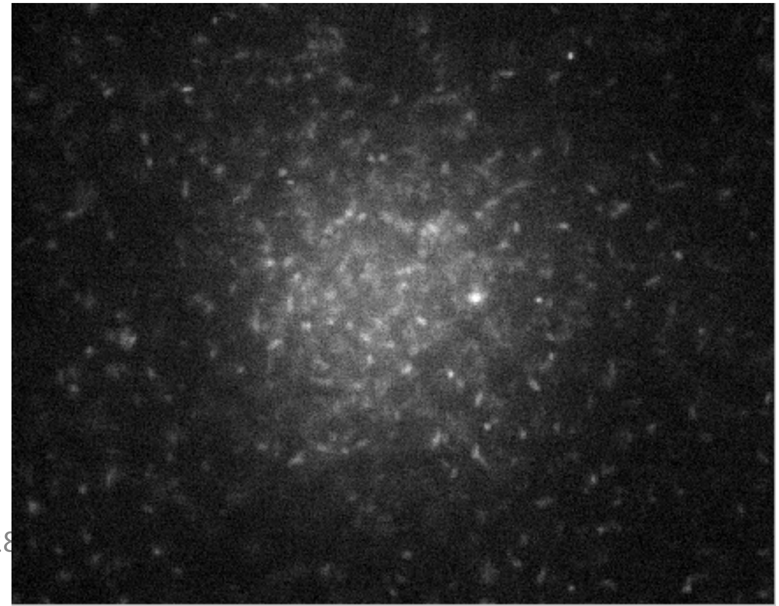
・The system evolves to equilibrium of maximum entropy.

Non-equilibrium system

・The system develops towards a self-organized state.

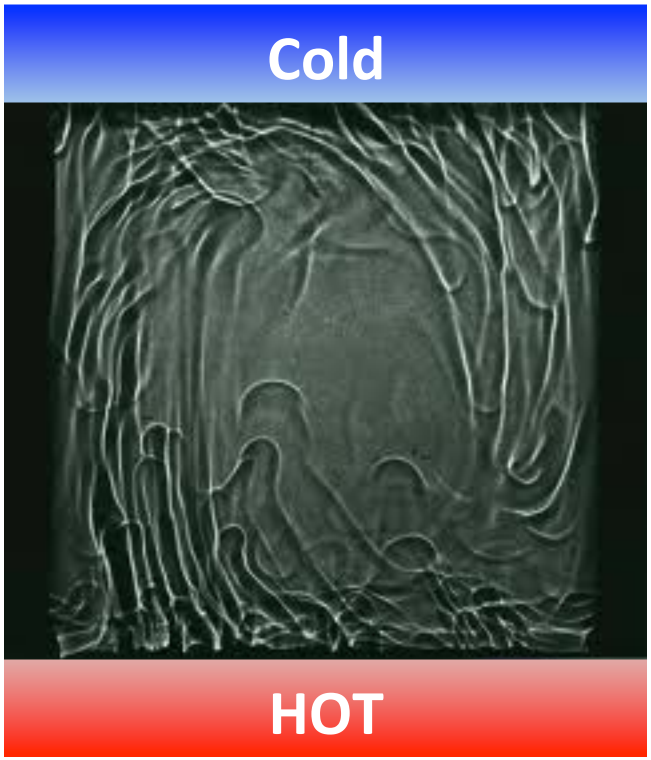
・The flow of mass or energy keeps system organized.





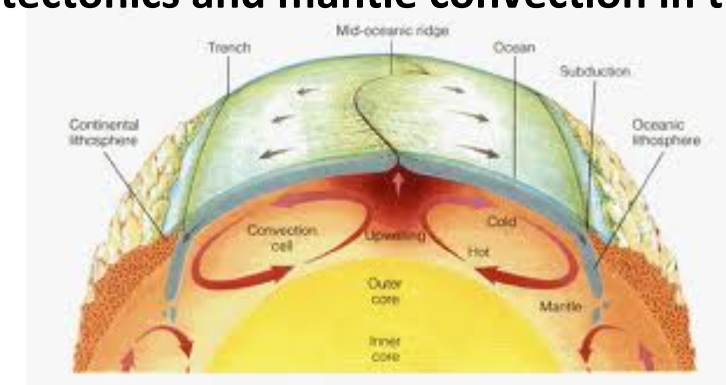
Non-equilibrium physics and the earth

Thermal convection

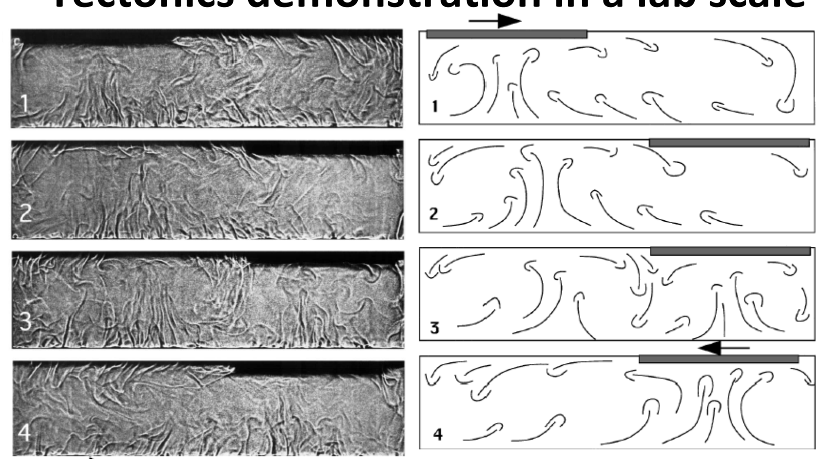


- Self-organization (non-equilibrium process) is essential for the earth's environment.

