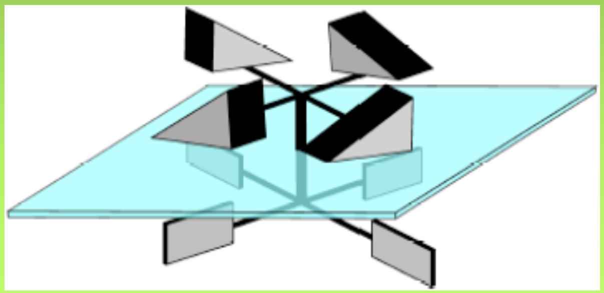
From Maxwell demon to Brownian refrigerator



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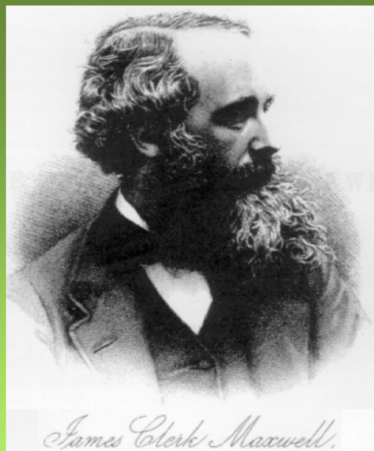
Maxwell demon



