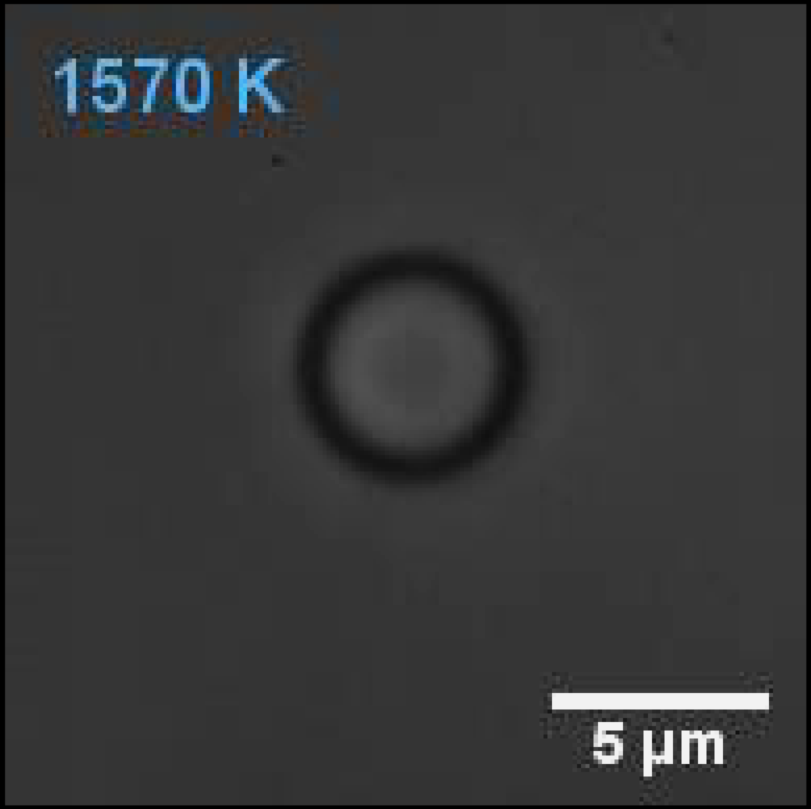
Tuning the performance of a micrometer-sized Stirling engine through reservoir engineering



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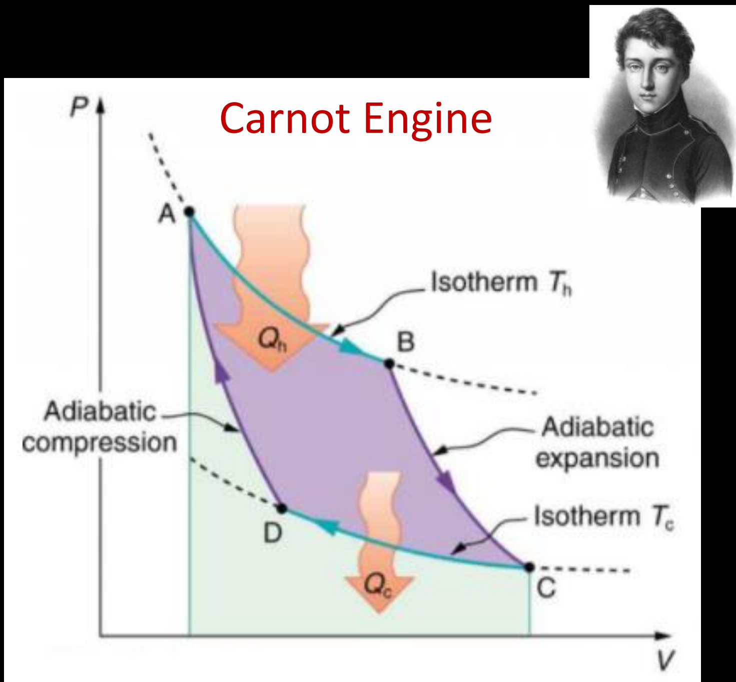
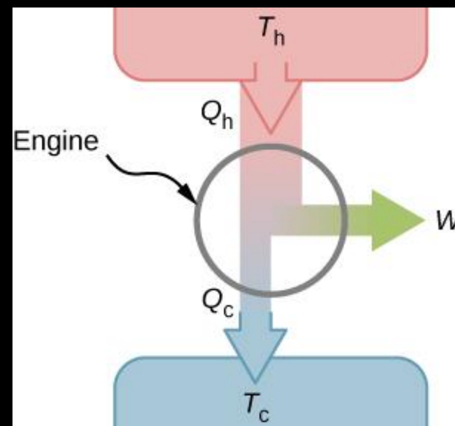
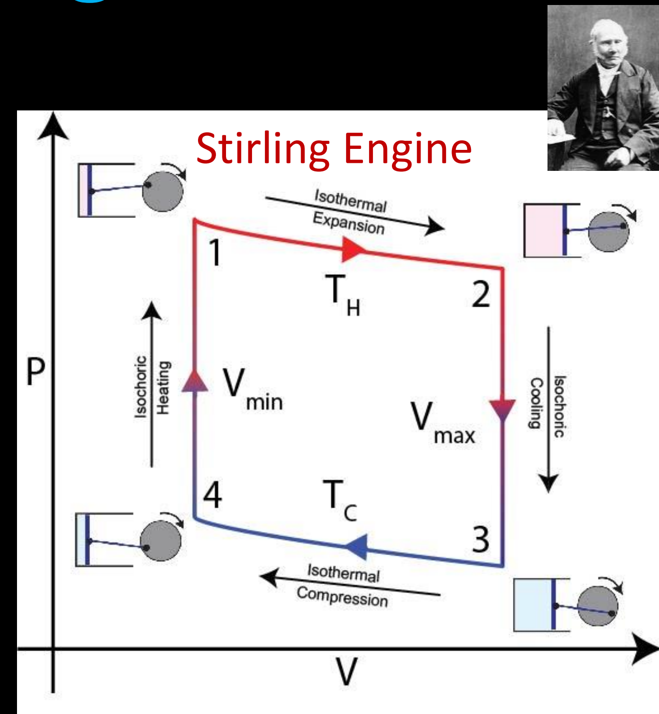
Nathan Leroux

Macroscopic heat engines







Reversible Process

$$\varepsilon_C = 1 - \frac{T_C}{T_H}$$

1st Law of thermodynamics

dQ+dW = dU

Efficiency $\varepsilon = \frac{W}{Q_H}$

$$W = nRT_C[1-\frac{T_H}{T_C}]\ln\frac{V_{max}}{V_{min}}$$

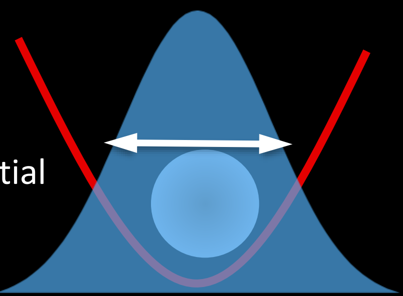
$$\varepsilon_{sat} = \varepsilon_C[1+\varepsilon_C C_V/\ln(\frac{V_{max}}{V_{min}})]$$

DOF of working fluid ~ $O(10^{23})$

What if the DOF are a few?