Plate tectonics and mantle convection in the earth

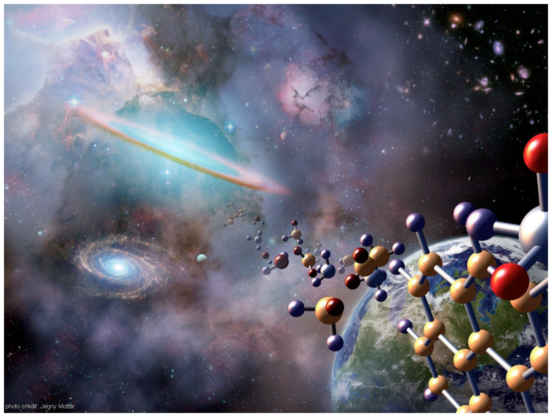


Tectonics demonstration in a lab scale

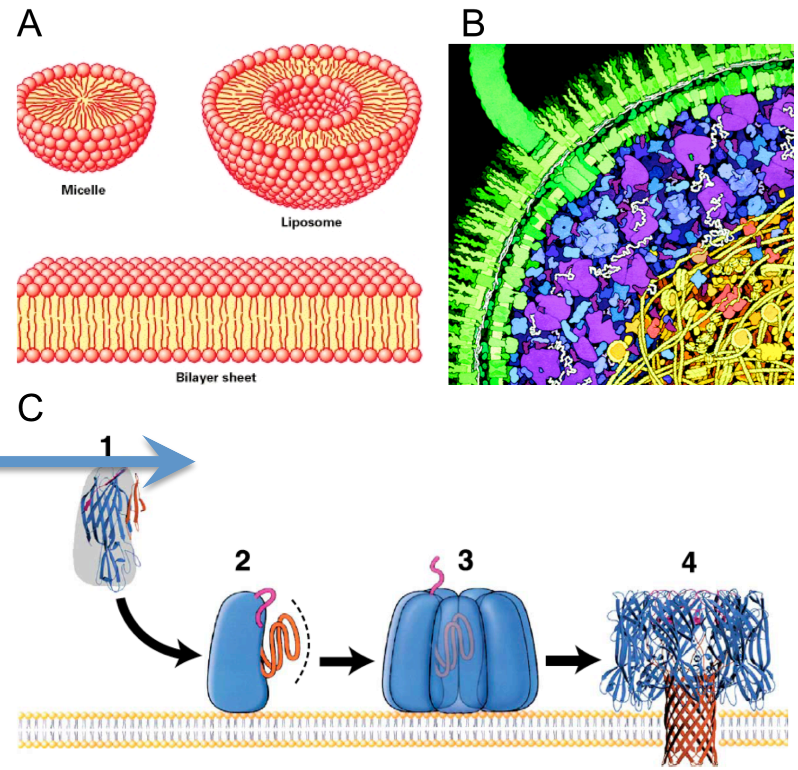


J Zhang and A Libchaber
Phys Rev Lett **84**, 4361 (2000)

Self-organization behind origin of cellular life



The origin of life



To obtain self-organized biological systems
⇒ Molecules should be concentrated
above critical concentration.
⇒ Molecules should be selected
for proper function.

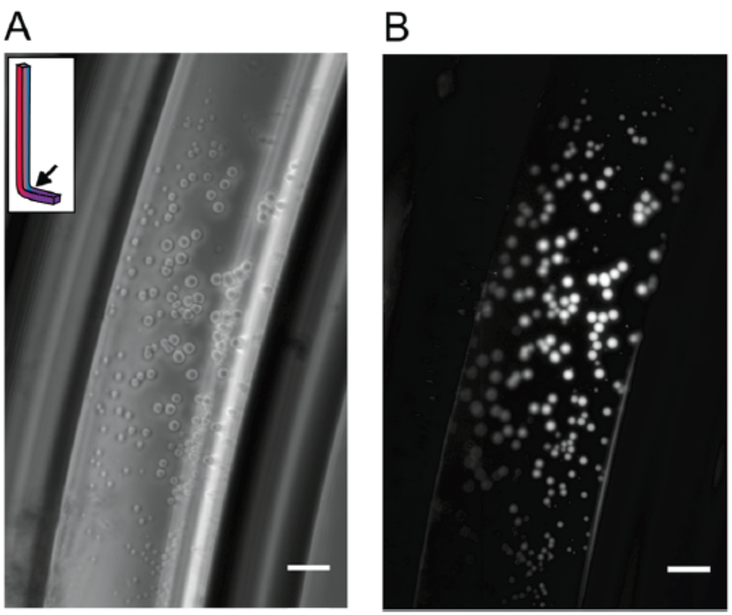
Did non-equilibrium processes drive (accelerate) the origin of life?

Thermal convection and the origin of life

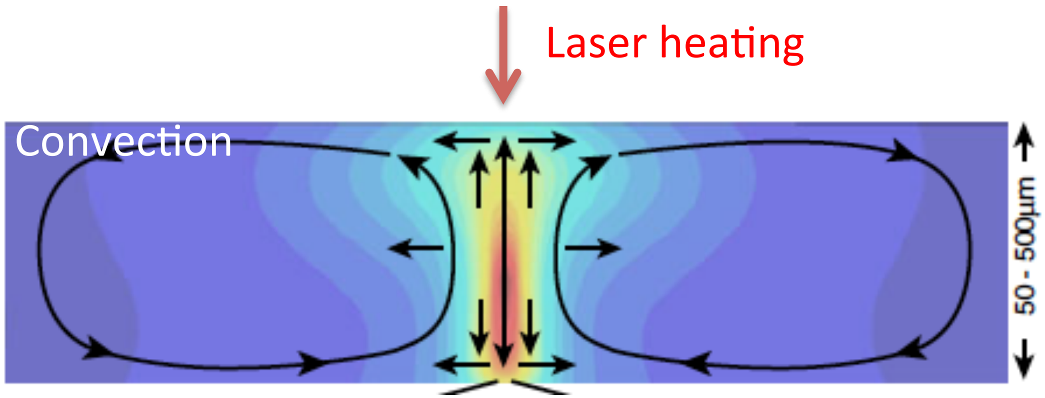
***Thermal convection*: well-known non-equilibrium system**

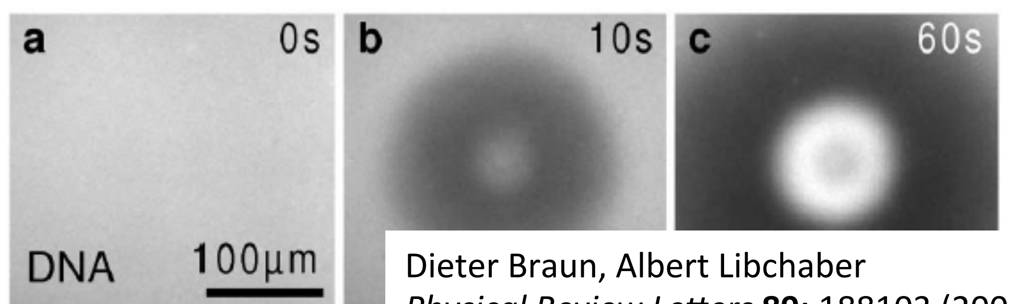
- Temperature gradients drive the flow of water.
- Thermal convection occurs if Reynolds number is large.