Maxwell

Theory of Heat 1871

Smoluchowski

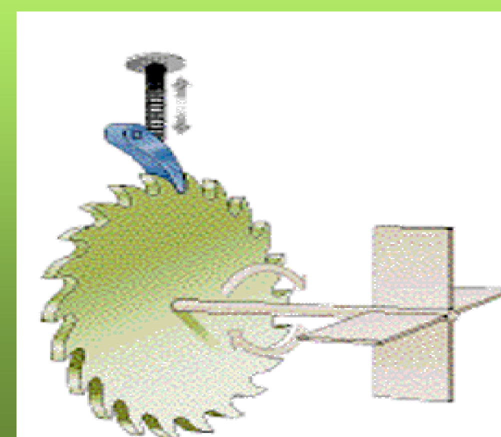
Munster 1912

es mit einem kleinen, einseitig wirkenden Ventil

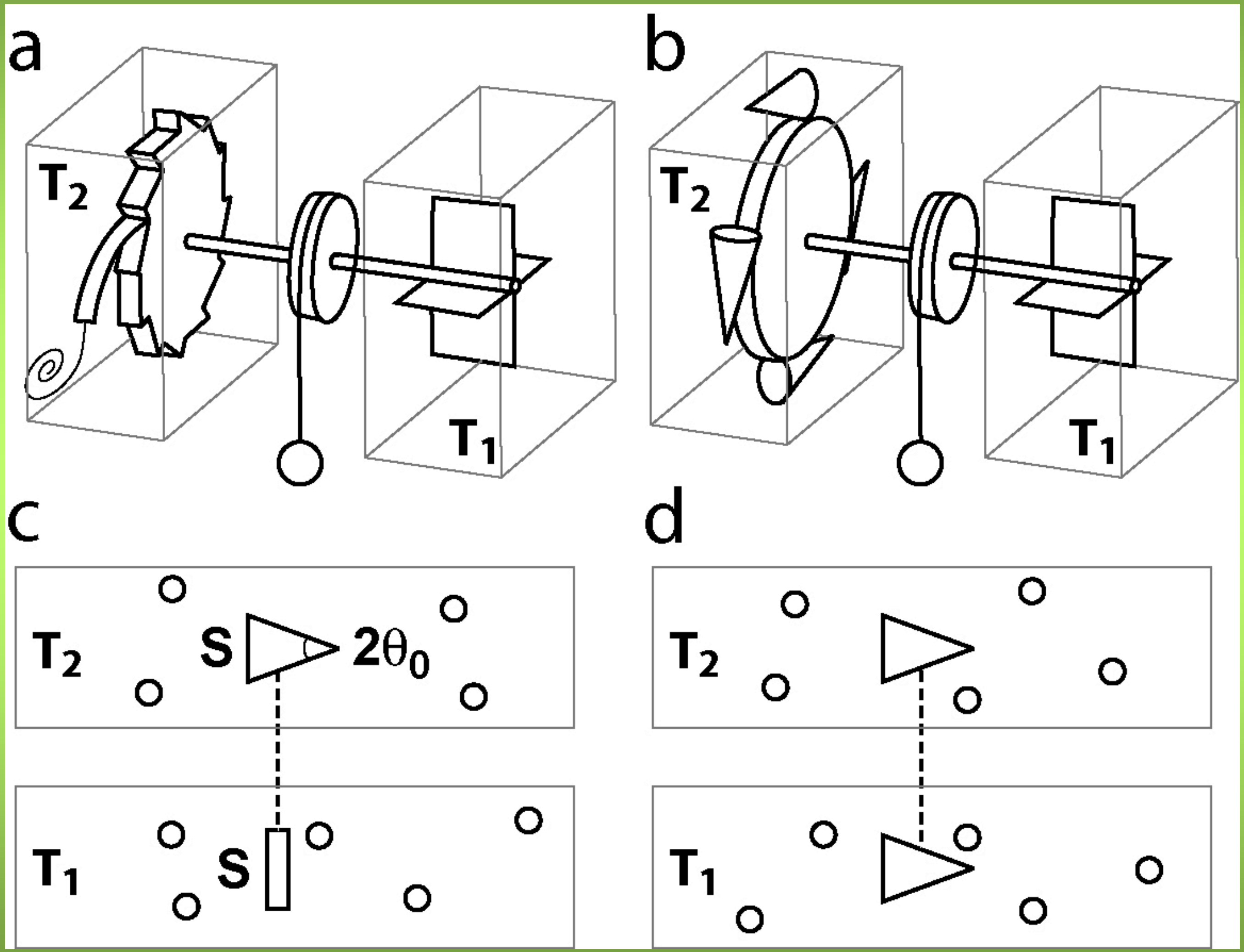
ein Zahnrad mit einer Sperrklinke

Feynman

Caltech 1961



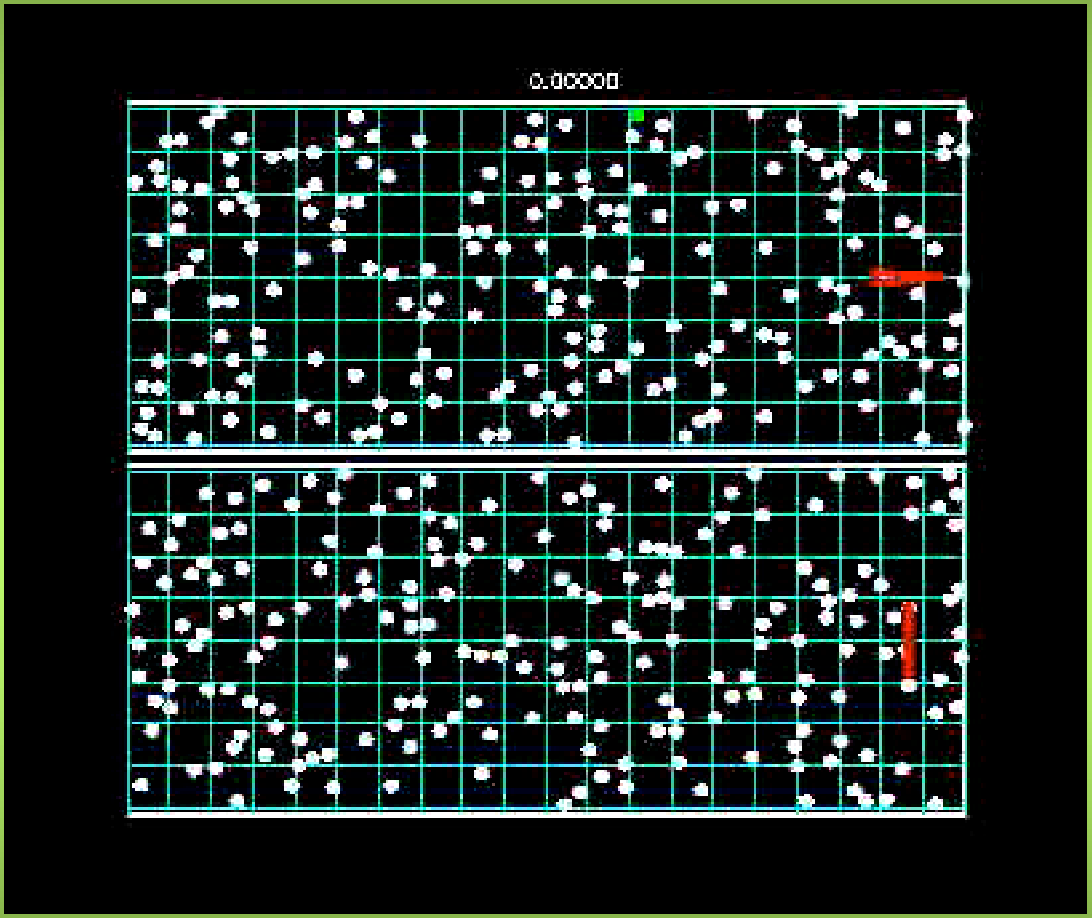
Simplified Feynman Smoluchowski ratchet