Conventional piston engine

Colloid in a harmonic potential



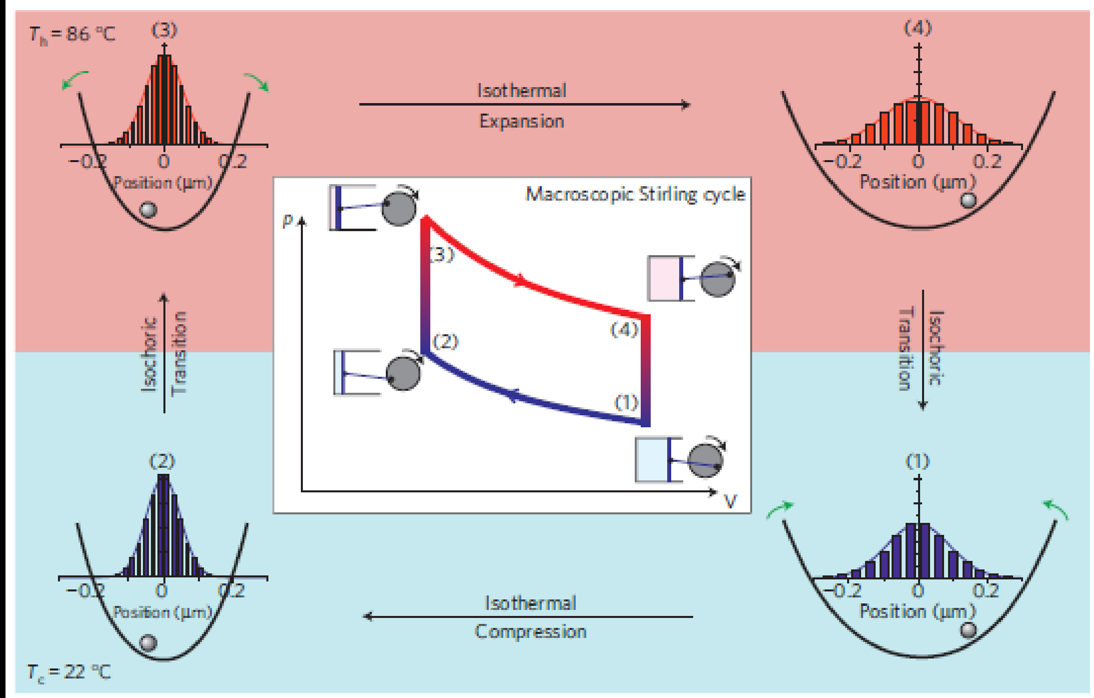
Working Gas ≡ Colloidal Particle

Piston ≡ Harmonic Potential

Pressure ≡ Position of Particle

Volume ≡ Stiffness of potential

Equipartition : $\frac{1}{2}\, k < x^2 > = \frac{1}{2}\, k_B\, T$


nature physics LETTERS
PUBLISHED ONLINE: 11 DECEMBER 2011 | DOI: 10.1038/NPHYS2163

Realization of a micrometre-sized stochastic heat engine

Valentin Blickle[1,2]* and Clemens Bechinger[1,2]

Calculation of thermodynamic quantities from a single fluctuating trajectory:

Work done

$$W_{cyc} = \int_{t_i}^{t_i+\tau} \frac{\partial U}{\partial k} \circ dk \equiv \frac{1}{2} \int_{t_i}^{t_i+\tau} x^2 \circ dk$$

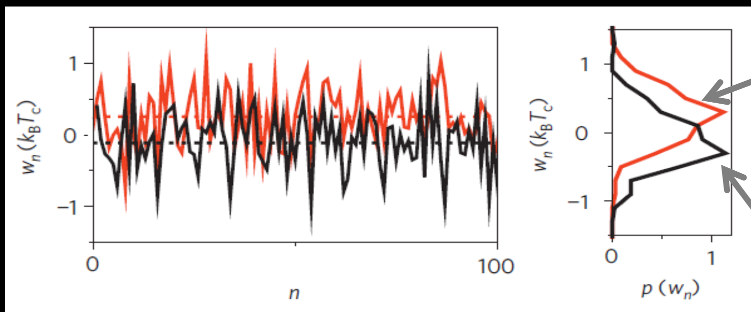
Heat

$$Q_{cyc} = \int_{t_i}^{t_i+\tau} \frac{\partial U}{\partial x}\, \dot{x}\, dt$$

Performance of mesoscale Stirling engine

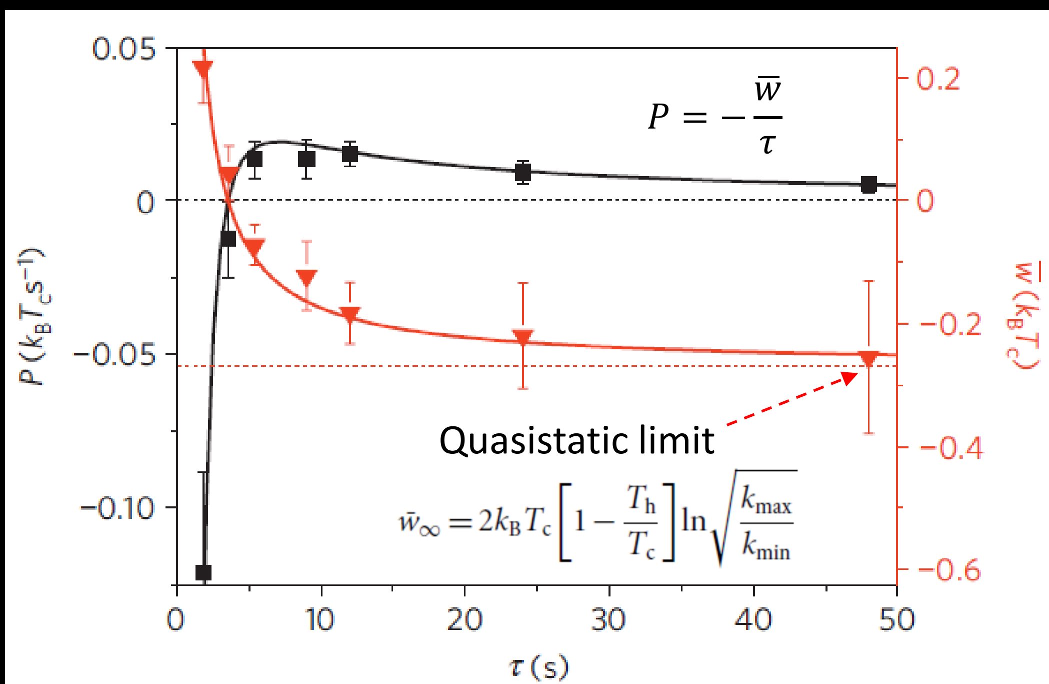
Thermodynamic quantities are not constant across cycles.

Fluctuations are comparable to mean.



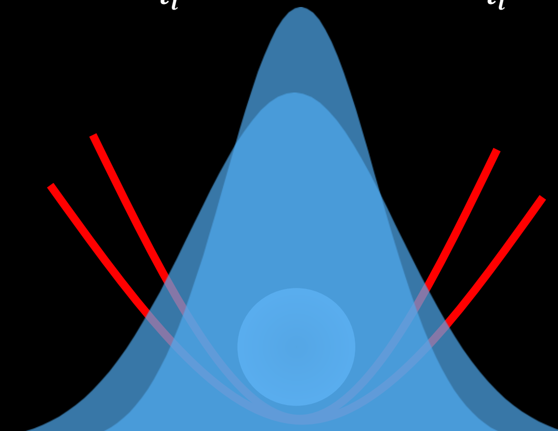
Heat Pump

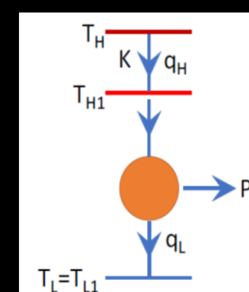
Heat Engine



BUILD-UP OF IRREVERSIBILITY

$$W_{cyc} = \int_{t_i}^{t_i+\tau} \frac{\partial U}{\partial k} \circ dk \equiv \frac{1}{2} \int_{t_i}^{t_i+\tau} x^2 \circ dk$$





Chambadal P (1957) . Armand Colin, Paris, France, 4 1-58

Novikov, I.I. (1958). *Journal of Nuclear Energy*. **7** (1–2): 125–128.

Curzon, F. L. & Ahlborn, B.. American Journal of Physics 43, 22–24 (1975)