- Thermal convection traps DNA and lipid vesicle. → accumulation

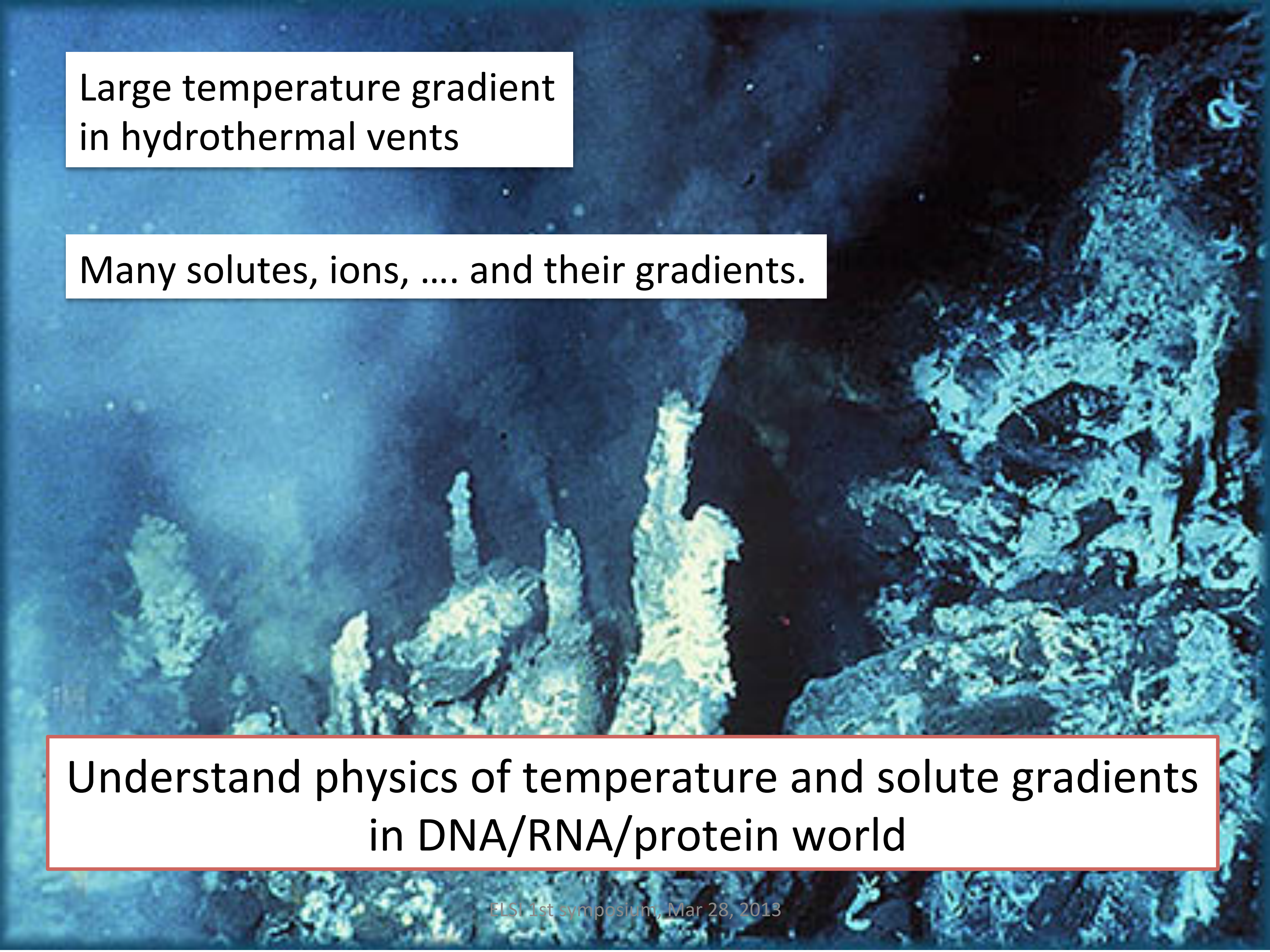


I Budin, RJ Bruckner, JW Szostak
J Am Chem Soc **131:** 9628 (2009)





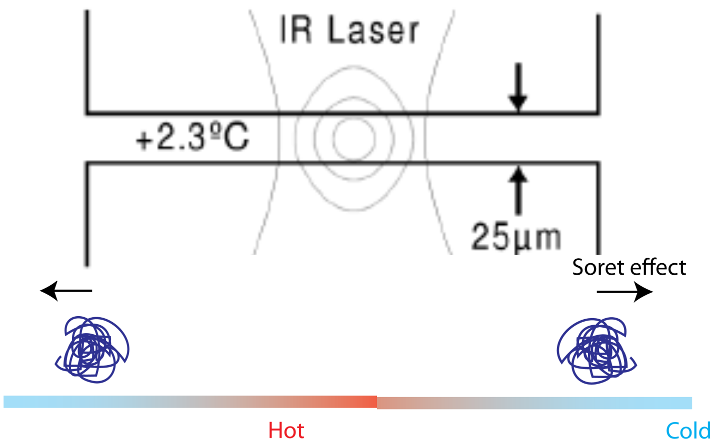
Dieter Braun, Albert Libchaber
Physical Review Letters **89:** 188103 (2002)


Large temperature gradient
in hydrothermal vents
Many solutes, ions, …. and their gradients.
Understand physics of temperature and solute gradients
in DNA/RNA/protein world

The Soret effect: Transport under a temperature gradient

The Ludwig-Soret effect: molecular transport discovered more than 100 years ago

- Molecules move with a velocity proportional to temperature gradient.
- Typical charged molecules, DNA, RNA, Proteins, move to Cold from Hot.