Triangulita

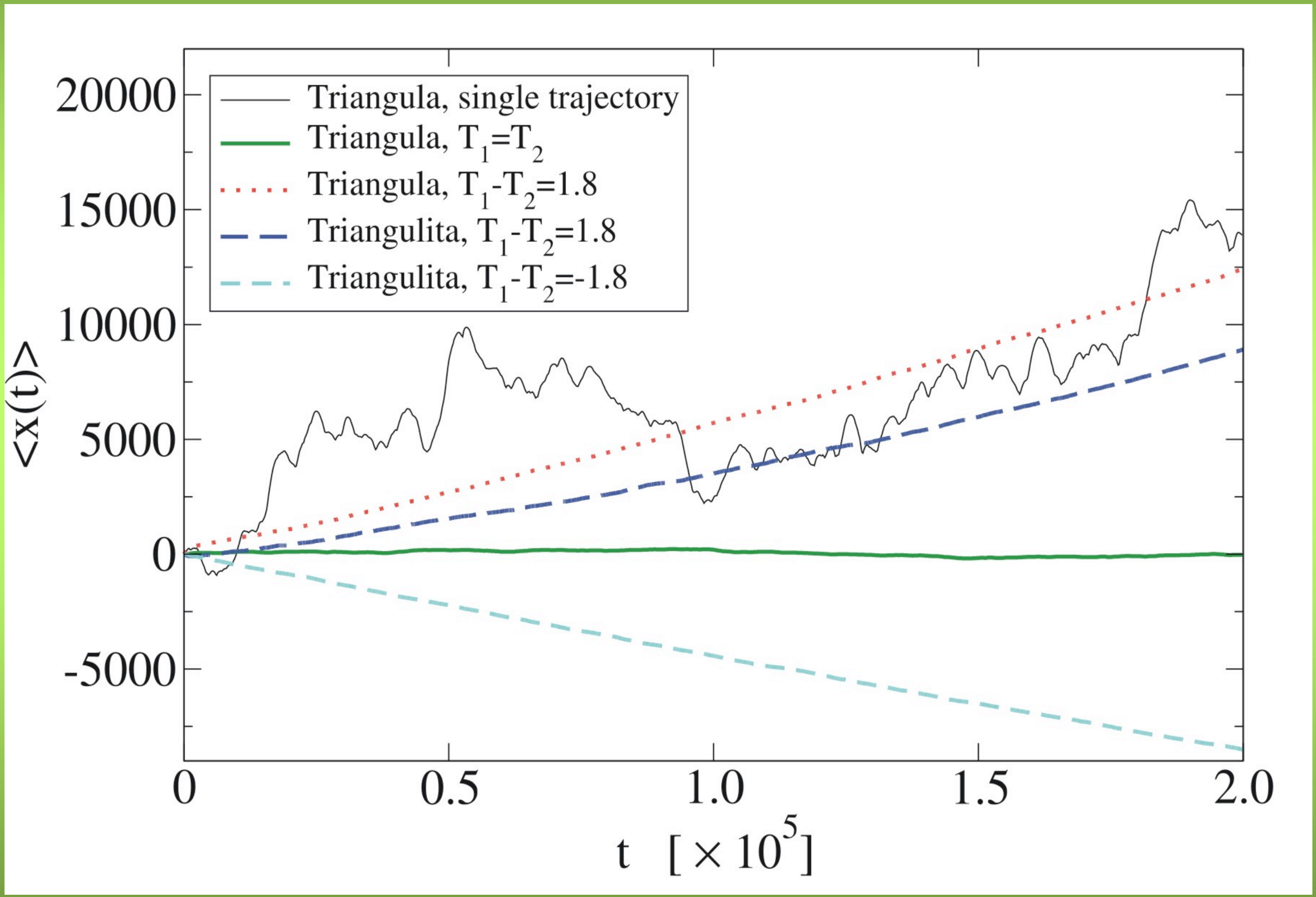
Triangula

Triangulita molecular dynamics



Triangula and Triangulita

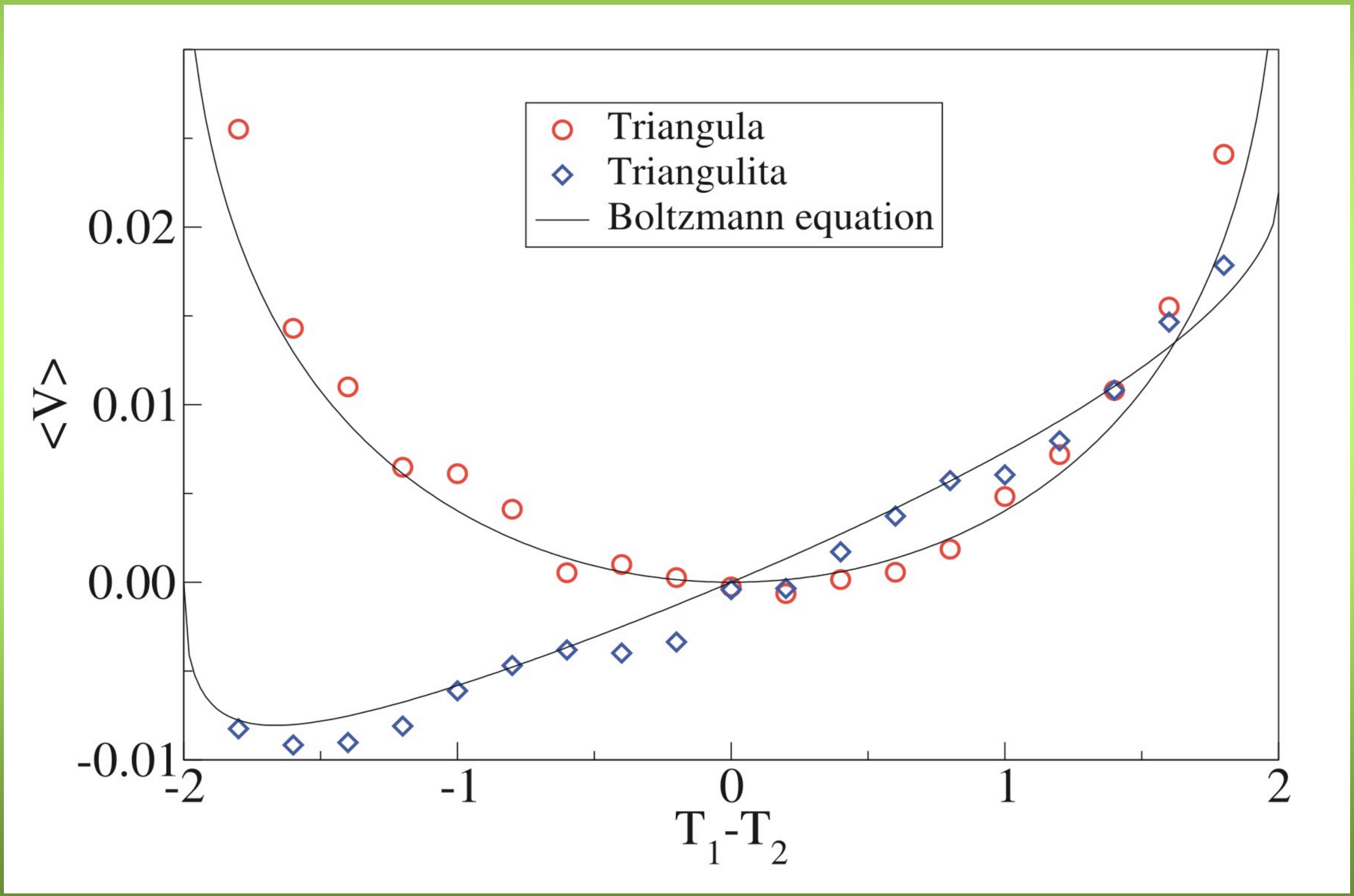
T_1=T_2 unbiased Brownian motion



$T_1 \neq T_2$ biased Brownian motion : Brownian motor

Theory: Boltmann-Master equation

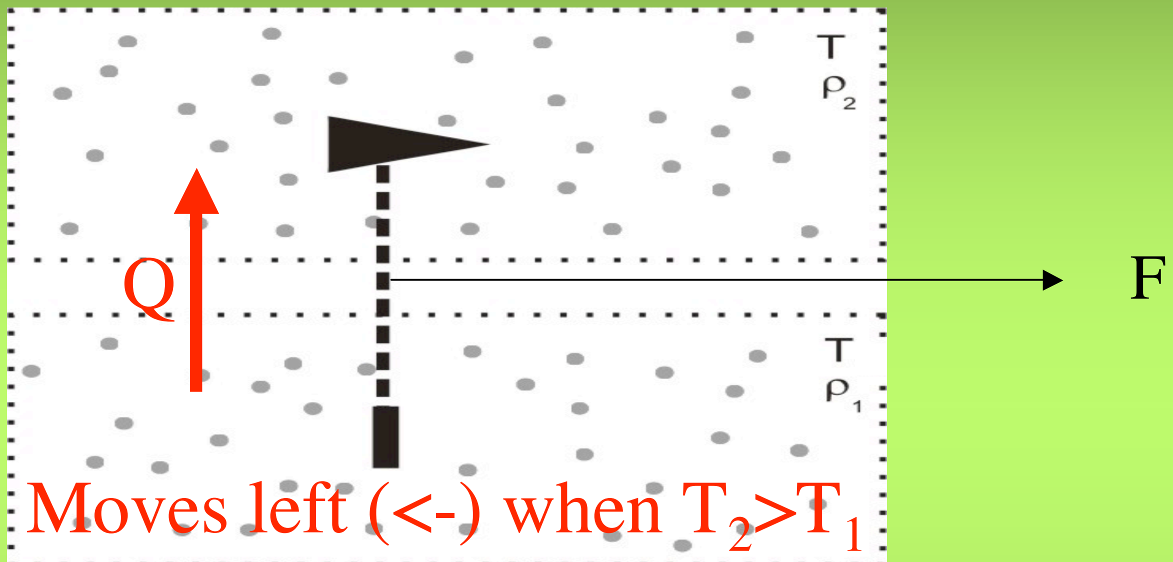