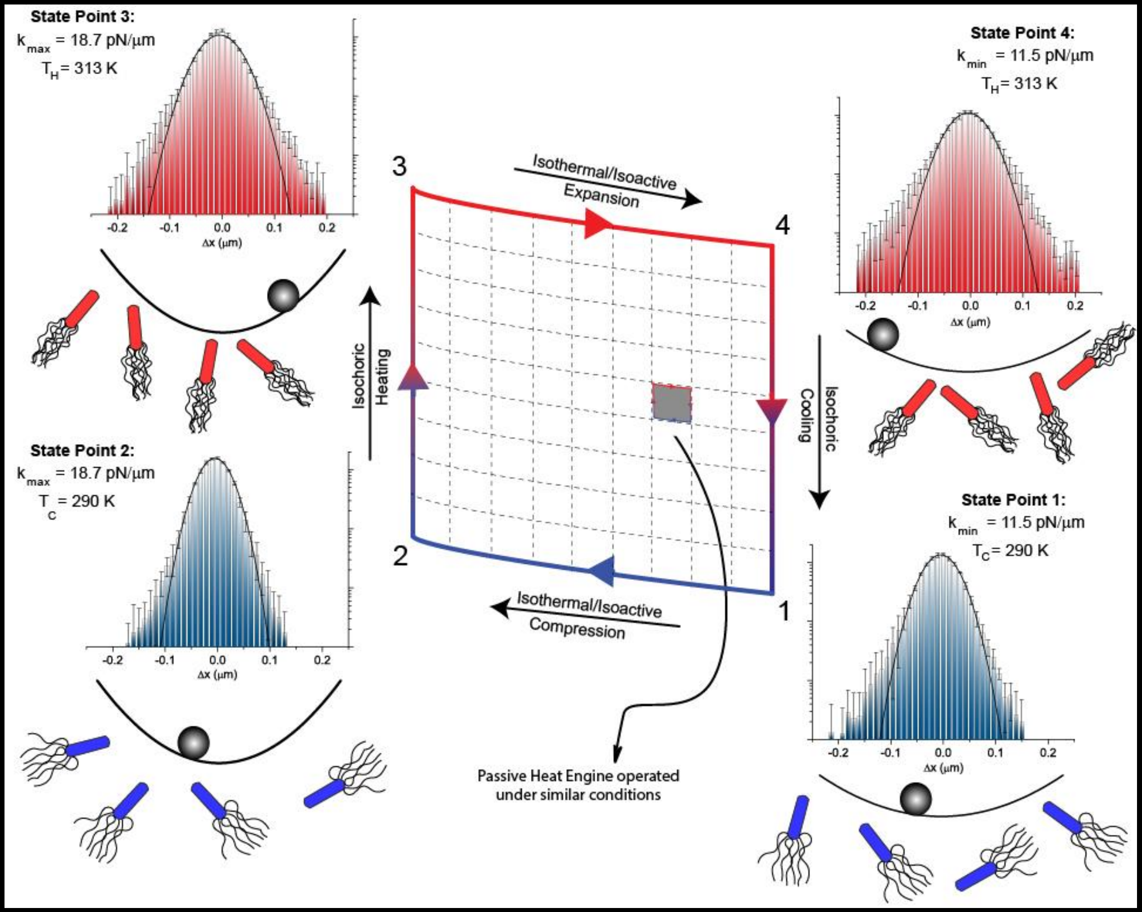
When operating between thermal baths mesoscale engines on an average perform like macroscopic ones....

What if the bath themselves are out-of-equilibrium....

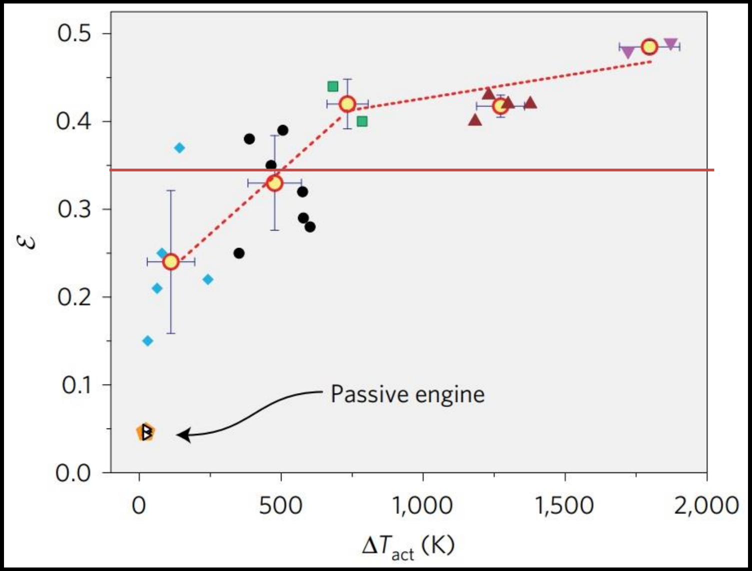
- NO MACROSCALE EQUIVALENT!

Natural micromachines have similar environments..

Superior performance of active engines



Performed work in 2 orders of magnitude higher than a thermal engine working with same ΔT



Stirling saturation efficiency:

$$\varepsilon_{sat} = \left(1 + \frac{1}{\ln\left(\frac{k_{max}}{k_{min}}\right)}\right) - 1$$

Quick take home…

LETTERS
PUBLISHED ONLINE: 29 AUGUST 2016 | DOI: 10.1038/NPHYS3870

nature physics

A micrometre-sized heat engine operating between bacterial reservoirs

Sudeesh Krishnamurthy[1], Subho Ghosh[2], Dipankar Chatterji[2], Rajesh Ganapathy[3,4] and A. K. Sood[1,3*]

Mesoscale active engines outperform passive ones due to non-Gaussian fluctuations

- Active engines only operated in the quasistatic limit

- Noise in bacterial baths both non-Gaussian and finite persistence.

Atleast in the quasistatic limit, engine operating between baths with white non-Gaussian noise should mimic passive engines.

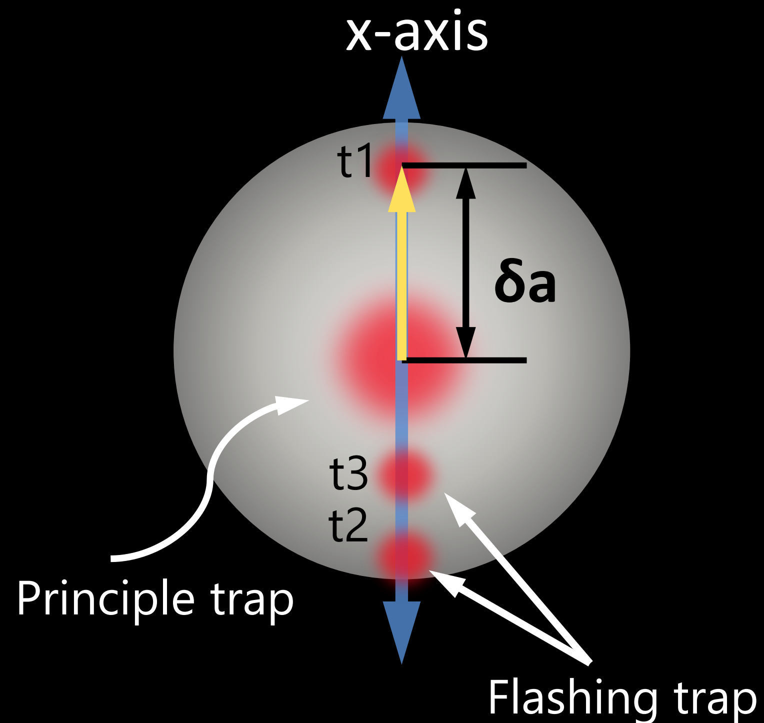
entropy MDPI

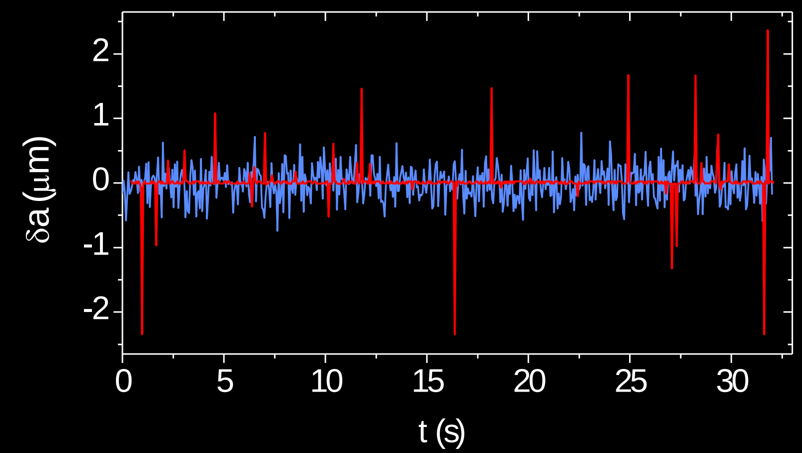
Article

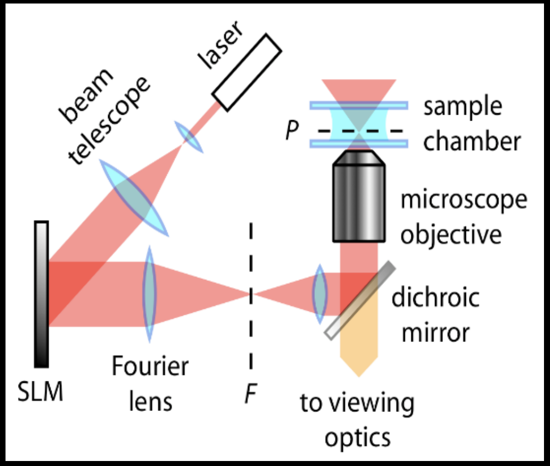
Stochastic Stirling Engine Operating in Contact with Active Baths