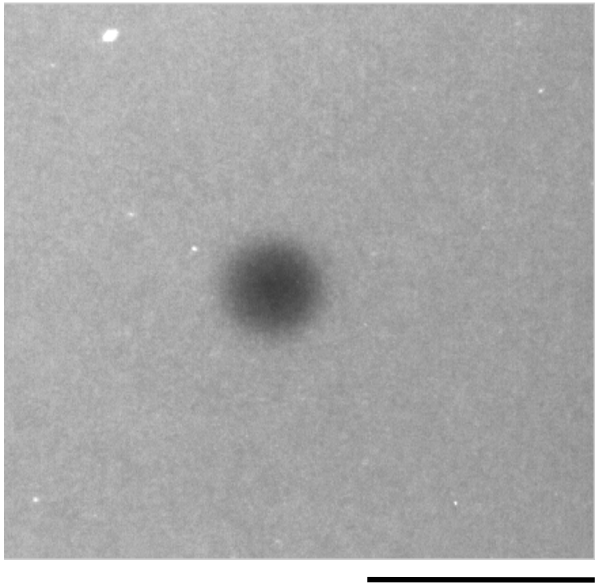


Velocity of thermal diffusion

$$v = -D_T \nabla T$$

Density flow of DNA

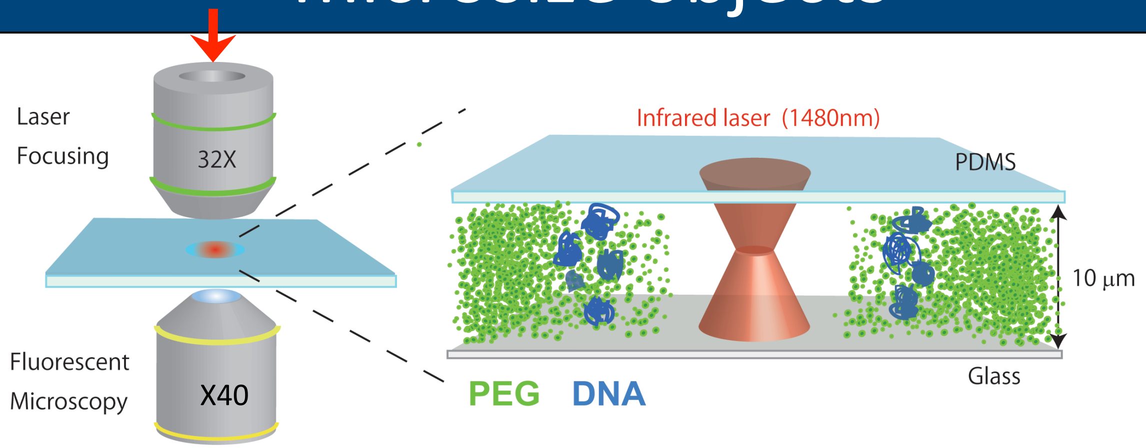
$$J = -D\nabla c - cD_T \nabla T$$



35 µm

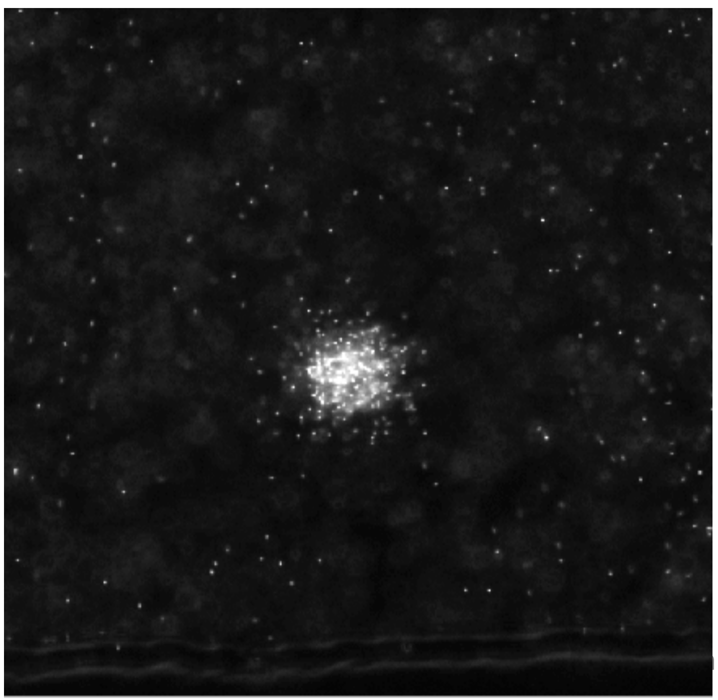
D Braun and A Libchaber
Phys Rev Lett **89:** 188103 (2002)

The Soret effect can trap and manipulate microsize objects

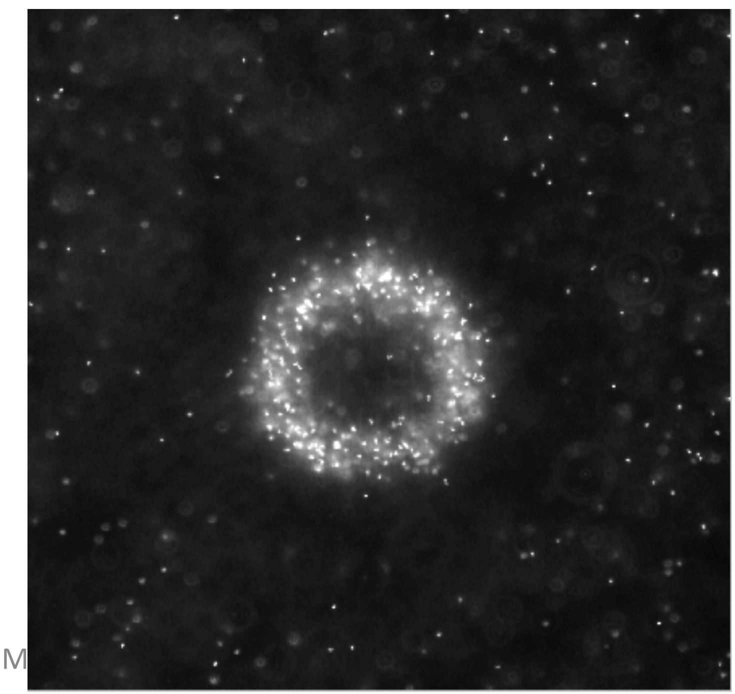


Accumulation of fluorescent beads (0.5 μm)