Numerical experiment: molecular dynamics



Brownian refrigerator ?!

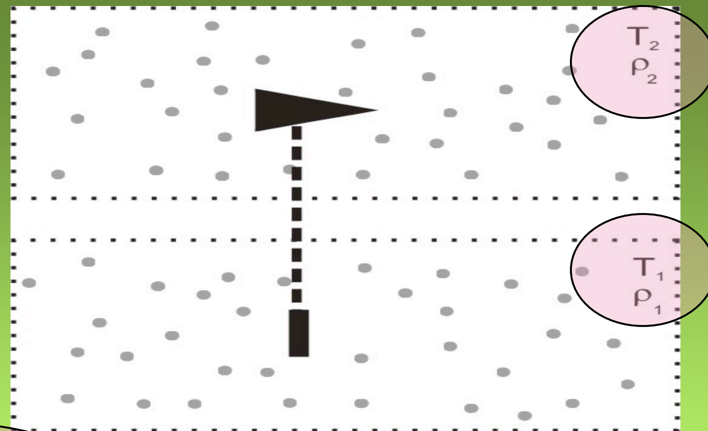
Equilibrium
$T_1=T_2=T$

Apply force F
Effect?



Le Chatelier: an action on a system at equilibrium induces processes that attenuate or counteract the original perturbation.

Implication Q ~ F !