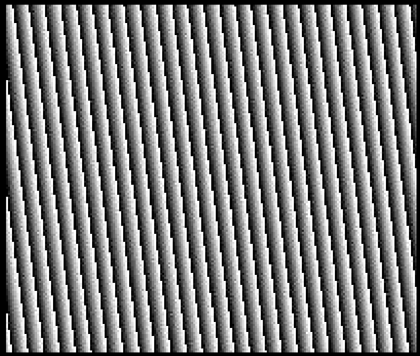
Ruben Zakine [1], Alexandre Solon [2], Todd Gingrich [2] and Frédéric van Wijland [1,*]

Engineering reservoirs

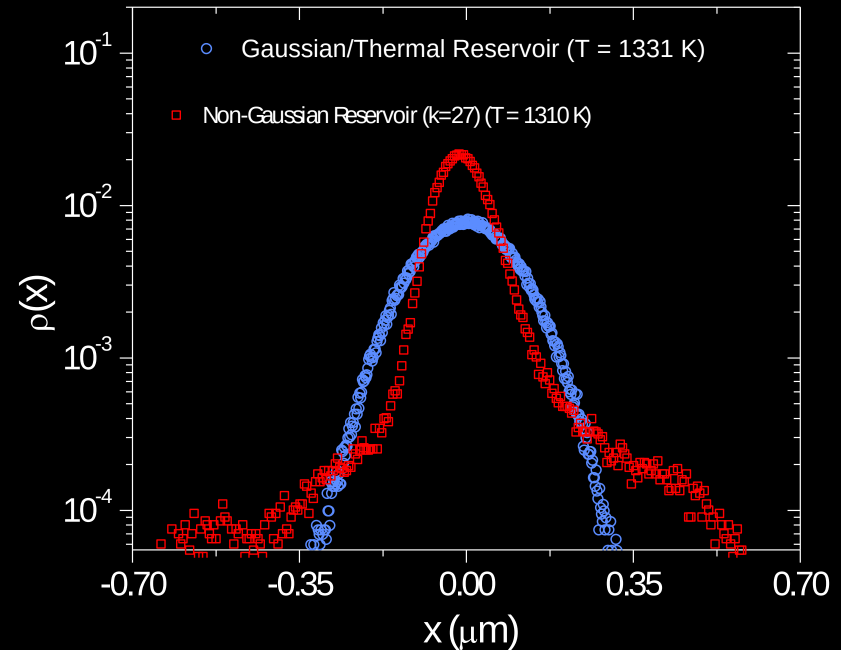






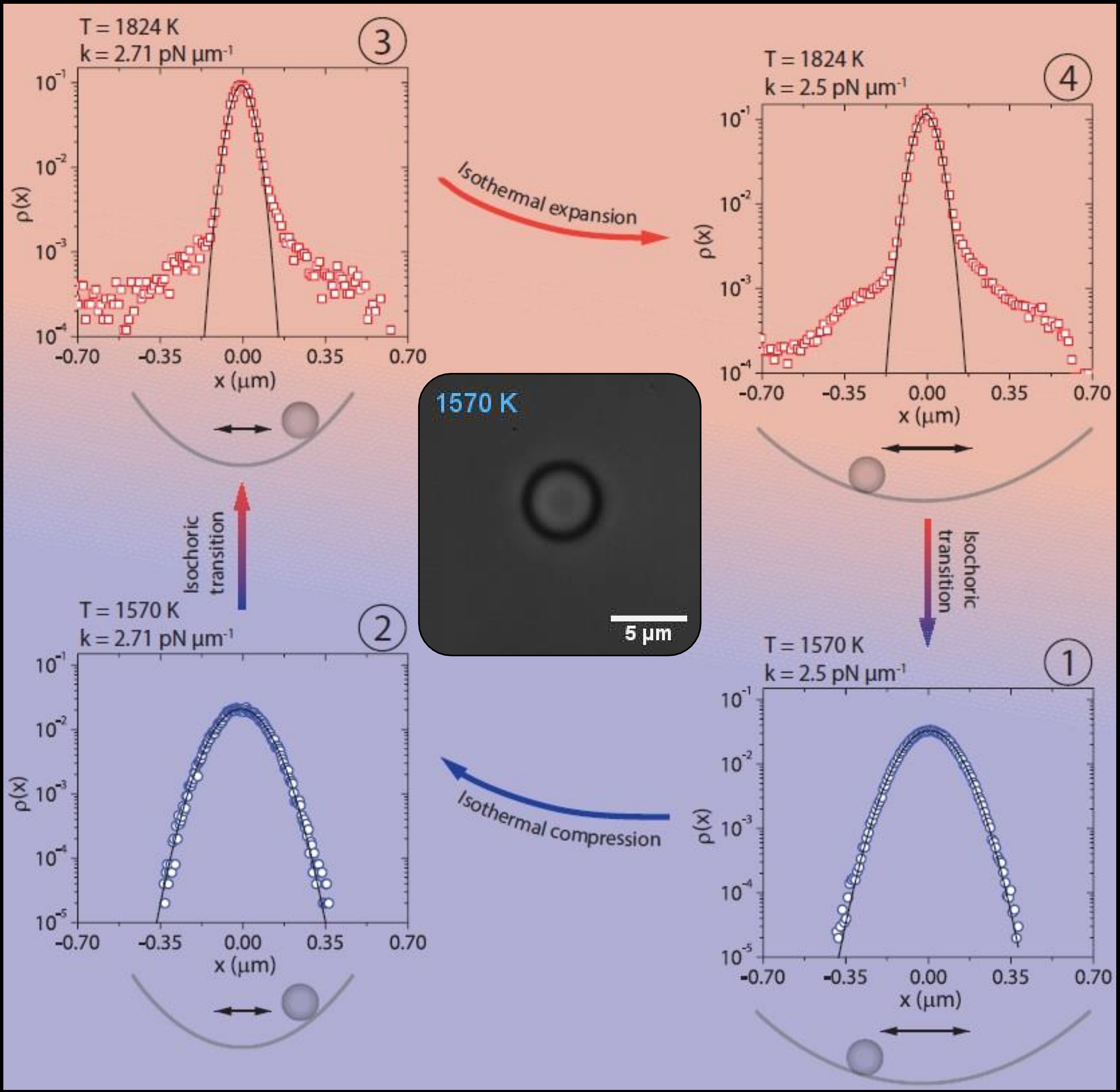


Computer-controlled phase-pattern



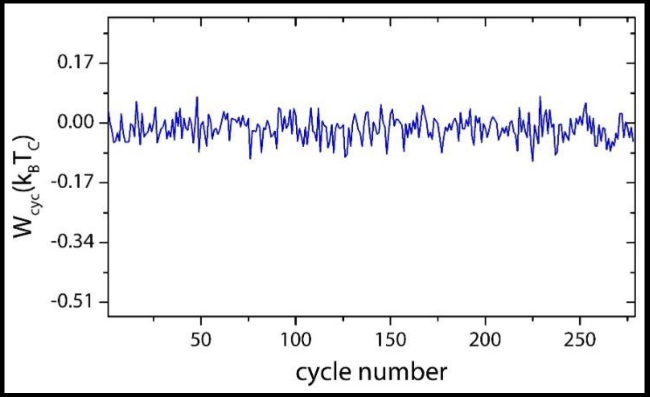
No further correlation is added.