Ring of fluorescent beads

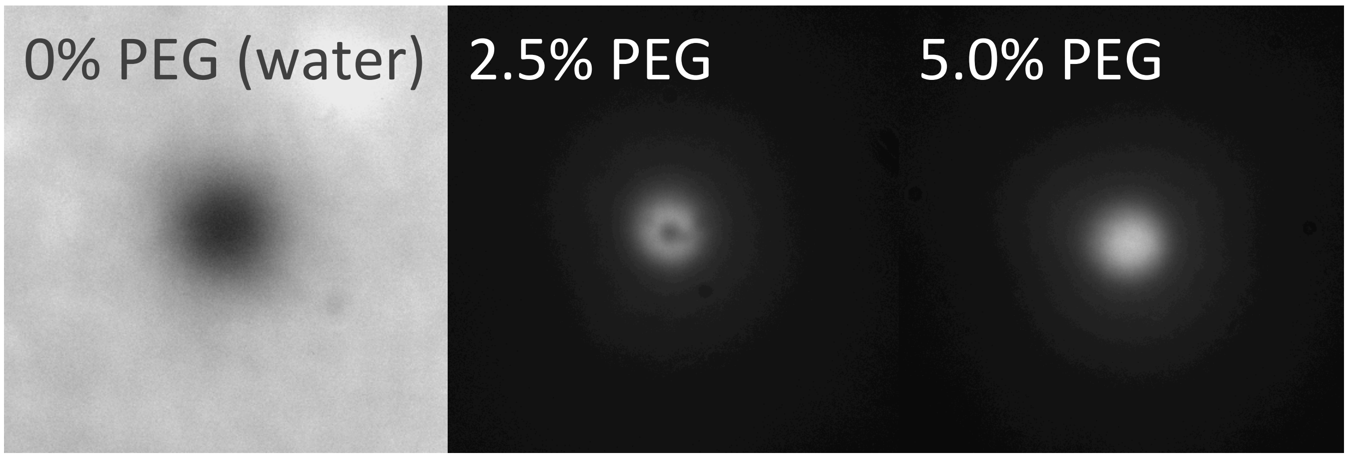


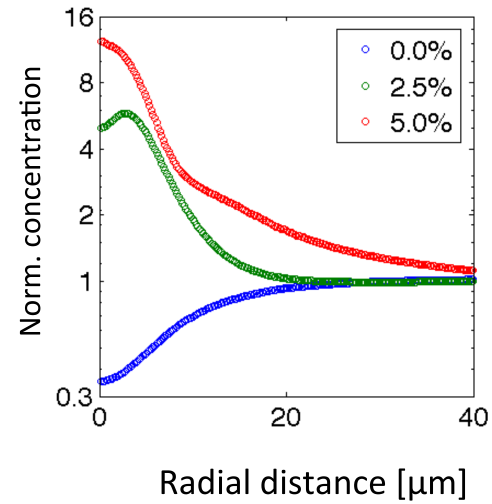
5%PEG



2% PEG

DNA 5.6kbp (ϕ=0.01%)





Depletion Localization Accumulation

H.R.Jiang, H.Wada, N.Yoshinaga, M.Sano
Physical Review Letters **102**: 208301 (2009)

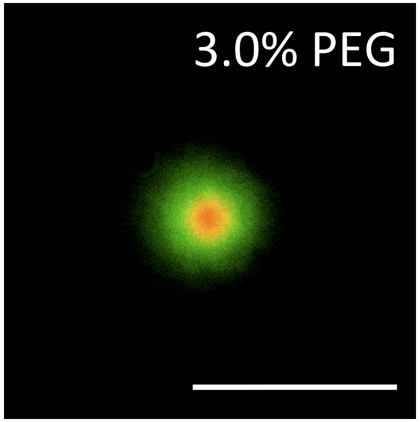
Yusuke T. Maeda, Axel Buguin, Albert Libchaber
Physical Review Letters **107**: 038301 (2011)

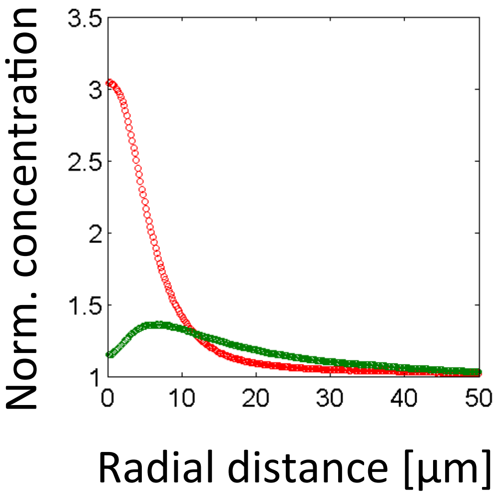
Scale bar 35 μm

Size-dependent localization and separation

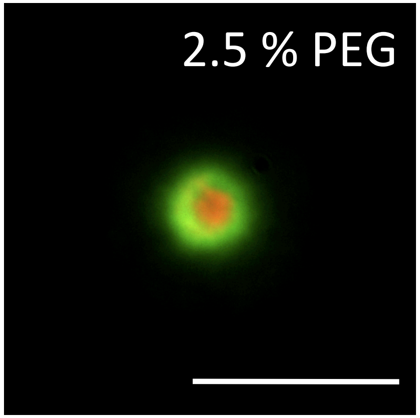
The separation of

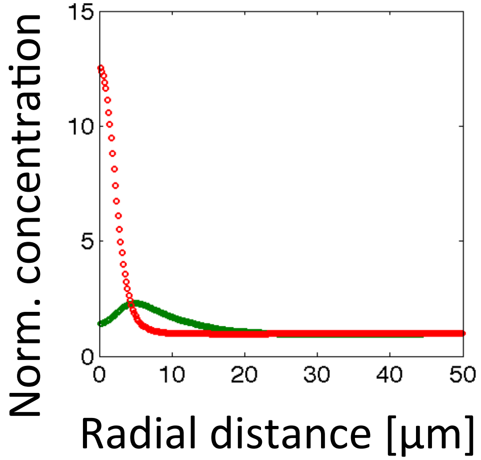
Long RNA (1.5 kb, ϕ=0.01%)/
short DNA (0.25 kbp, ϕ=0.01%)





Large colloid (0.5 µm, ϕ=0.01%) /
Small colloid (0.1 µm, ϕ=0.01%)





Scale bar 35 µm

Diffusiophoresis model agrees with experimental observation

- **PEG gradient generates the osmotic force (diffusiophoresis) on DNA surface.**

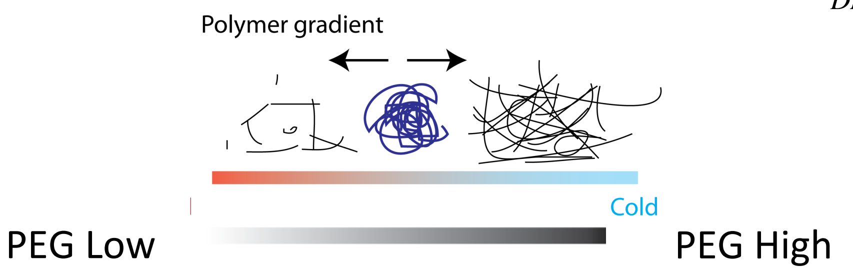
Depletion: 0% PEG

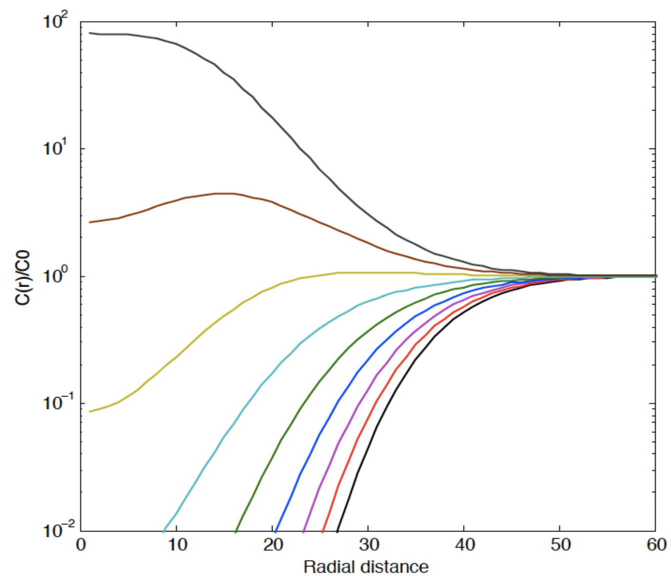
$$J = -D\nabla c_{DNA} - c_{DNA} D_T \nabla T - c_{DNA} u$$