T-gradient -> particle motion

thermodynamic force -> flux

$X_2 = \Delta T / T^2$ **cross effect** $J_1 = \dot{x}$

$J_1 = L_{12} X_2$

Onsager symmetry $J_2 = L_{21} X_1$ $L_{12} = L_{21}.$

mechanical force F -> heat flux

$X_1 = F/T$ $J_2 = \dot{Q}$

Linear irreversible thermodynamics

$$J_1 = L_{11}X_1 + L_{12}X_2$$
$$J_2 = L_{21}X_1 + L_{22}X_2.$$

T-gradient –> particle flux

$X_2 = \Delta T/T^2$ $\quad J_1 = \dot{x}.$

Since $L_{12} = L_{21}.$

Force –> heat flux

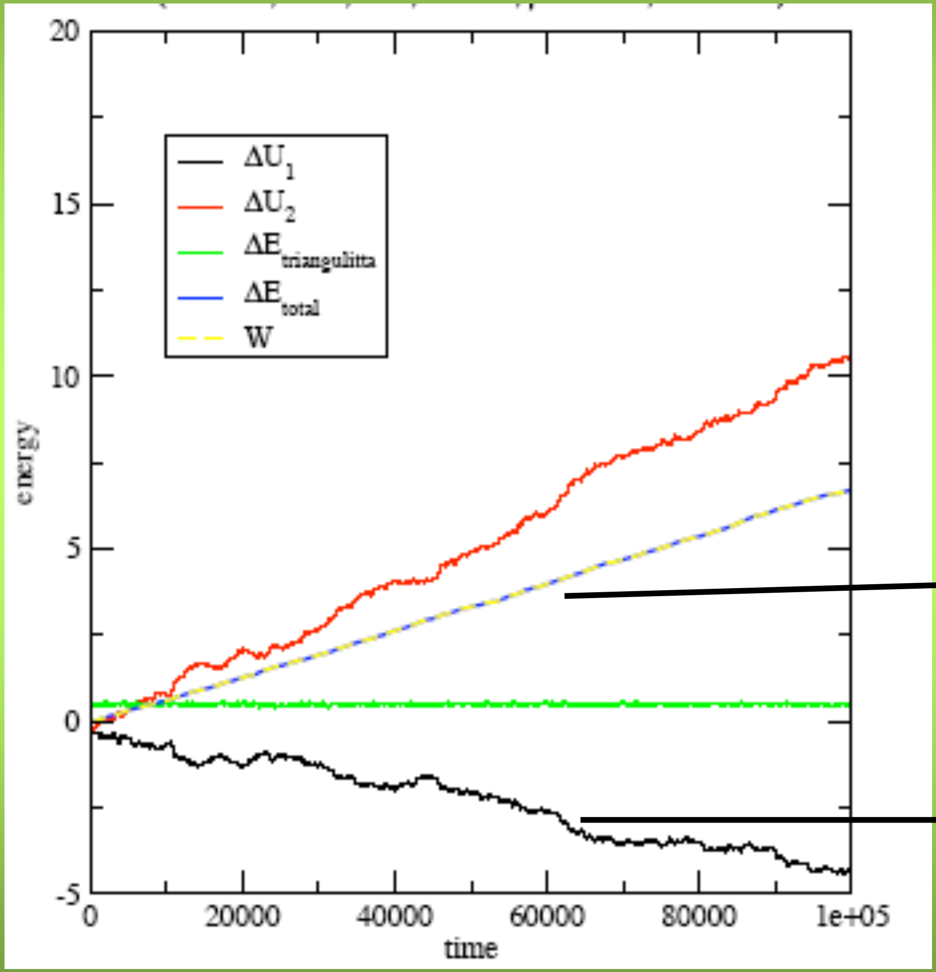
$X_1 = F/T$ $\quad J_2 = \dot{Q}.$

$$\langle V\rangle_{\text{Triangulita}} = \rho_1\rho_2(1-\sin^2\theta_0)\frac{\sqrt{2\pi k_B m}}{2M} \times \frac{(T_1-T_2)\sqrt{T_1}}{[2\rho_1\sqrt{T_1}+\rho_2\sqrt{T_2}(1+\sin\theta_0)]^2}$$

$$L_{12} = \rho_1\rho_2(1-\sin^2\theta_0)\left(\frac{m}{M}\right)\sqrt{\frac{\pi k_B}{2m}} \times \frac{T^{3/2}}{[2\rho_1+\rho_2(1+\sin\theta_0)]^2}.$$

$$\dot{Q}_{1\to 2} = \rho_1\rho_2(1-\sin^2\theta_0)\left(\frac{m}{M}\right)\sqrt{\frac{\pi k_B T}{2m}} \times \frac{F}{[2\rho_1+\rho_2(1+\sin\theta_0)]^2}.$$

Application external force F (X_1 = F/T)?