Stirling cycle between engineered reservoirs

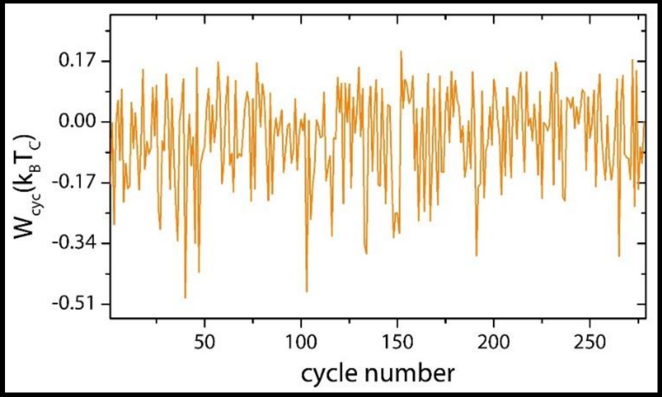


Work distributions

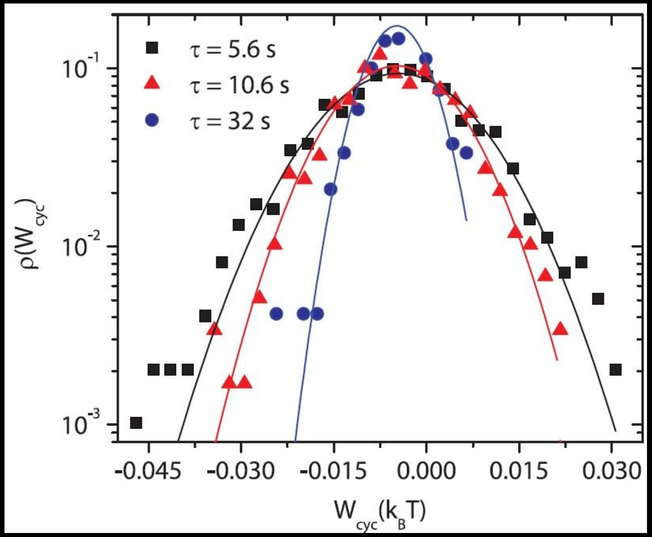
τ = 5.6s of Gaussian engine



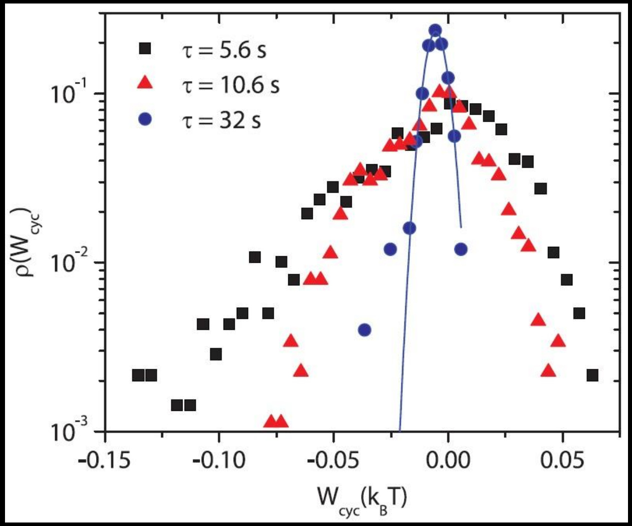
τ = 5.6s of non-Gaussian engine



Gaussian engine



Non-Gaussian engine



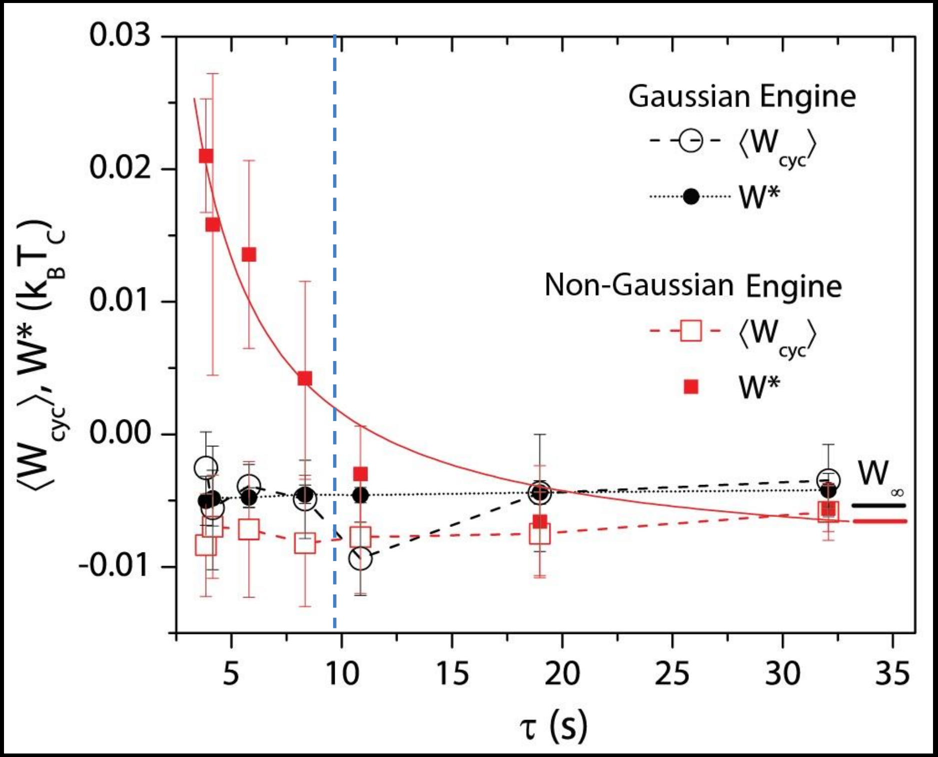
Work distributions are Gaussian

Work distributions are increasingly skewed with smaller τ

Noise induced irreversibility

W* = Most probable/mode of the distribution of Work per cycle

<W> = Average/mean of the distribution of Work per cycle



W* turns positive (stalling) below τ = 10s

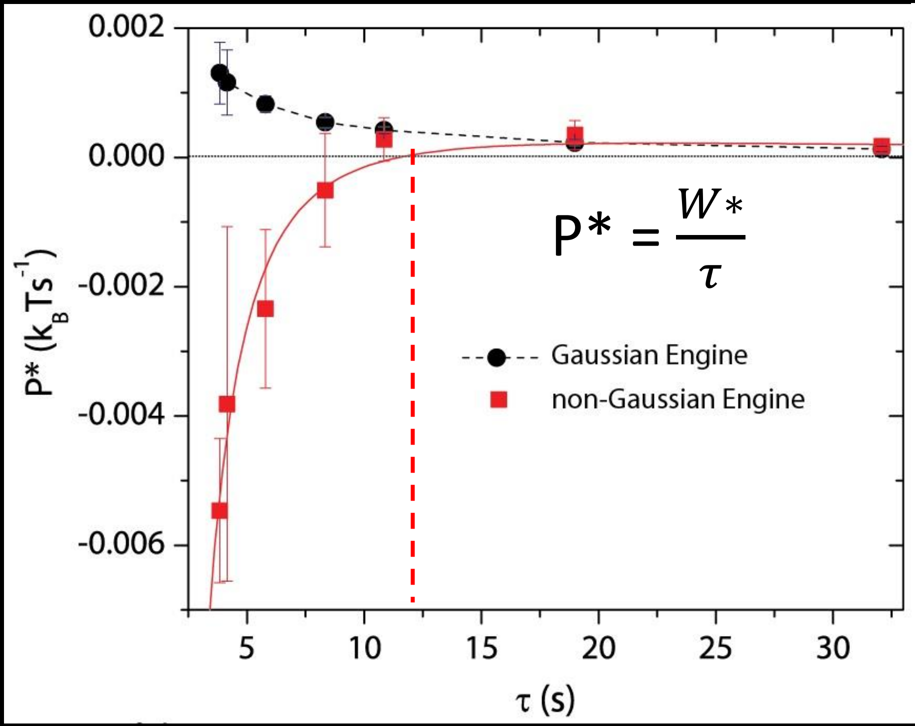
Irreversibility is entirely due to non-Gaussian statistics

$$W(\tau) = W_\infty + W_{diss} \equiv W_\infty + \frac{\Sigma}{\tau}$$

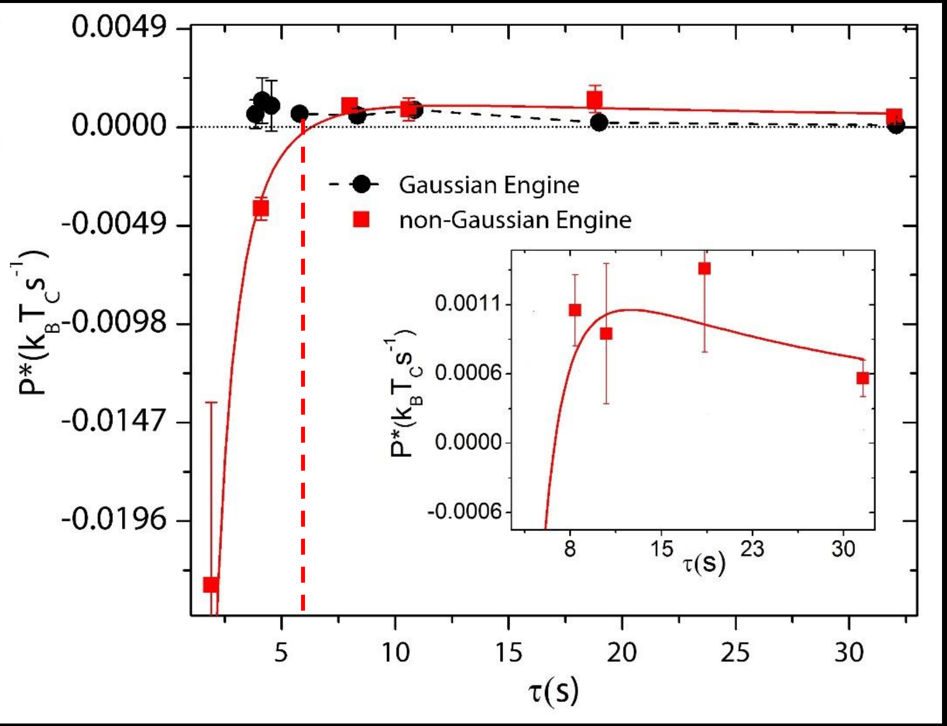
Statistics dependent

Tuning performance with non-Gaussian noise

Kurtosis/tailedness of p(x) = 20



Kurtosis/4th moment of p(x) = 10



Curzon-Ahlborn profile in non-Gaussian engine

Curzon-Ahlborn efficiency ε_{CZ}=0.026
matches ε_{max}=0.025

Noise modulates maximum power production mode without altering efficiency

Thank You

For further details:

nature COMMUNICATIONS

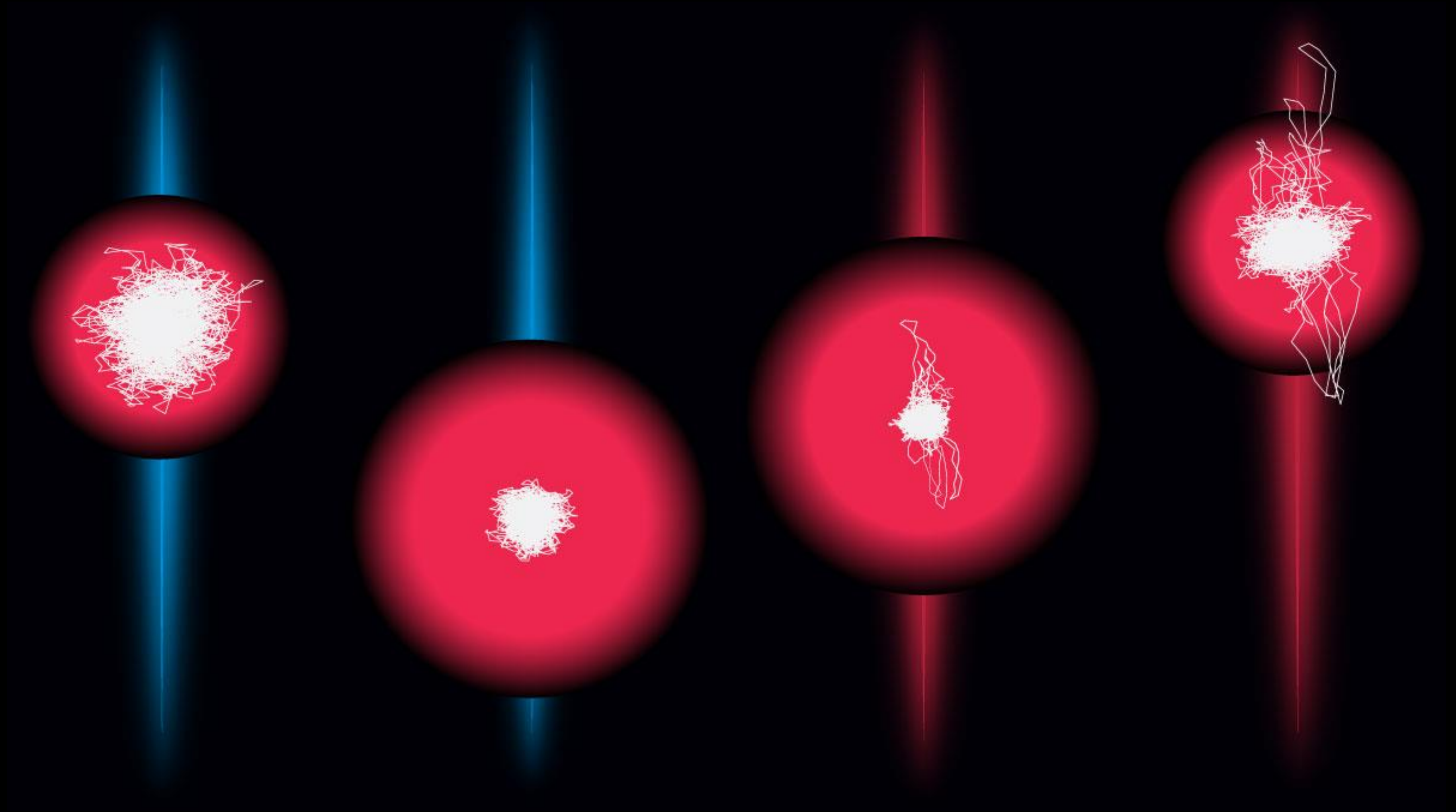
ARTICLE

Check for updates

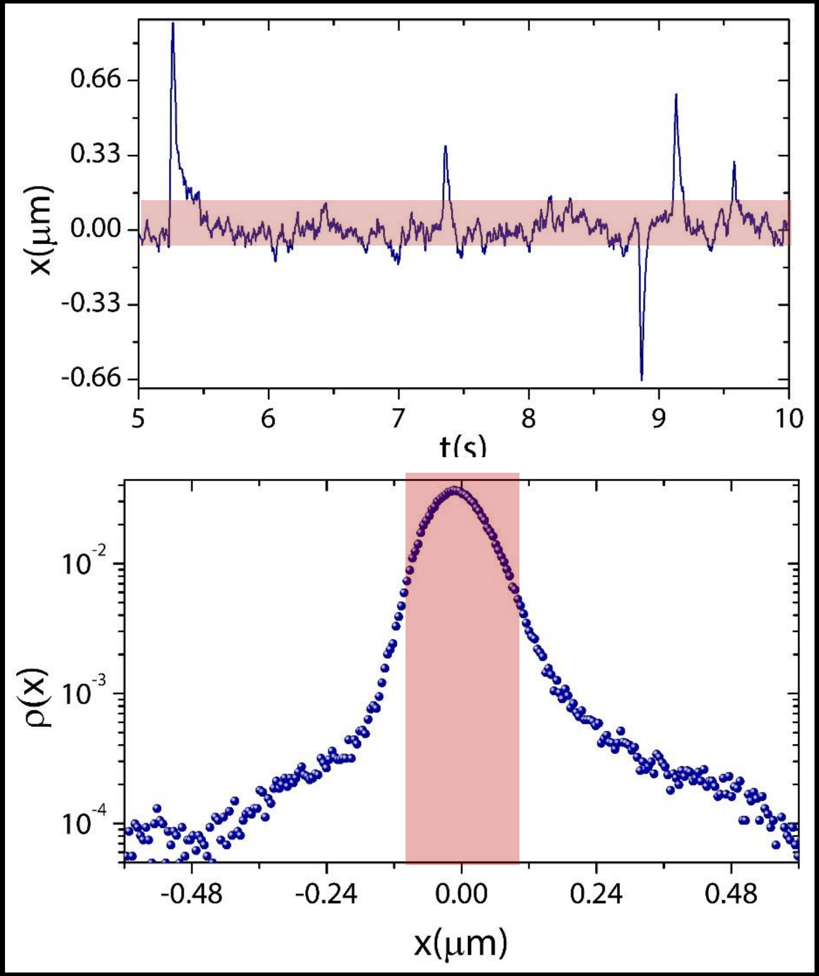
https://doi.org/10.1038/s41467-021-25230-1 OPEN

Tuning the performance of a micrometer-sized Stirling engine through reservoir engineering

Niloyendu Roy[1✉], Nathan Leroux[2], A. K. Sood[3,4] & Rajesh Ganapathy[4,5]

