Squeezed thermal reservoirs for efficient heat engines and cooler computers

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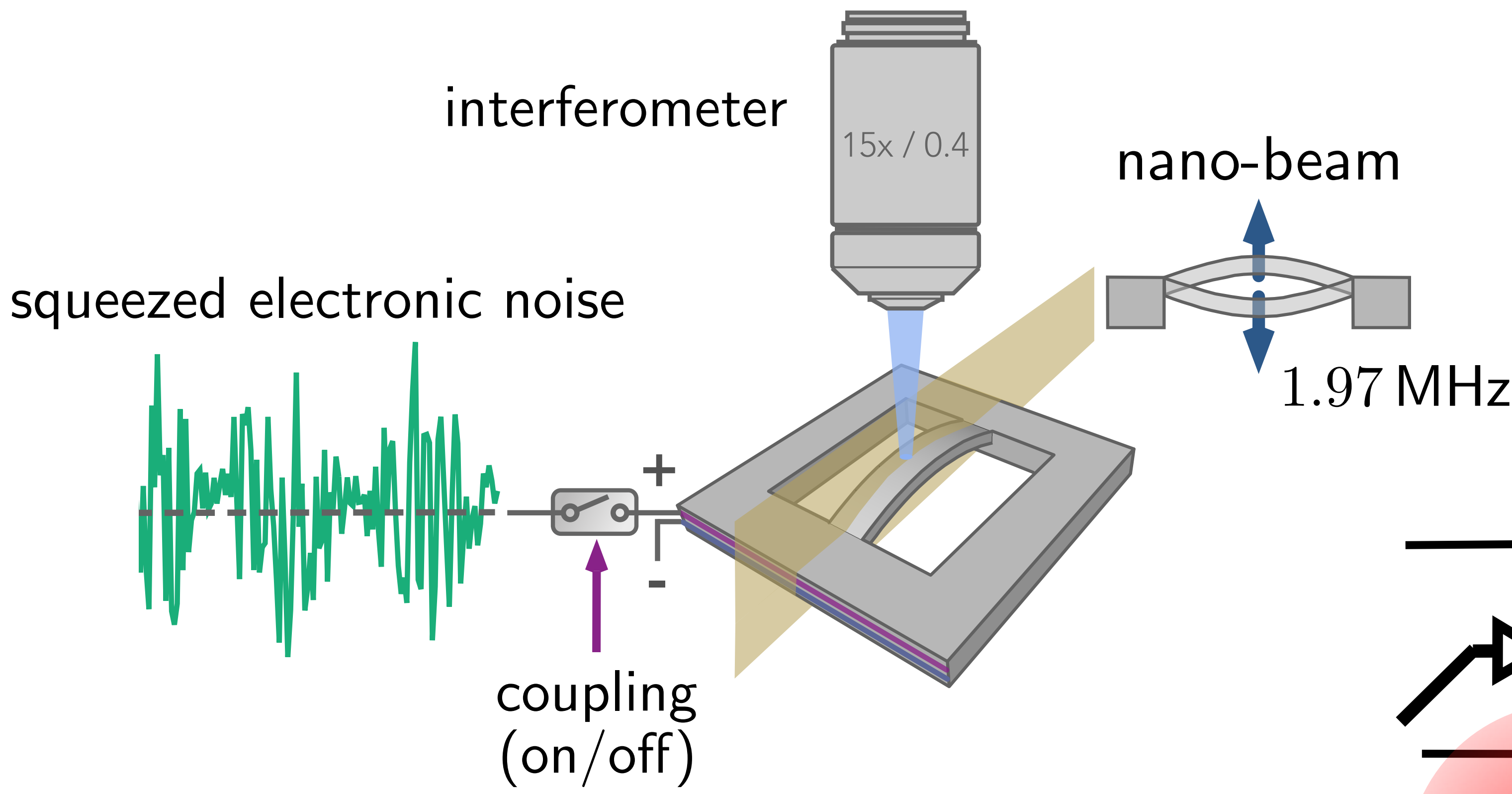
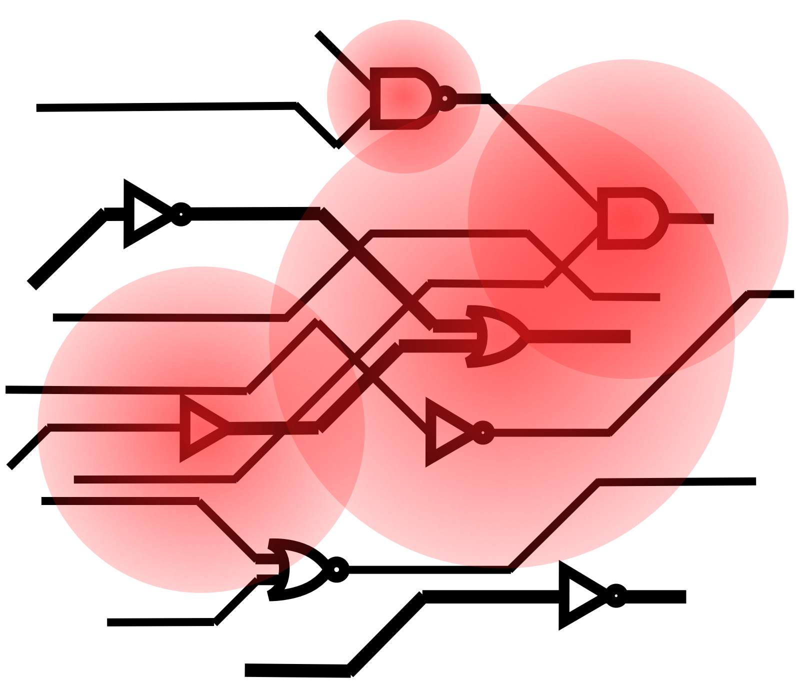
Content

1. Minimalist heat engine driven by squeezed thermal noise
2. Landauer's erasure principle in a squeezed thermal memory



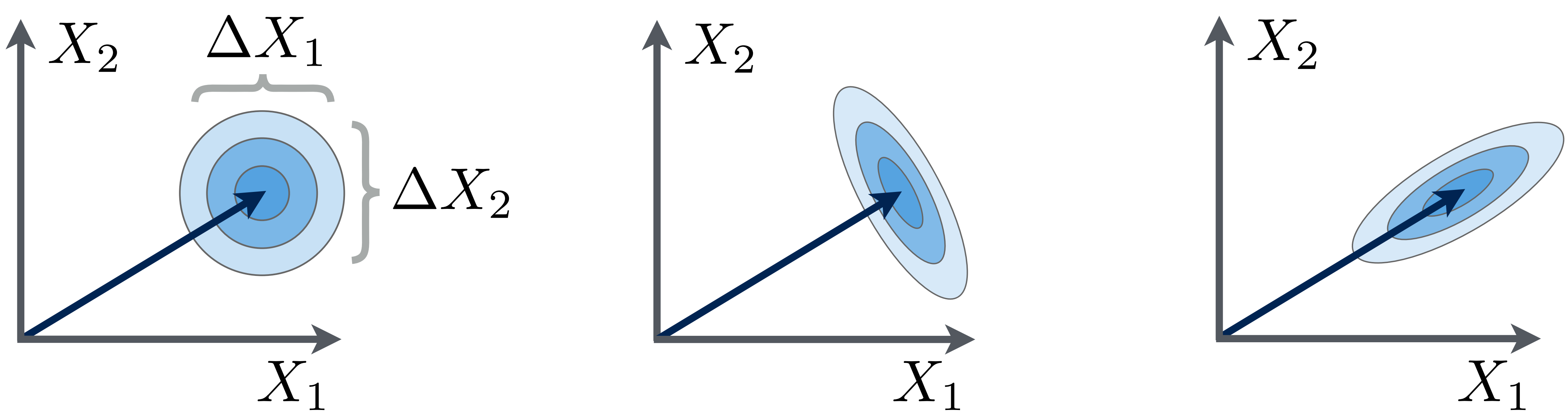


Squeezed states

Coherent state of light:

$$E(t) \propto \; X_1 \cos \omega t + X_2 \sin \omega t$$

minimum uncertainty: $\Delta X_1 \, \Delta X_2 = \frac{1}{4}$

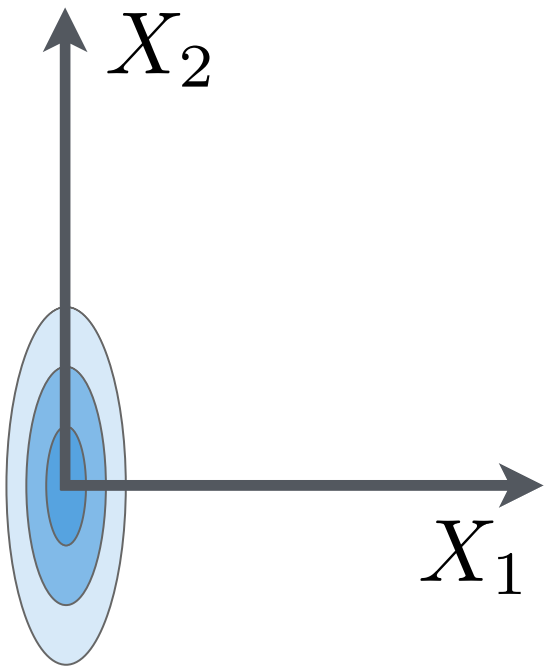


amplitude squeezed

phase squeezed

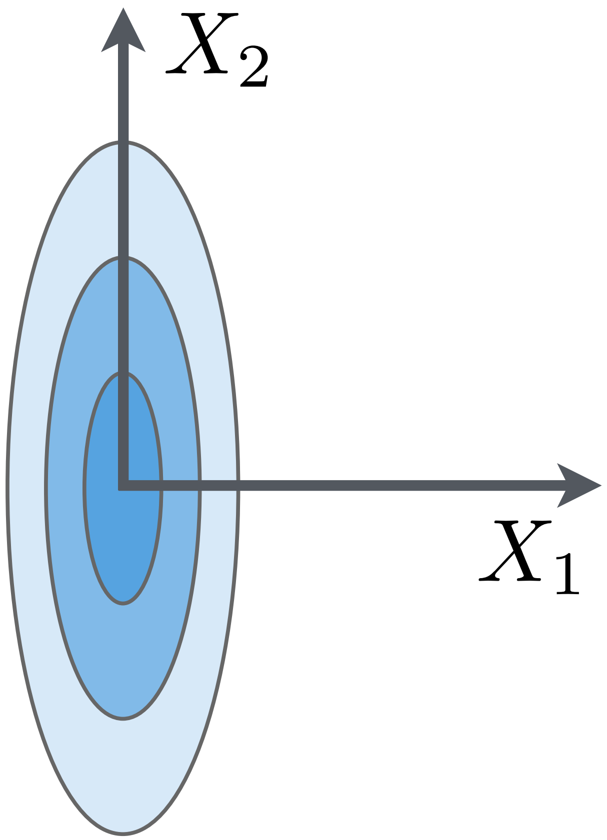
Squeezed states

squeezed vacuum state



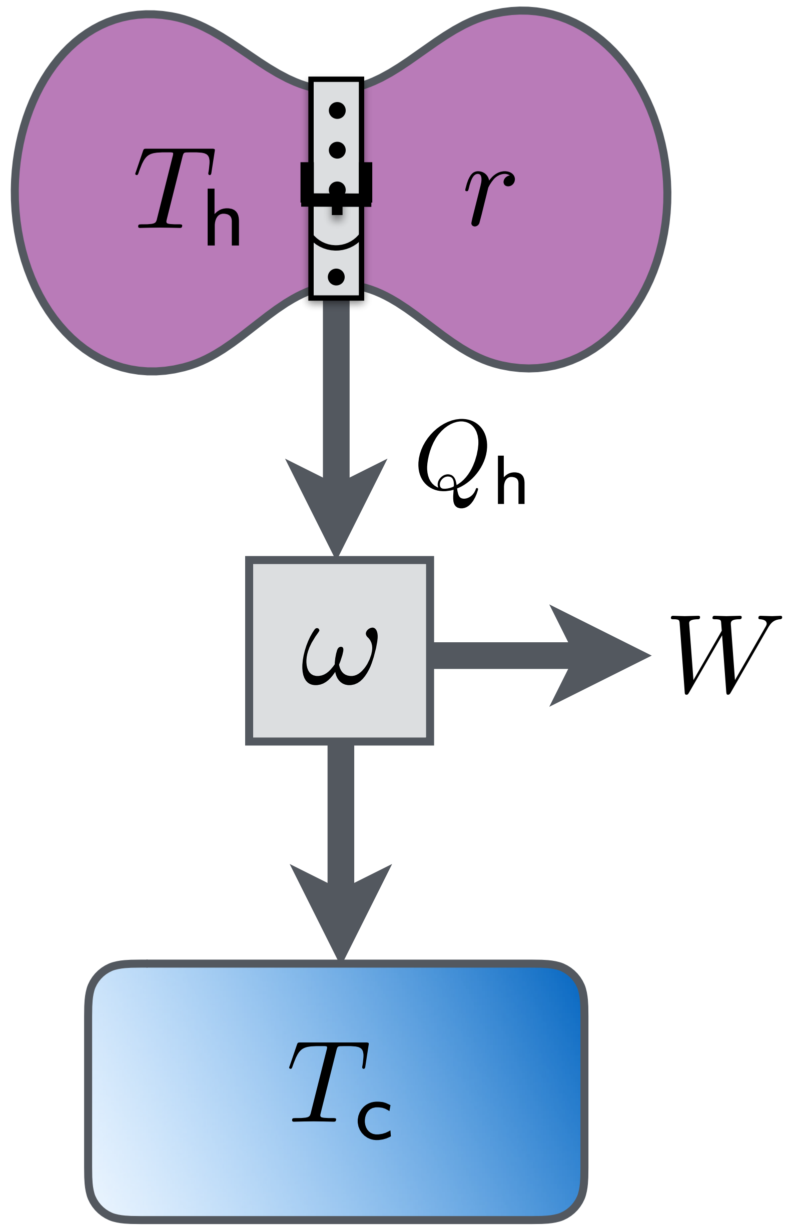
$$\Delta X_1 \, \Delta X_2 = \frac{1}{4}$$

squeezed thermal state



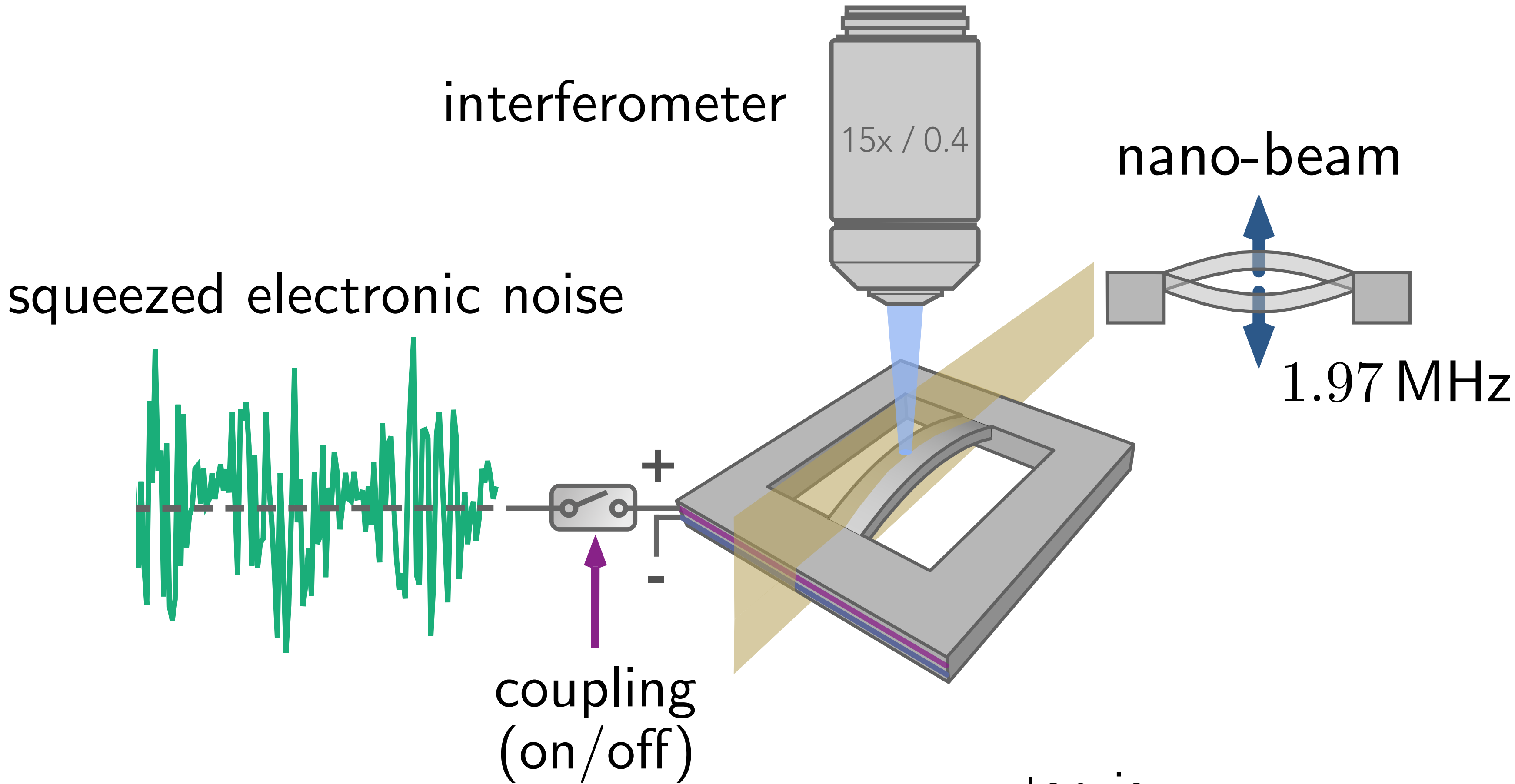
$$\Delta X_1 \, \Delta X_2 > \frac{1}{4}$$