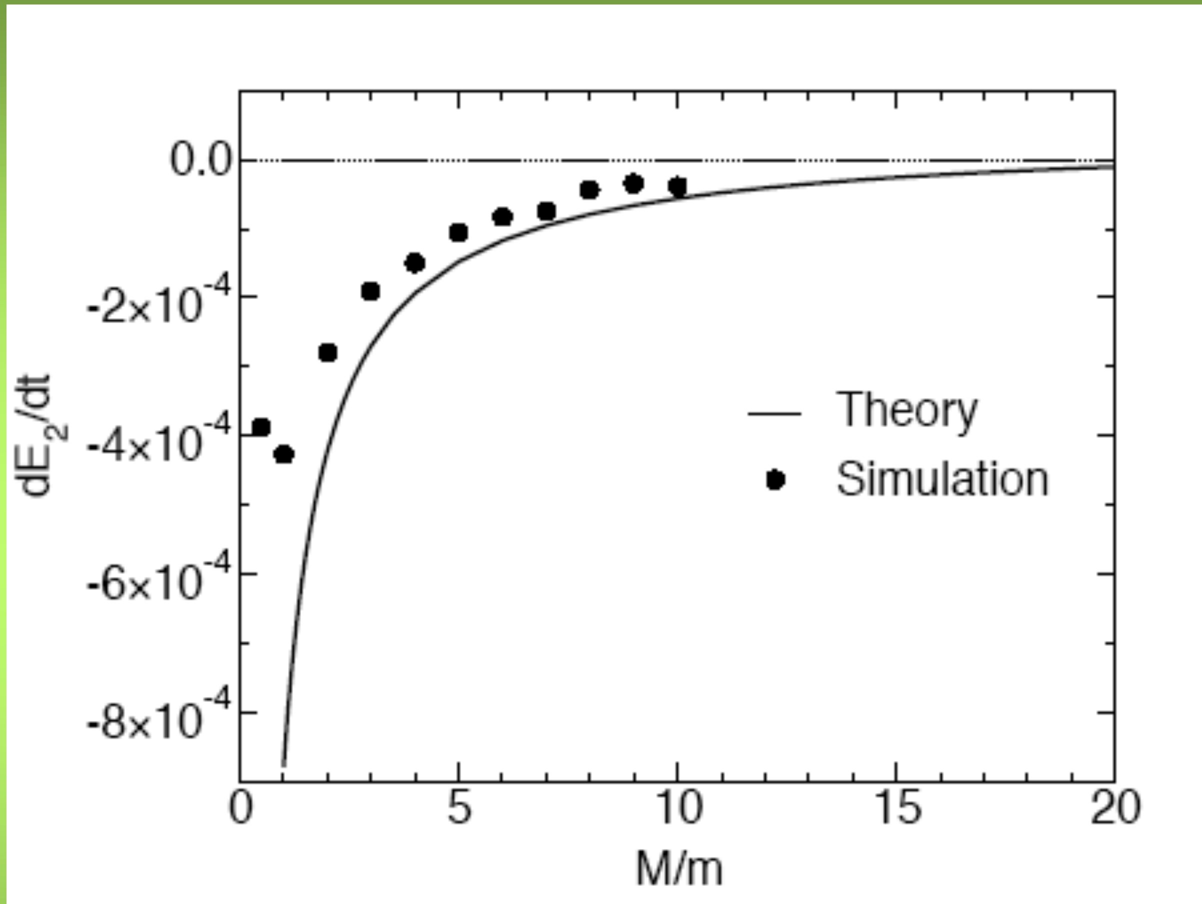
particle motion

$$J_1 = L_{11}X_1 + \cancel{L_{12}X_2}$$
$$J_2 = L_{21}X_1 + \cancel{L_{22}X_2}.$$