Normal Diffusion | The Soret effect | Diffusiophoresis

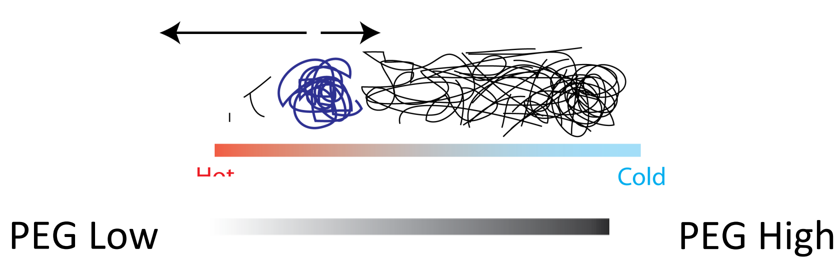
$$c_{DNA}(r) = c_{DNA}^{0} \exp\left[-S_T (T(r) - T_0) + \left(c_{PEG}^{0} - c_{PEG}(r)\right)V\right]$$

Localization: 1～3% PEG





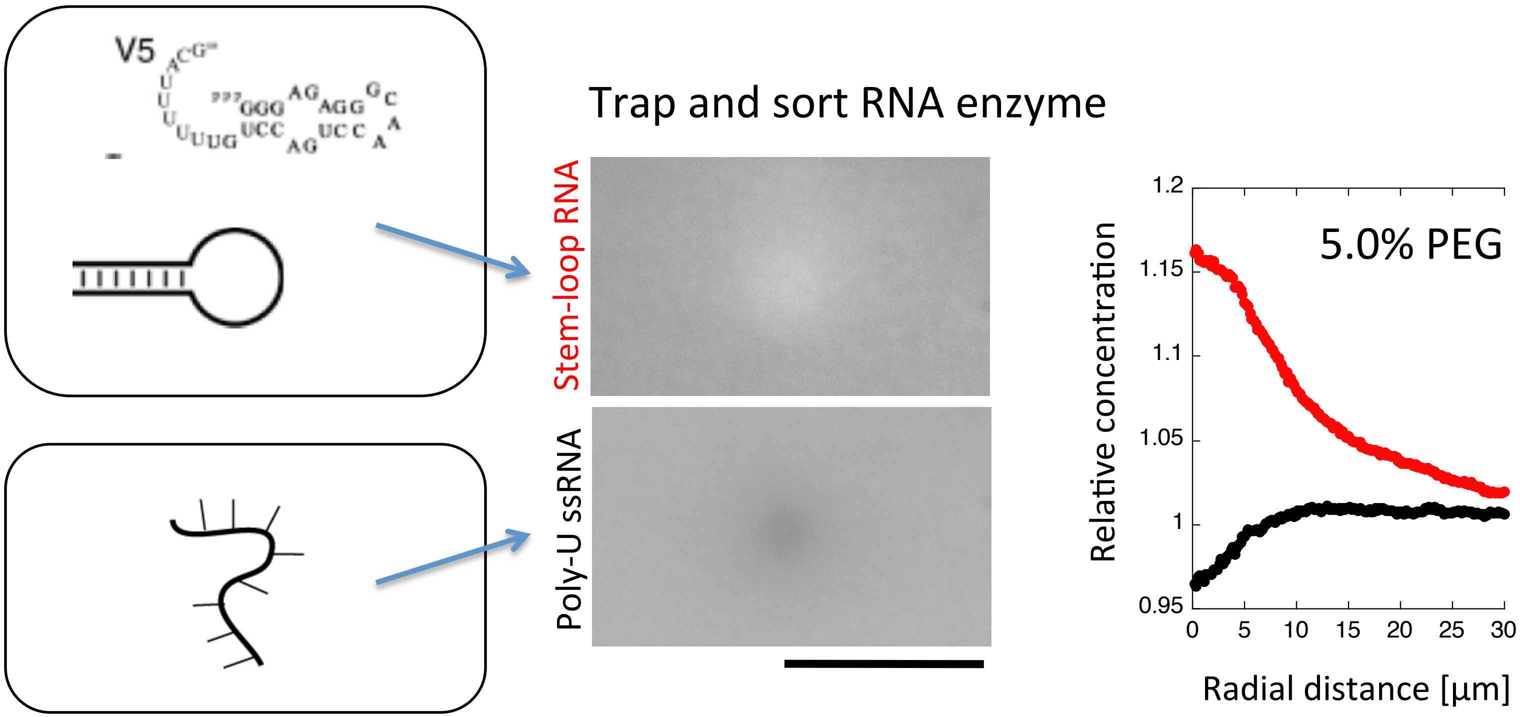
Accumulation: >3% PEG



J.L. Anderson, *Ann. Rev. Fluid. Mech* **21**, 61 (1989)

Jiang, et al PRL (2009); Maeda, et al PRL (2011)