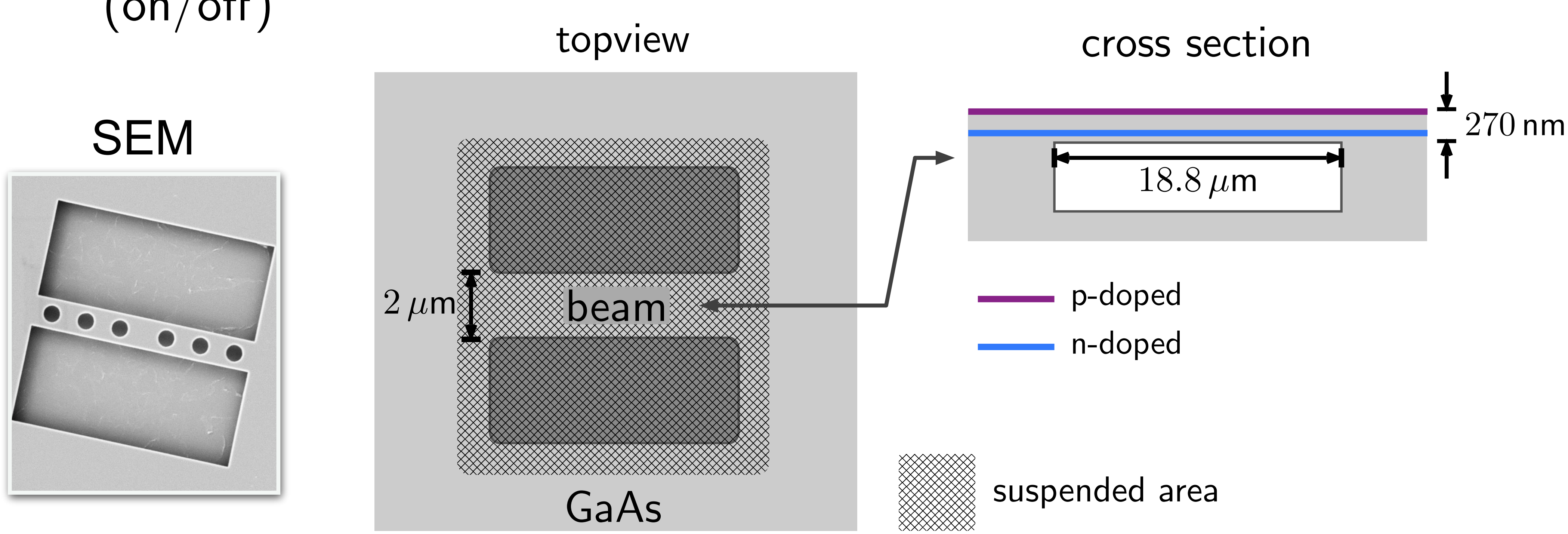
Otto cycle with squeezed thermal reservoirs