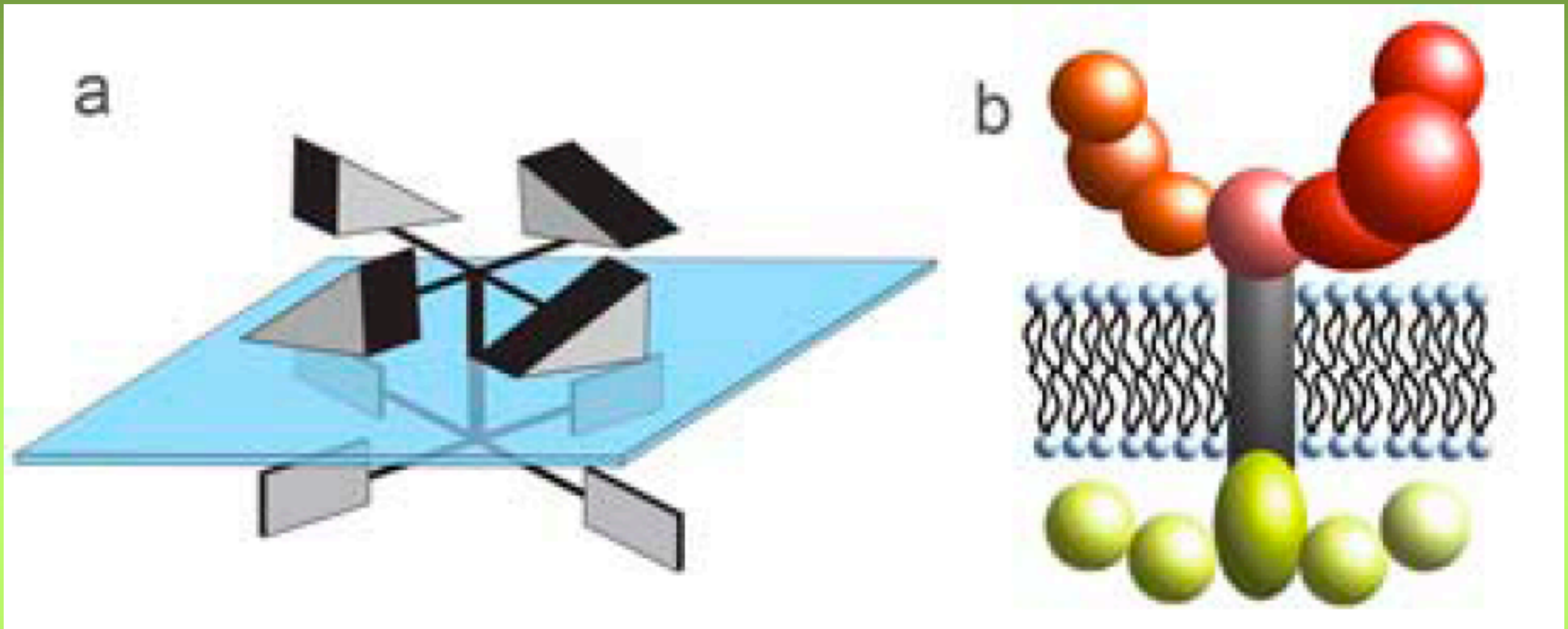
heat flow

Joule heating
$F J_1 \sim F^2$

Cooling flux
$\dot{Q} = J_2 \sim F$



0.0
-2x10^-4
-4x10^-4
-6x10^-4
-8x10^-4
dE2/dt
0
5
10
15
20
M/m
Theory
Simulation



physiological condition T ~300 K M ~ 10^5m F~0.1 pN

$\dot{Q}$ ~ 5 10^{-17} J/sec

aqueous reservoir of 0.1 μm diameter: cooling of 1 K/min

DISCUSSION

Feynman-Smoluchowski ratchet is unnecessarily complicated
Fully microscopic mechanical model

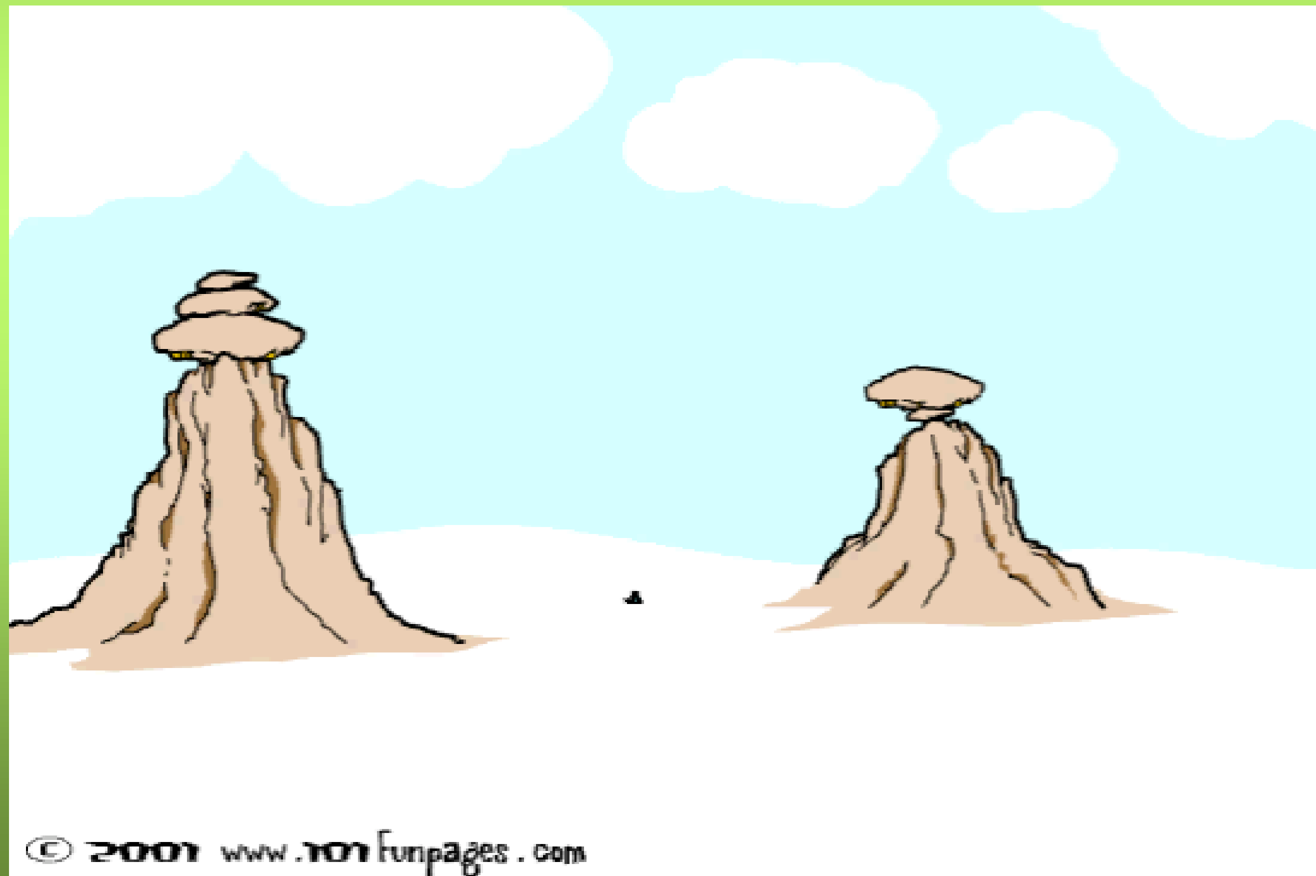
Hard disk molecular dynamics: only round-off error
Theory: perturbation in m/M, but exact, no adjustable parameters