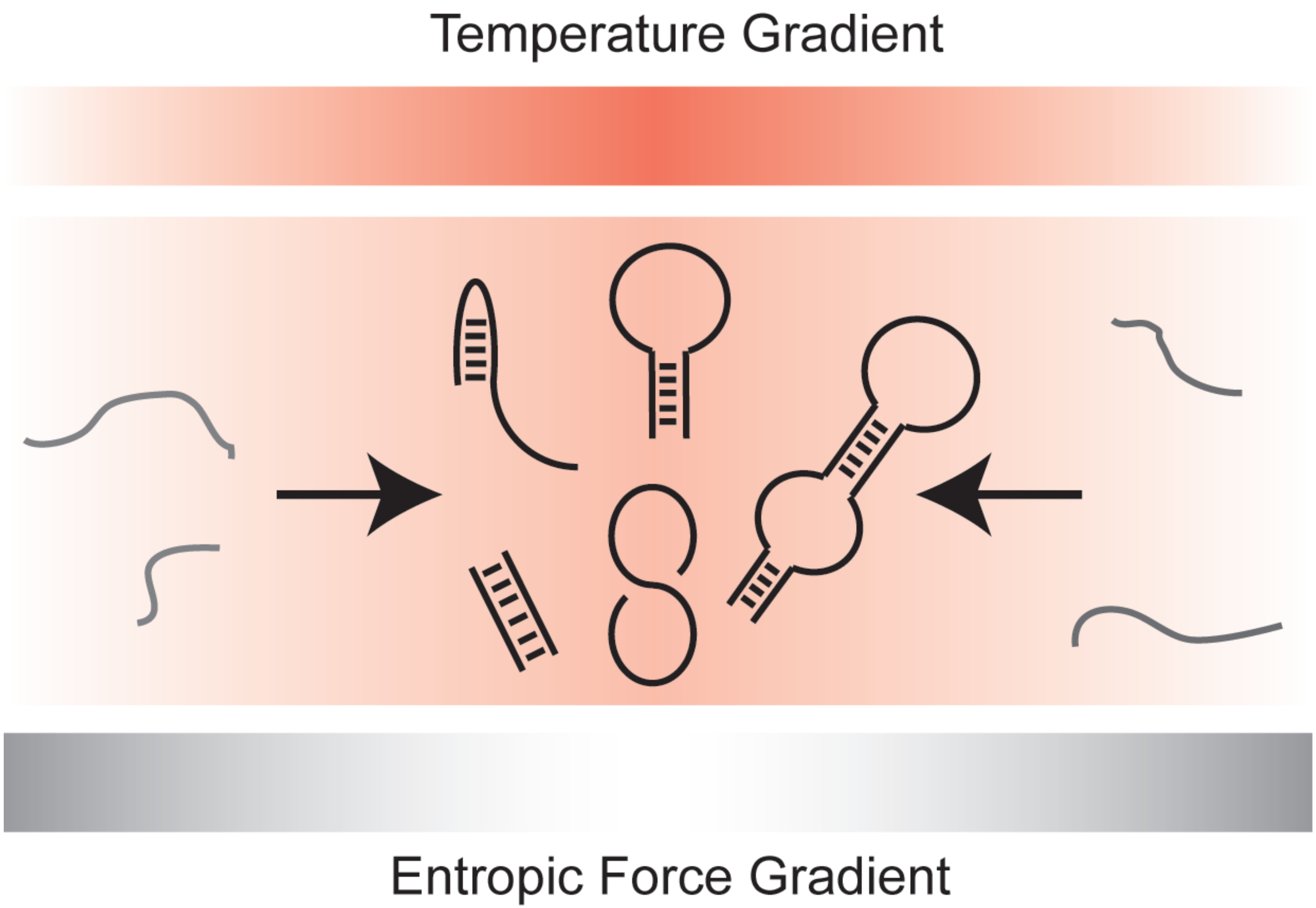
Folding dependent trapping of small RNA



- Stem DNA/RNA, RNA enzyme that has stem longer than 6-bp: **Accumulation**
- ssDNA/ssRNA up to 120 nt: **Depletion**

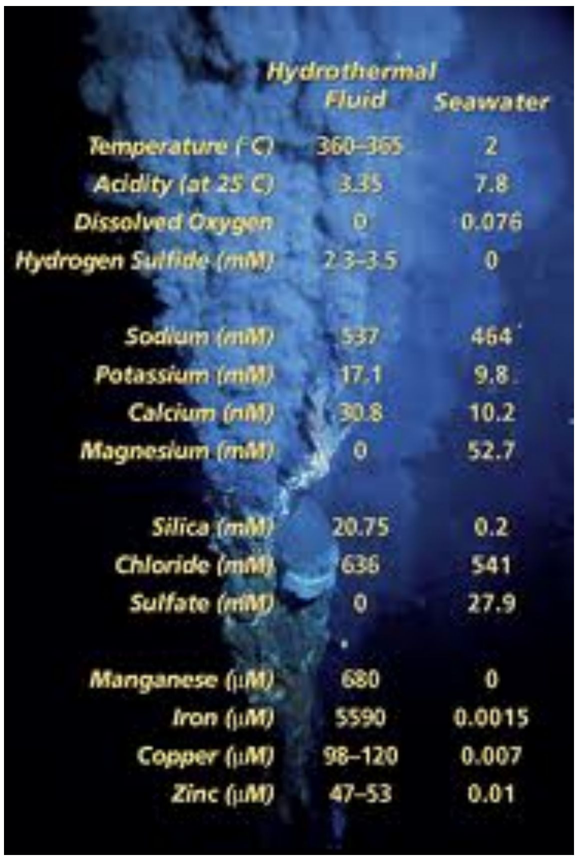
Scale bar 35 µm

YT Maeda, T Tlusty, A Libchaber
Proc Natl Acad Sci USA **109:** 17972 (2012)
CJ Wienken, P Baaske, S Duhr, D Braun
Nucleic Acid Research **39**, e52 (2011)