J. Roßnagel, O. Abah, F. Schmidt-Kaler, K. Singer, & E. Lutz, *PRL* **112**, 030602 (2014).

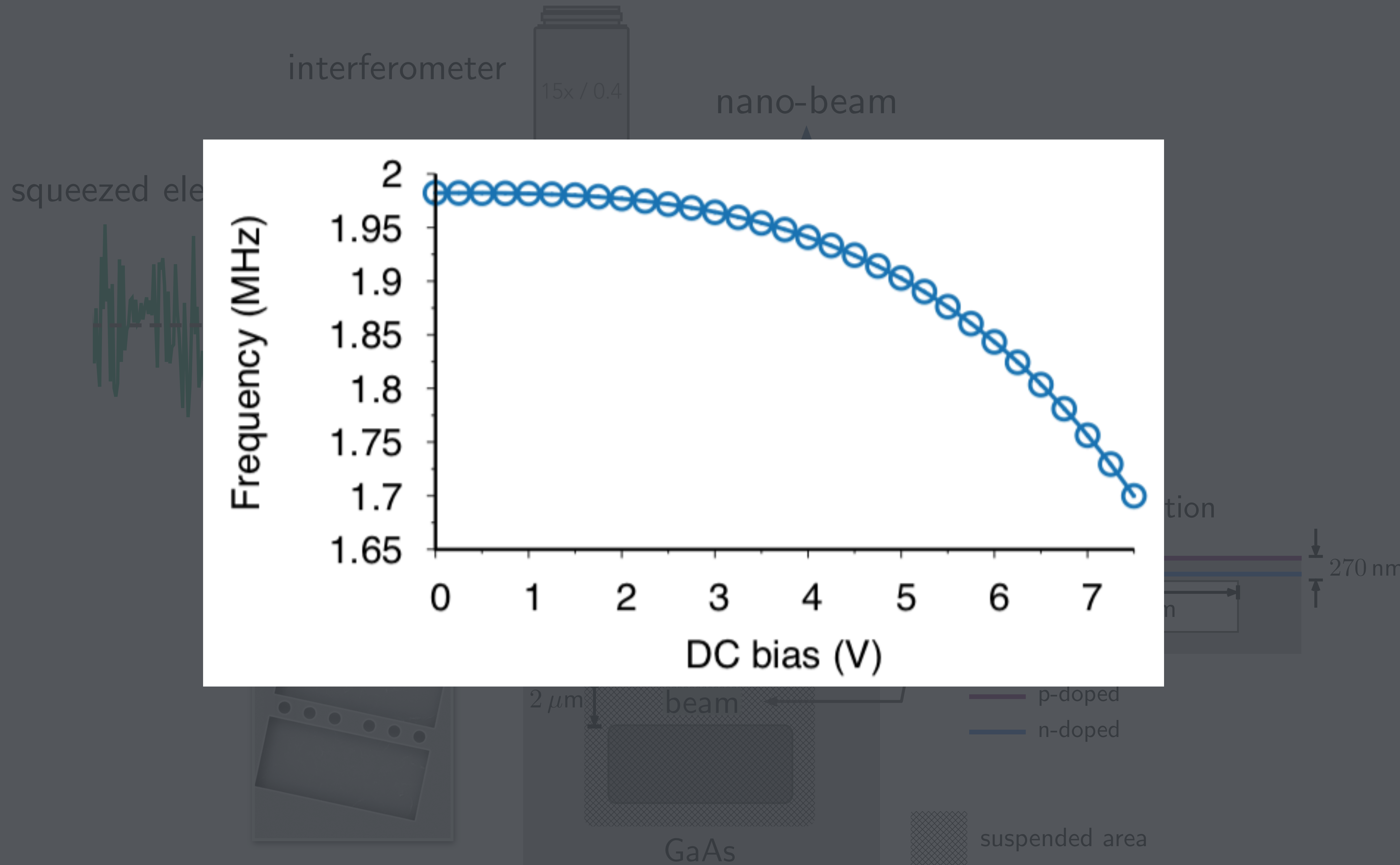
Tunable nano-beam oscillator





J. Klaers, S. Faelt, A. Imamoglu & E. Togan, Phys. Rev. X 7, 031044 (2017).

Tunable nano-beam oscillator



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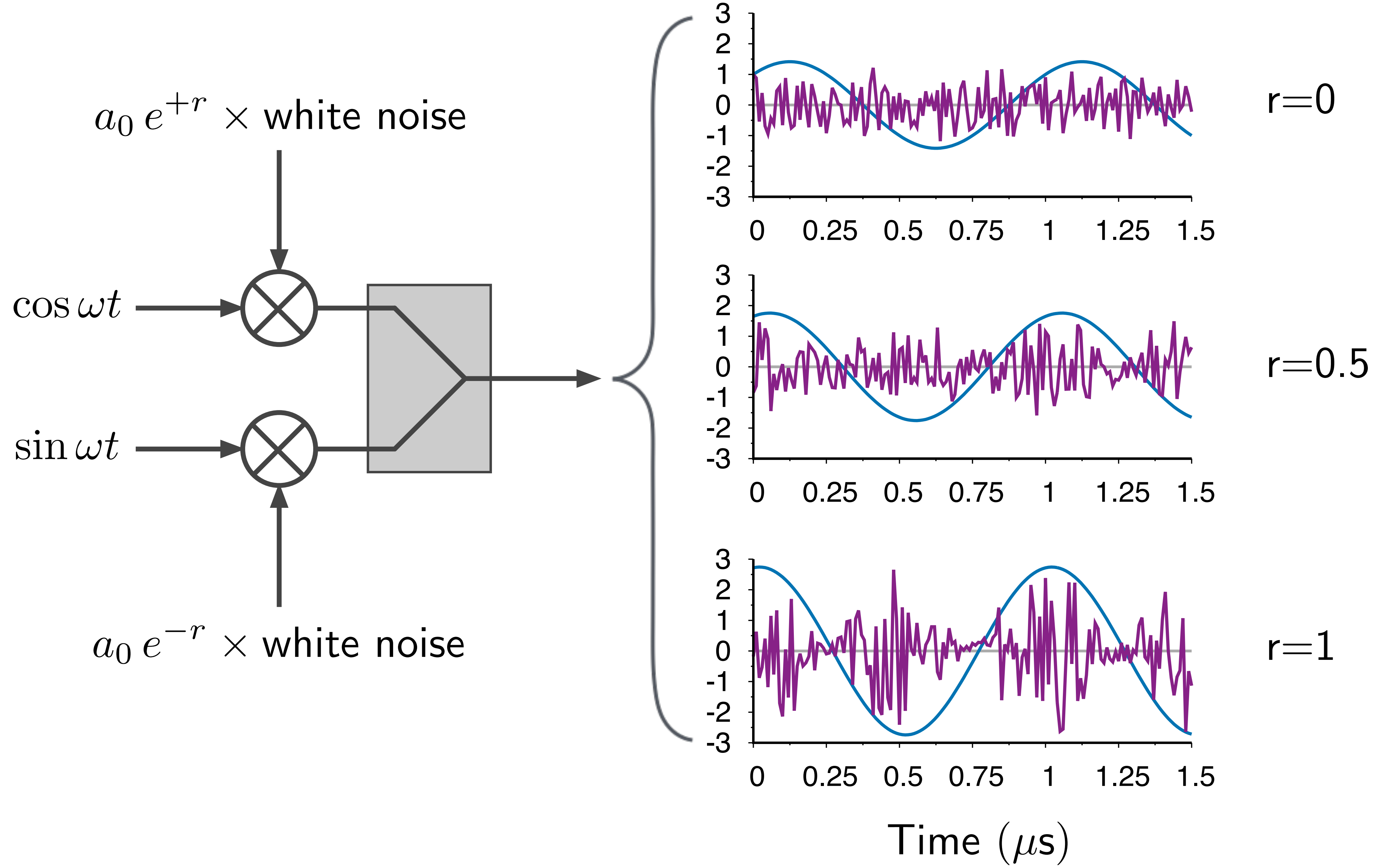
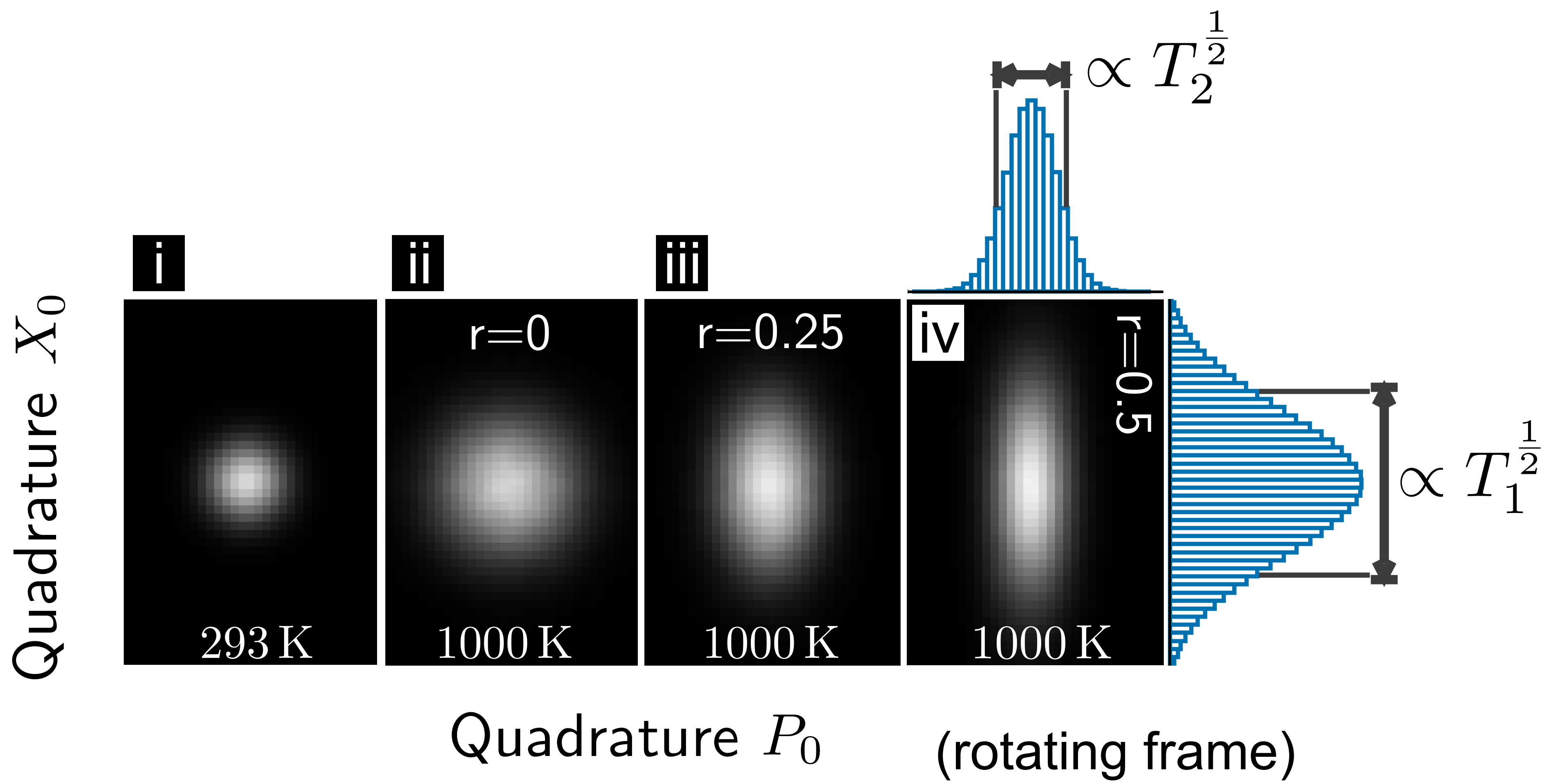
Squeezed heat bath

Squeezed heat is provided by engineered electronic noise:



$$f_{\mathrm{bath}}(t) = a_0 \left[\mathrm{e}^{+\tilde{r}} \xi_1(t)\ \cos(\omega t) + \mathrm{e}^{-\tilde{r}} \xi_2(t)\ \sin(\omega t) \right]$$

Squeezed thermal states



$$\rho(x_0) = \sqrt{\frac{\hbar\omega}{2\pi k_B T_1}} \exp\left(-\frac{\hbar\omega x_0^2}{2k_B T_1}\right)$$

$$\rho(p_0) = \sqrt{\frac{\hbar\omega}{2\pi k_B T_2}} \exp\left(-\frac{\hbar\omega p_0^2}{2k_B T_2}\right)$$

two temperatures:

$$T_{1,2} = T \exp(\pm 2r)$$

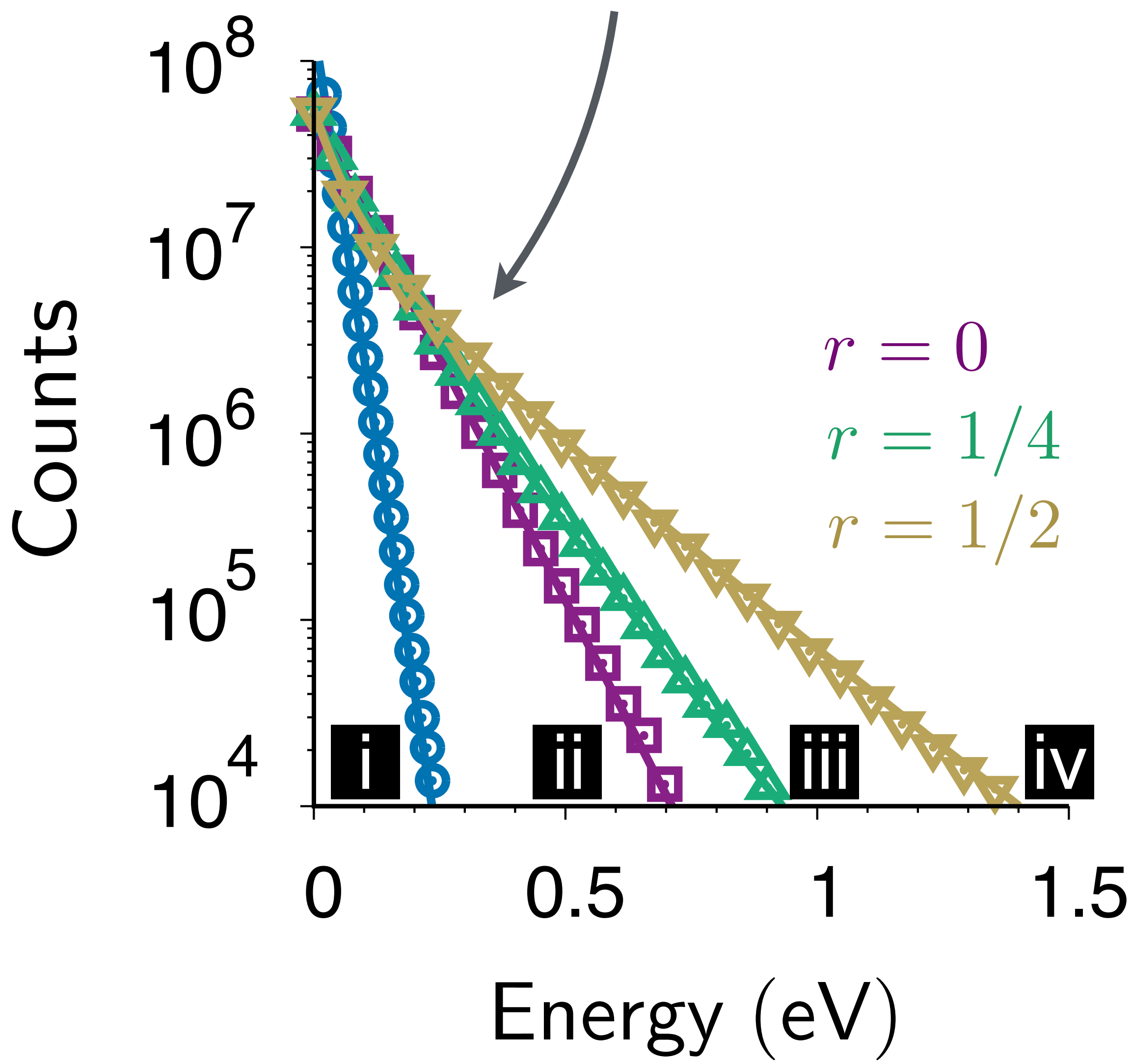
$$\rightarrow T = \sqrt{T_1 T_2}$$

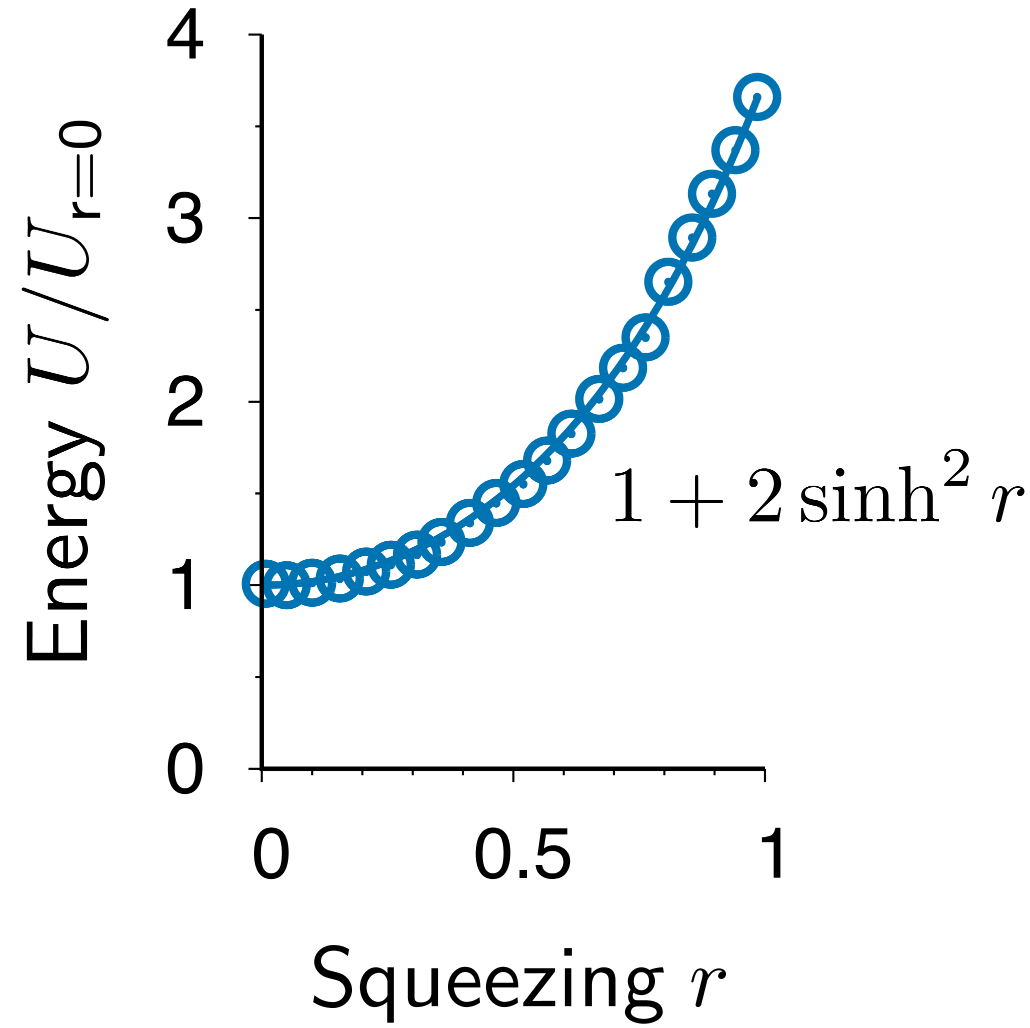
(geometric mean)

Early experiments: Rugar & Grütter (1991)
Theory: Fearn et al. (1988), Kim et al. (1989), Tucci (1991), …

Energy statistics & caloric EOS

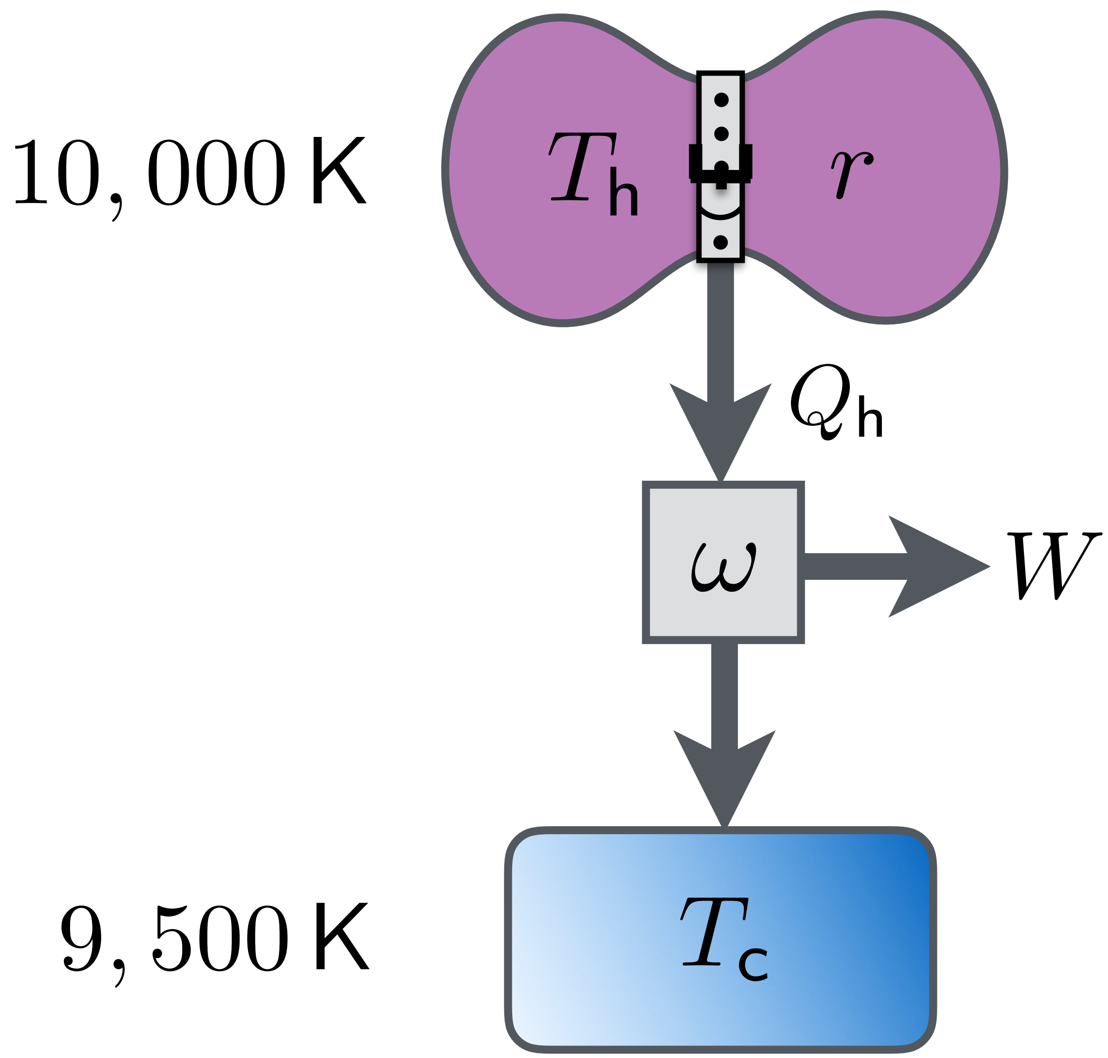
$$\rho(E) = \frac{1}{k_{\mathrm{B}}T}\, I_0\left(\frac{E\,\sinh 2r}{k_{\mathrm{B}}T}\right)\,\exp\left(-\frac{E\,\cosh 2r}{k_{\mathrm{B}}T}\right)$$





i	$T = 293\,\mathrm{K}$
ii iii iv	$T = 1000\,\mathrm{K}$

Otto cycle with squeezed heat



2 adiabats, 2 isochores

design choice:

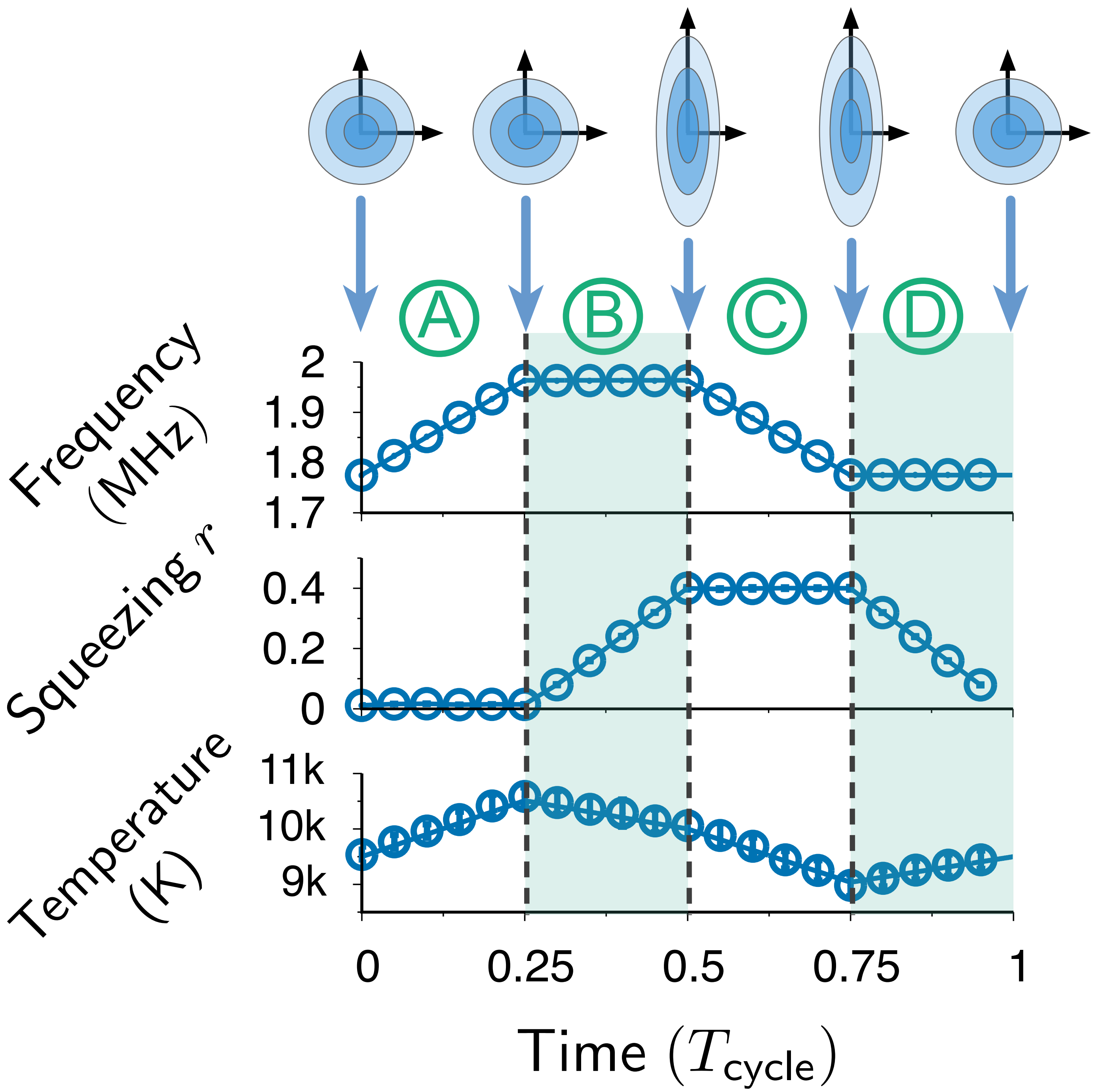
$$\omega_{\mathrm{min}} < \omega < \omega_{\mathrm{max}}$$

maximum power:

$$\frac{\omega_{\mathrm{max}}}{\omega_{\mathrm{min}}} = \cosh r \sqrt{T_{\mathrm{h}}/T_{\mathrm{c}}}$$

Theory: Roßnagel et al., *PRL* **112**, 030602 (2014).

Cycle implementation



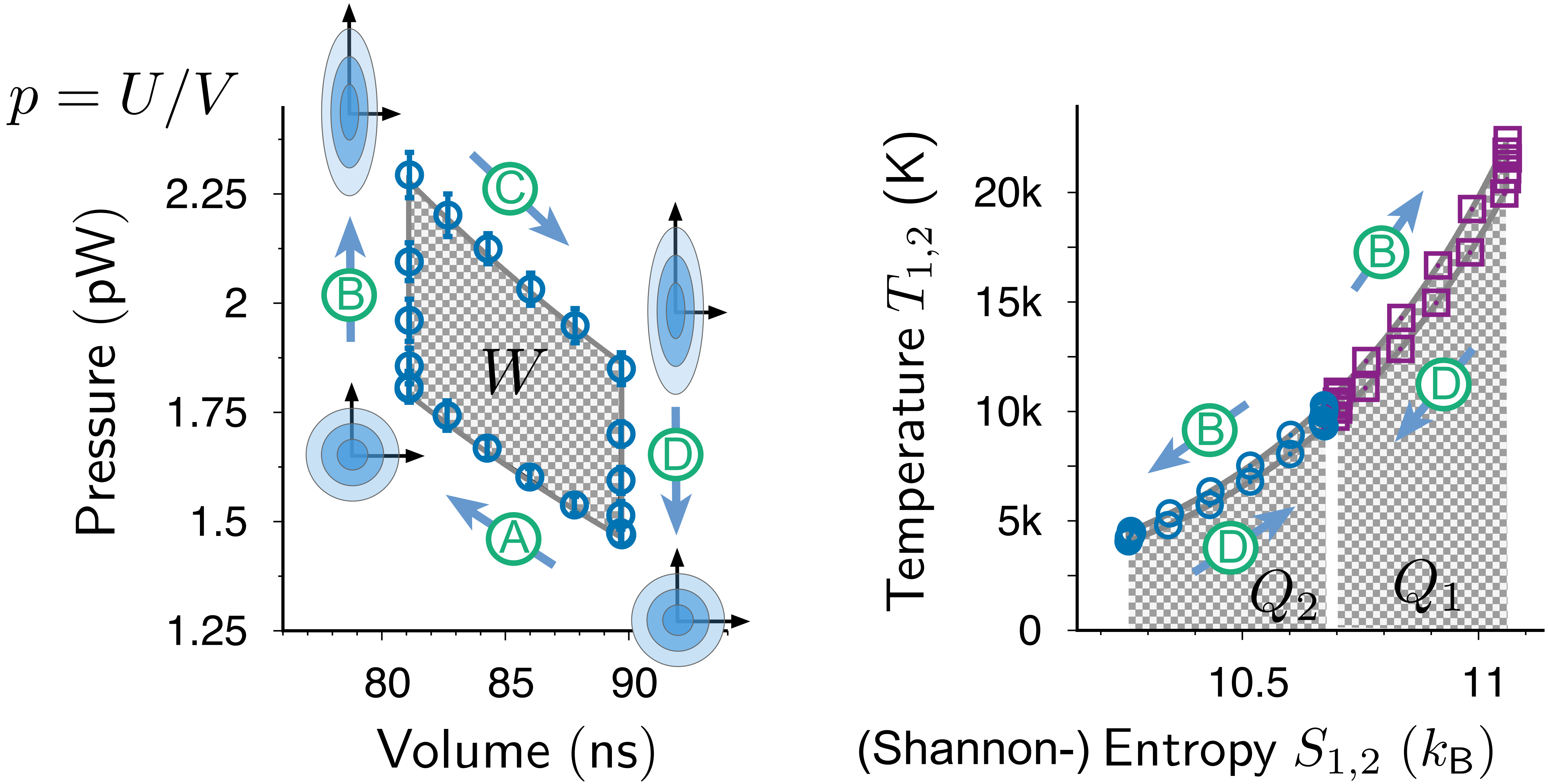
(A) isentropic compression
$T_i/\omega = \text{const}$