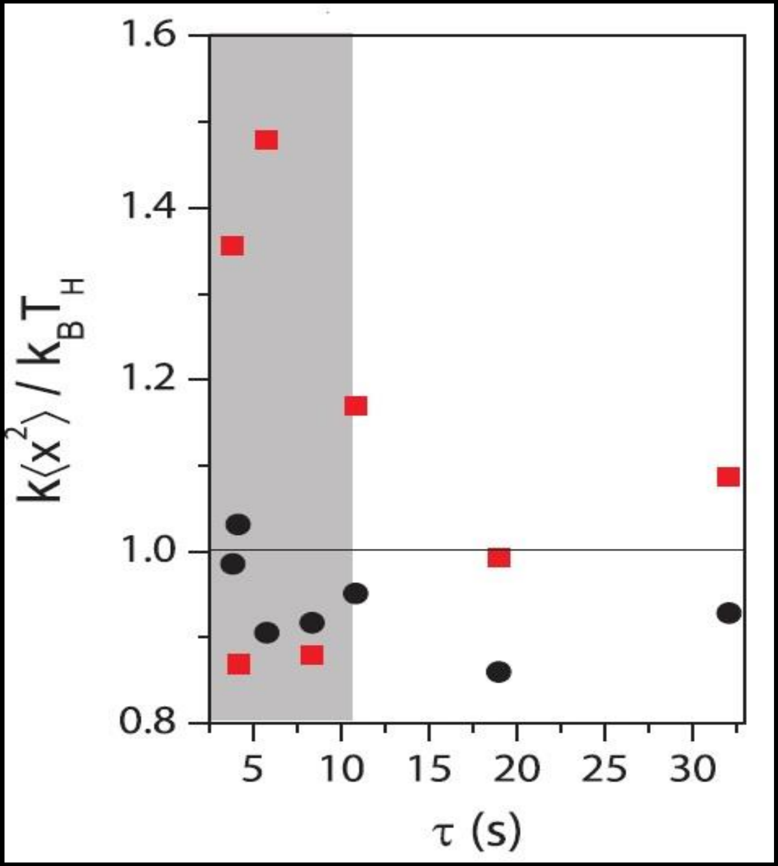


Origins of irreversibility



Poor sampling at smaller τ :
Particle is less likely to encounter spikes in shorter isotherms. Hence excursions (useful Work) rarely occur during expansion

Direct signature of equilibrium violation

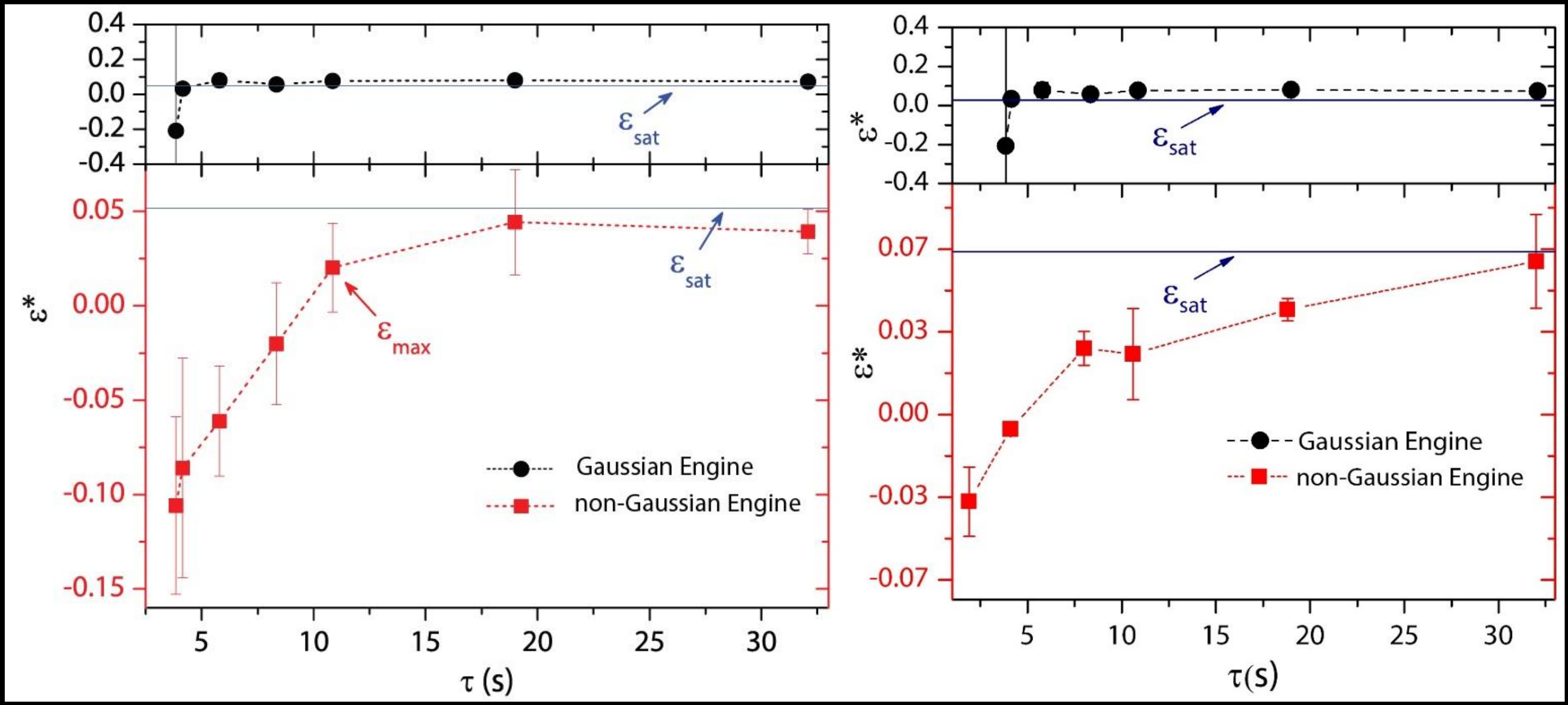


Non-Gaussianity of x violates equipartition in the stalling range of τ

Efficiency

$$\epsilon^* = \frac{W^*}{\underbrace{< W_H > + < Q_{boundary} >} + < Q_{isochoric} >}$$

Isothermal heat Q_H dissipated during hot isotherm



Curzon-Ahlborn efficiency ε_{CZ}=0.026
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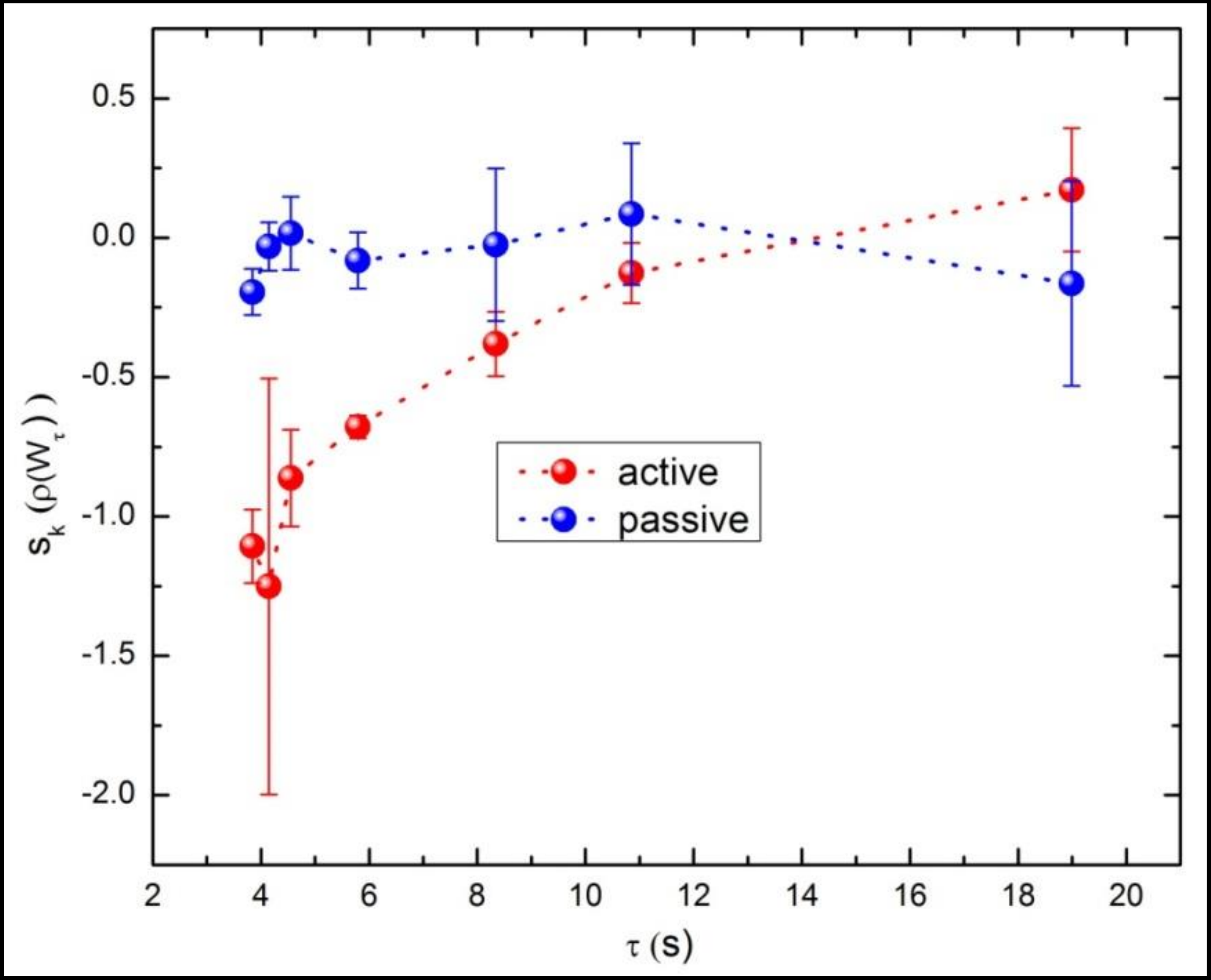
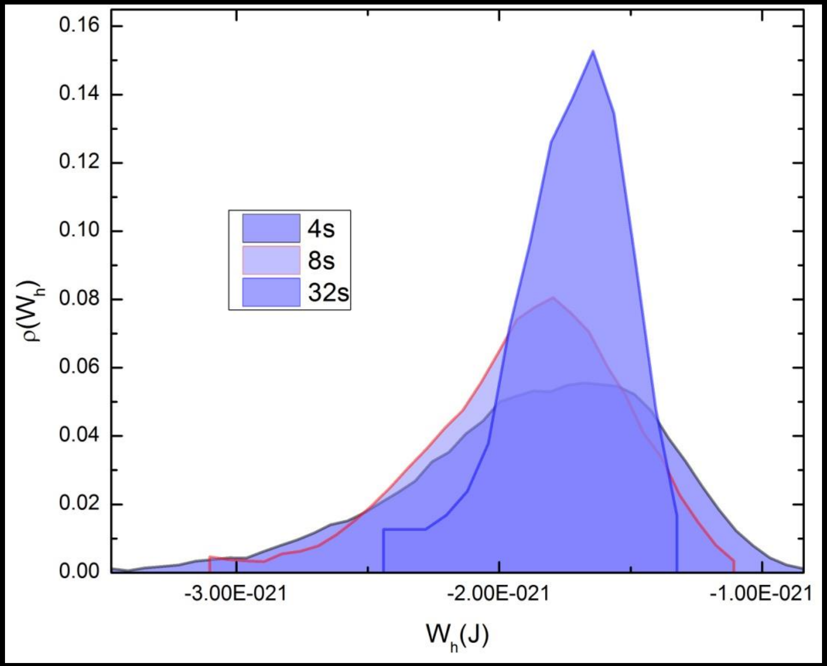
Skewness of work distributions