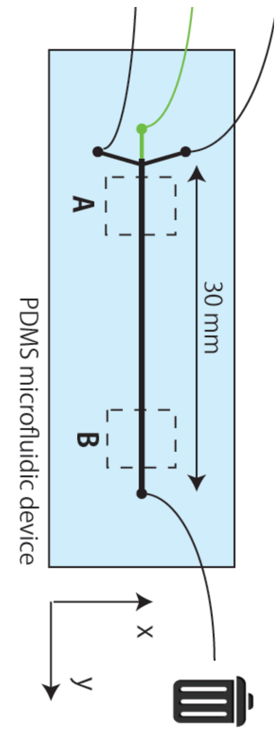

Temperature Gradient
Entropic Force Gradient

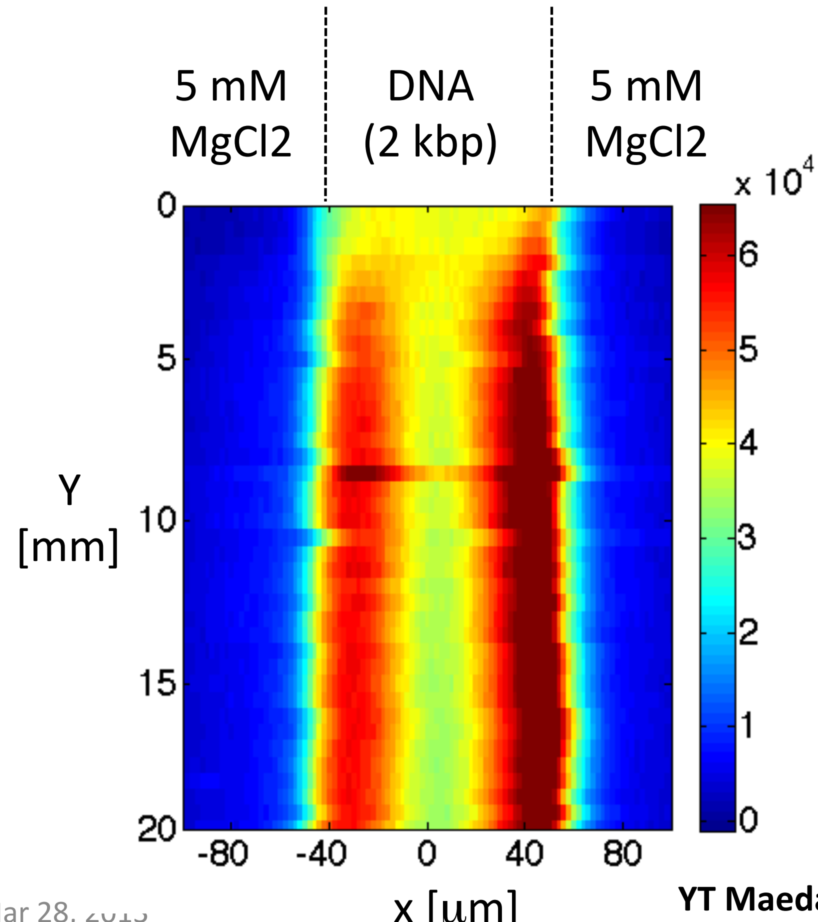
- One may criticize PEG is artificial.

- Most abundant solute in nature is ions.
- Ions, e.g. Mg, can do as well as PEG.



	Hydrothermal Fluid	Seawater
Temperature (°C)	360–365	2
Acidity (at 25°C)	3.35	7.8
Dissolved Oxygen	0	0.076
Hydrogen Sulfide (mM)	2.3–3.5	0
Sodium (mM)	537	464
Potassium (mM)	17.1	9.8
Calcium (nM)	30.8	10.2
Magnesium (mM)	0	52.7
Silica (mM)	20.75	0.2
Chloride (mM)	636	541
Sulfate (mM)	0	27.9
Manganese (μM)	680	0
Iron (μM)	5590	0.0015
Copper (μM)	98–120	0.007
Zinc (μM)	47–53	0.01





YT Maeda, unpublished

The Soret effect and isotope fractionation

JUNE 1, 1939 PHYSICAL REVIEW VOLUME 55

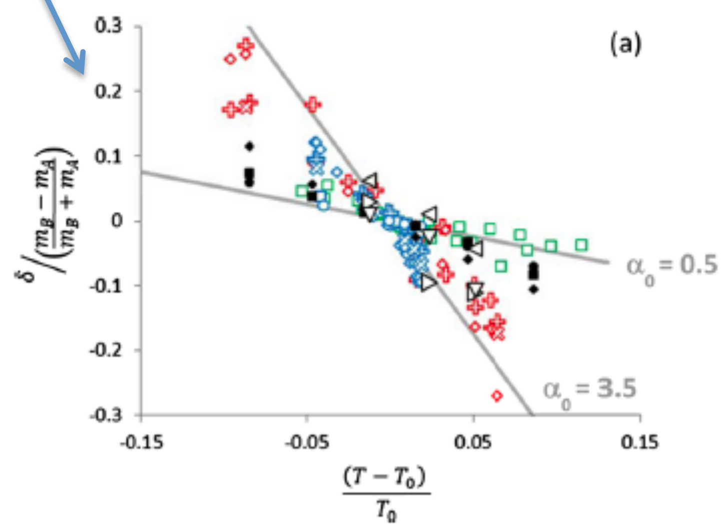
On the Theory of Isotope Separation by Thermal Diffusion

W. H. FURRY, R. CLARK JONES, *Research Laboratory of Physics, Harvard University, Cambridge, Massachusetts*
AND
L. ONSAGER, *Department of Chemistry, Yale University, New Haven, Connecticut*
(Received April 6, 1939)

- The Soret effect was studied for isotope separation.
- Recent studies show isotope fractionation through the Soret effect in silica melts.

DJ Lacks, et al.
Phys Rev Lett **108:** 065901 (2012)
F Huang, et al.
Nature **464**: 396 (2010)

Non-zero means isotope separation



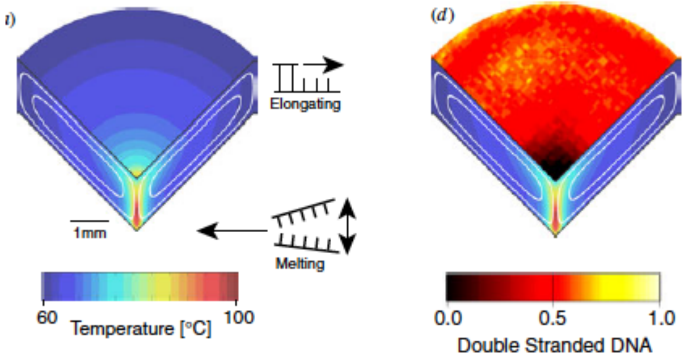
Non-equilibrium transport could be related to both the earth and life.

Summary and future problems

- DNA/RNA as a solute moves along a temperature gradient. It is called Soret effect.
- Non equilibrium process, the Soret effect, leads accumulation and separation of DNA/RNA.
- Accumulation and selection of RNA enzymes may accelerate the birth of RNA world.

Future challenges in the origin of life out of equilibrium

- Evolution and natural selection through non-equilibrium process
- Replications of DNA and RNA far from equilibrium
- Origin of genetic code



DNA replication under convection
D Braun, N Goddard, A Libchaber
Phys Rev Lett **91:** 158103 (2003)

- Albert Libchaber (Rockefeller)
- Axel Buguin (Curie Institute)
- Tsvi Tlusty (Weizmann Institute)
- Jack Merrin (Rockefeller)
- Pradeep Kumar (Rockefeller)
- Hanna Salman (Pittsburgh)
- Alex Grosberg (NYU)
- Vincent Noireaux (Minnesota)
- Yuta Shimamoto (Rockefeller)
- Tarun M Kapoor (Rockefeller)
- Masaki Sano (Tokyo)
- Hirofumi Wada (Ritsumeikan)
- Natsuhiko Yoshinaga (Tohoku)
- Hong-ren Jiang (Tokyo, NUT)

NSF

The Rockefeller University 1901

さきがけ PRESTO

Hakubi 白眉

公益財団法人 上原記念生命科学財団 THE UEHARA MEMORIAL FOUNDATION