(B) isochoric heat addition
$\omega = \text{const}$

(C) isentropic expansion
$T_i/\omega = \text{const}$

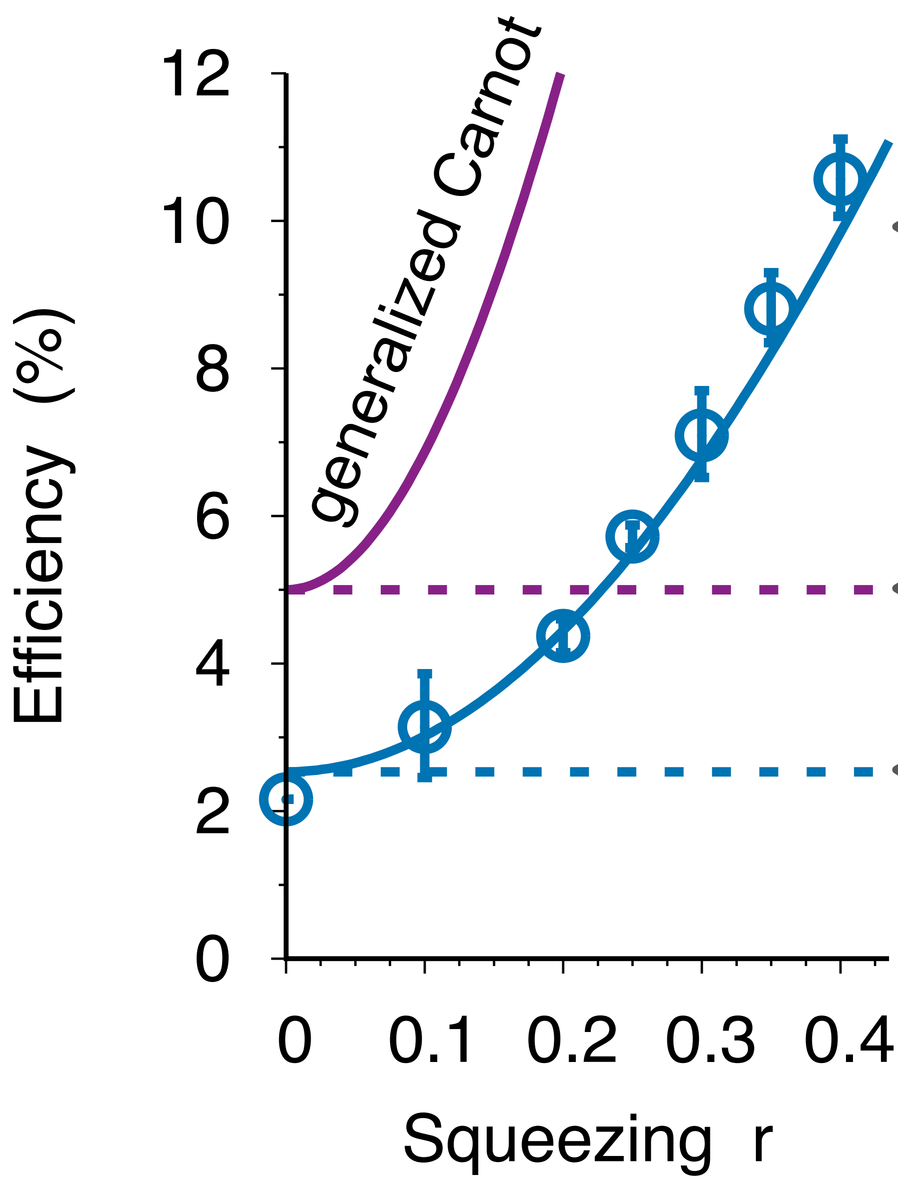
(D) isochoric heat rejection
$\omega = \text{const}$

p-*V*-diagram & *T*-*S*-diagram



$$\left.\begin{aligned} W &\simeq 26\,\mathrm{meV} \\ Q_\mathrm{h} = Q_1 - Q_2 &\simeq 244\,\mathrm{meV} \end{aligned}\right\} \eta = W/Q_\mathrm{h} = (10.6 \pm 0.5)\%$$

Efficiency



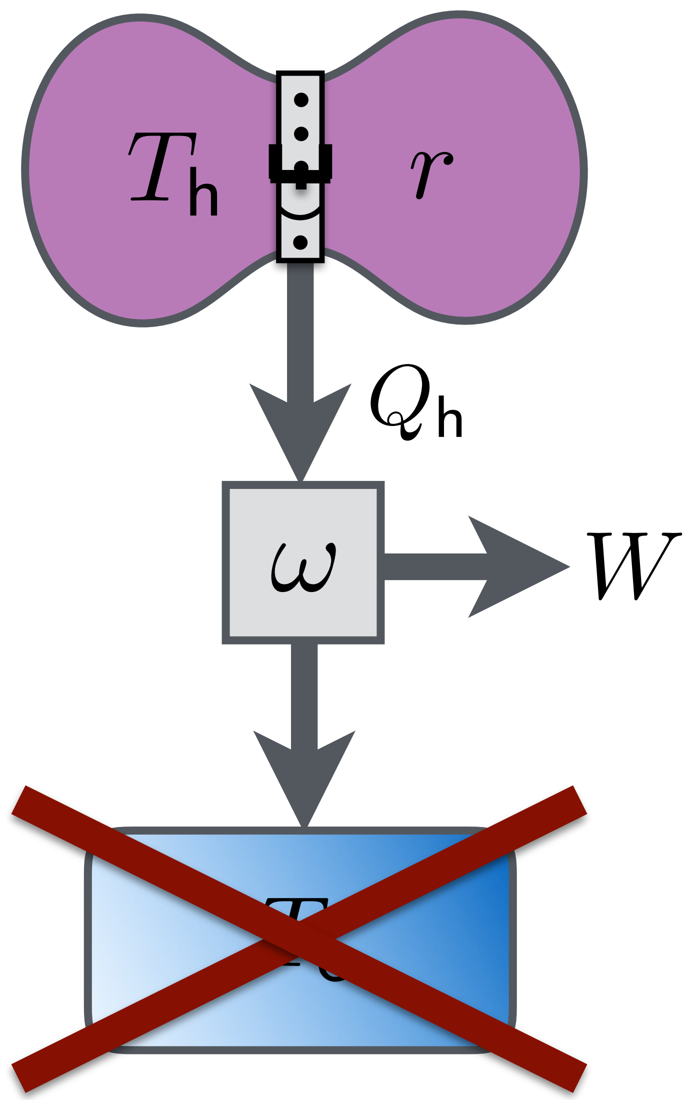
$\leftarrow 1 - \sqrt{T_c/T_h}\,/\cosh r$

$\leftarrow 1 - T_c/T_h$ (Carnot)

$\leftarrow 1 - \sqrt{T_c/T_h}$ (Curzon-Ahlborn)