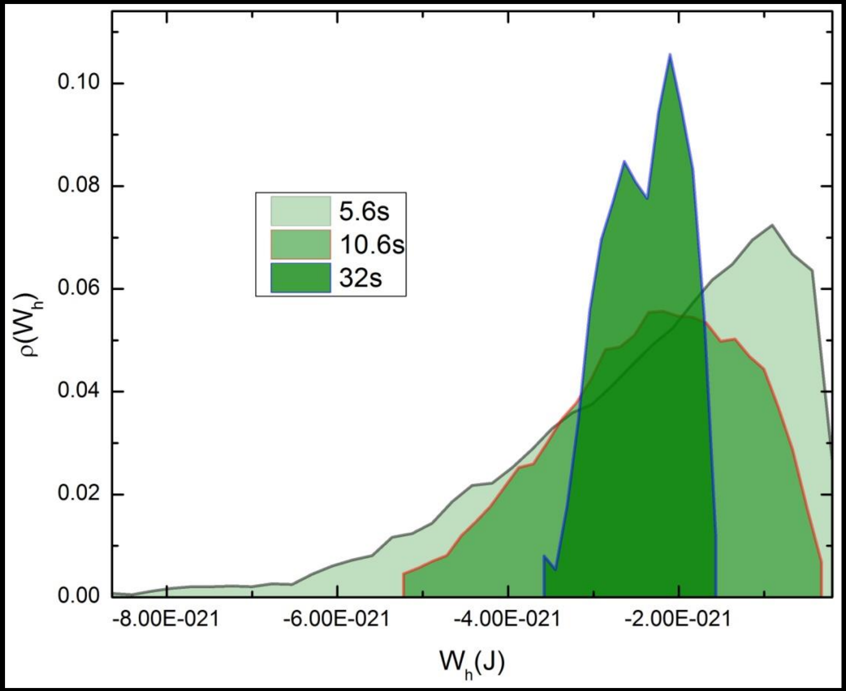


Work distribution of hot isotherm

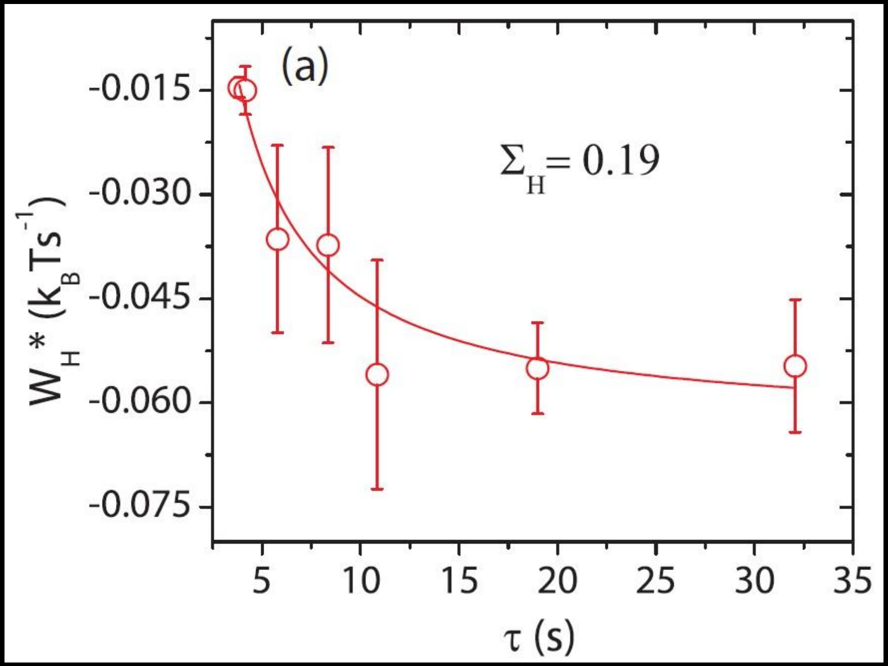
Gaussian engine

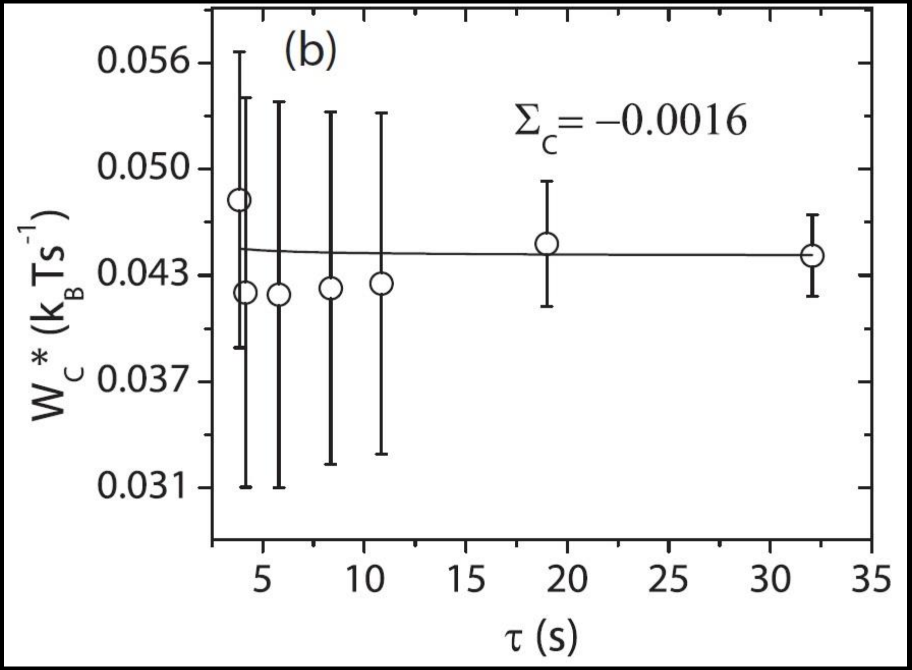


Non-Gaussian engine



Work per isotherm





Construction of δa