$T_1=T_2$: no Maxwell demon
$T_1 \neq T_2$: Brownian motor ~ speed of sound * sqrt{m/M}

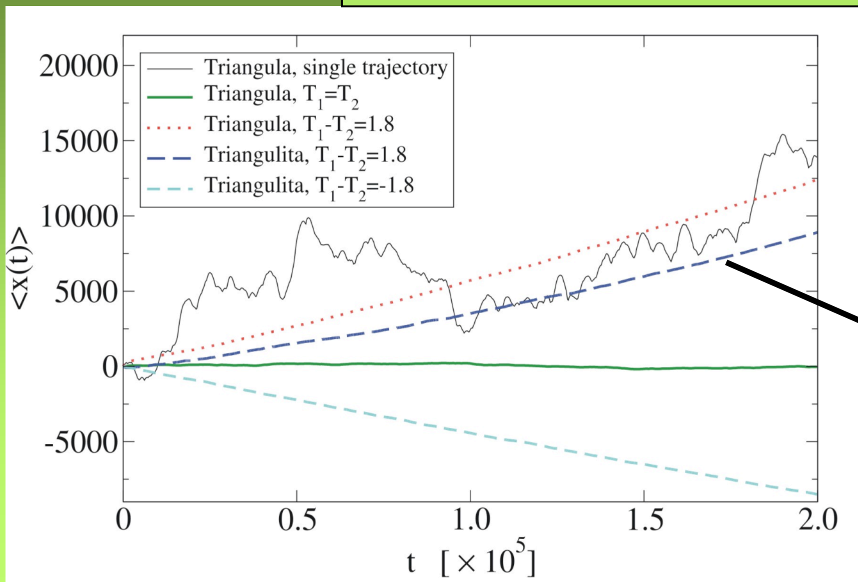
Onsager symmetry: from motor to refrigerator
Heat flux ~ power input * sqrt{m/M}
Dominates for small applied force (torque)

Carnot efficiency: yes in principle

C. Van den Broeck, R. Kawai and P. Meurs, Phys Rev Lett **93**, 090601 (2004)
P. Meurs, C. Van den Broeck and A, Garcia, Phys Rev **E70**, 051109 (2004)
C. Van den Broeck, P. Meurs and R. Kawai, New J Phys **7**, 10 (2005)
C. Van den Broeck, Phys Rev Lett **95**, 190602 (2005)
C. Van den Broeck and R. Kawai, Brownian refrigerator, Phys Rev Lett (2006)



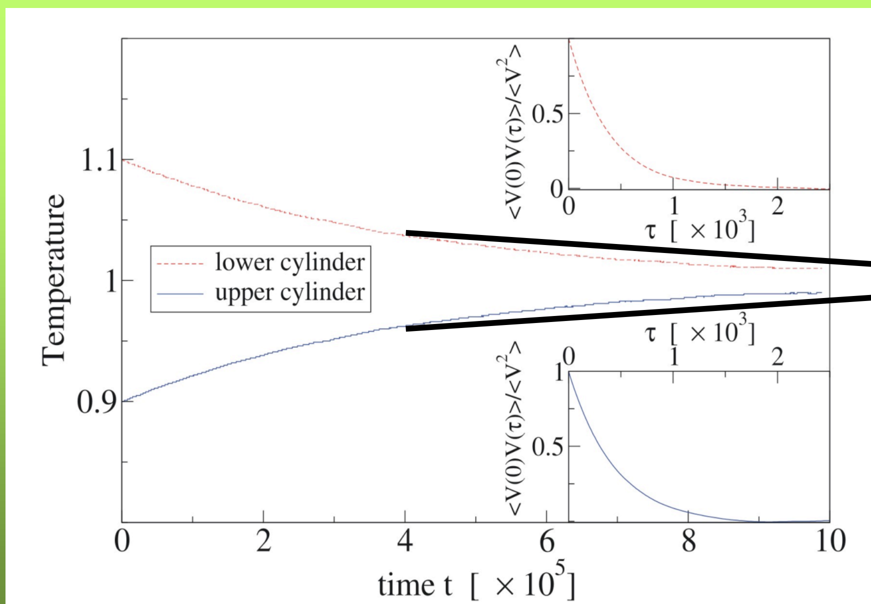
$\Delta T = T_2 - T_1$ external force F=0



$$J_1 = \cancel{L_{11}X_1} + L_{12}X_2$$
$$J_2 = \cancel{L_{21}X_1} + L_{22}X_2.$$

$$\langle V \rangle_{\text{Triangula}} = \rho_1\rho_2(1-\sin\theta_0)\frac{\sqrt{2\pi k_B m}}{4M}\frac{(T_1-T_2)(\sqrt{T_1}-\sqrt{T_2})}{[\rho_1\sqrt{T_1}+\rho_2\sqrt{T_2}]^2}.$$

$\dot{x} =$



$$\dot{Q}_{1\to 2} = \kappa\,(T_1 - T_2)$$