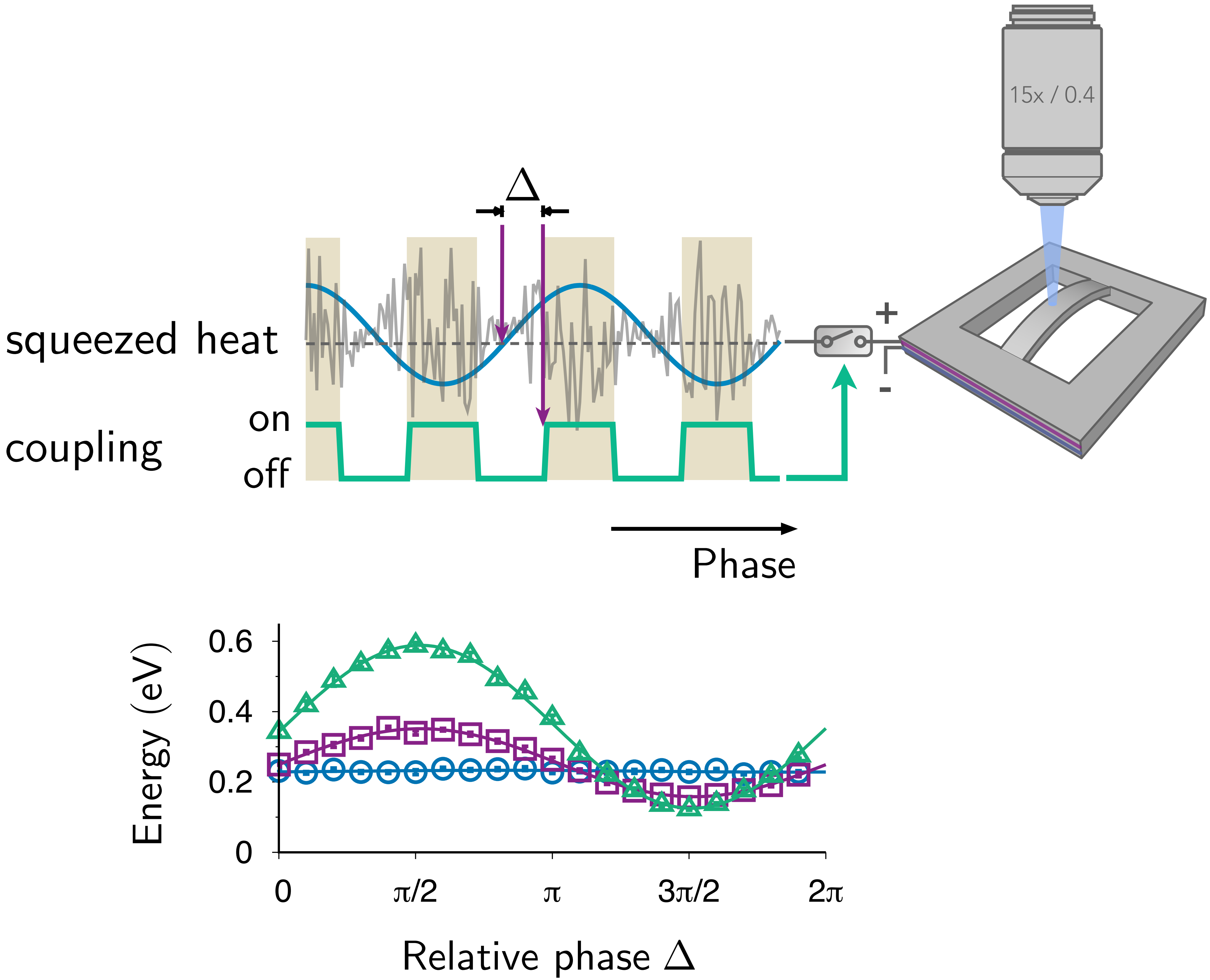
Work extraction from a single heat bath

$$T = 10,000\,\mathsf{K}$$
$$r = 0.3$$

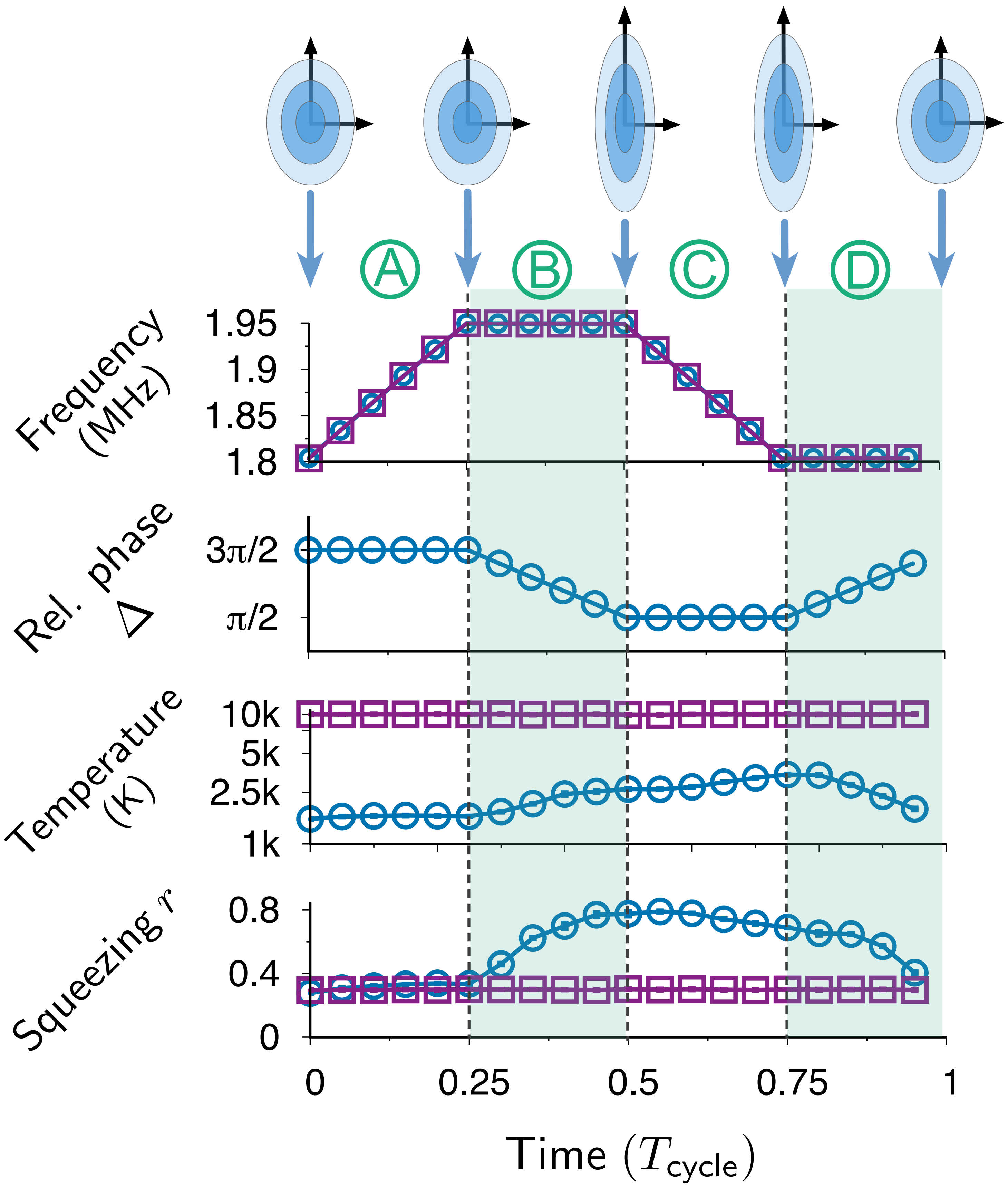


See also: Scully et al., *Science* **299**, 862-864 (2003).
(work from quantum coherence)

Phase-selective coupling



Cycle process with a single bath



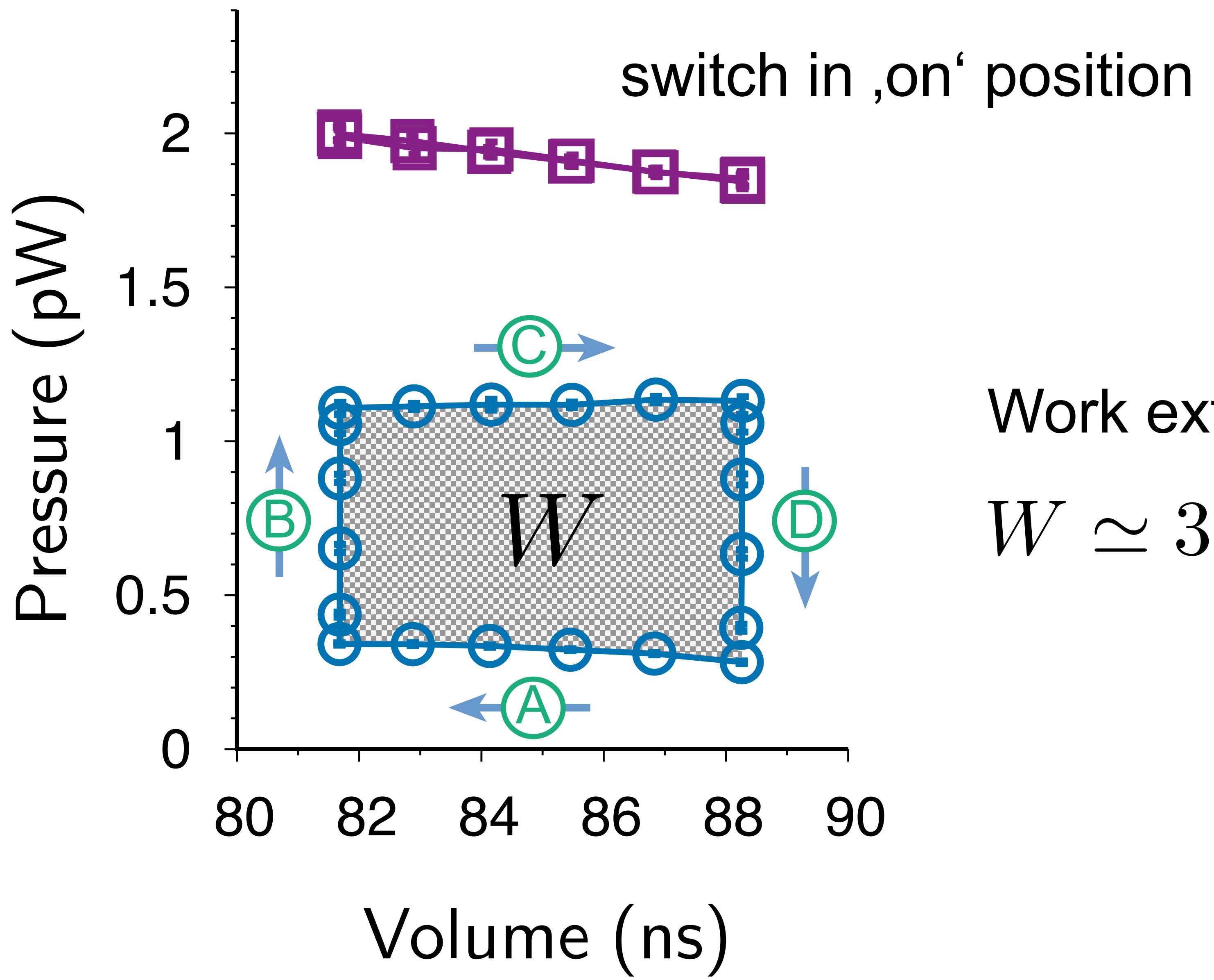
Ⓐ „isophasal“ compression
$\Delta = \text{const}$

Ⓑ isochoric heat addition
$\omega = \text{const}$

Ⓒ „isophasal“ expansion
$\Delta = \text{const}$

Ⓓ isochoric heat rejection
$\omega = \text{const}$

Work extraction



Work extracted per cycle:

$W \simeq 37\,\mathrm{meV}$

Nanomechanical heat engine

- realization of a minimalist heat engine driven by squeezed thermal reservoirs
- efficiency unbounded by Carnot limit
- work extraction from single reservoir

Further information:

J. Klaers, S. Faelt, A. Imamoglu & E. Togan, Phys. Rev. X 7, 031044 (2017).

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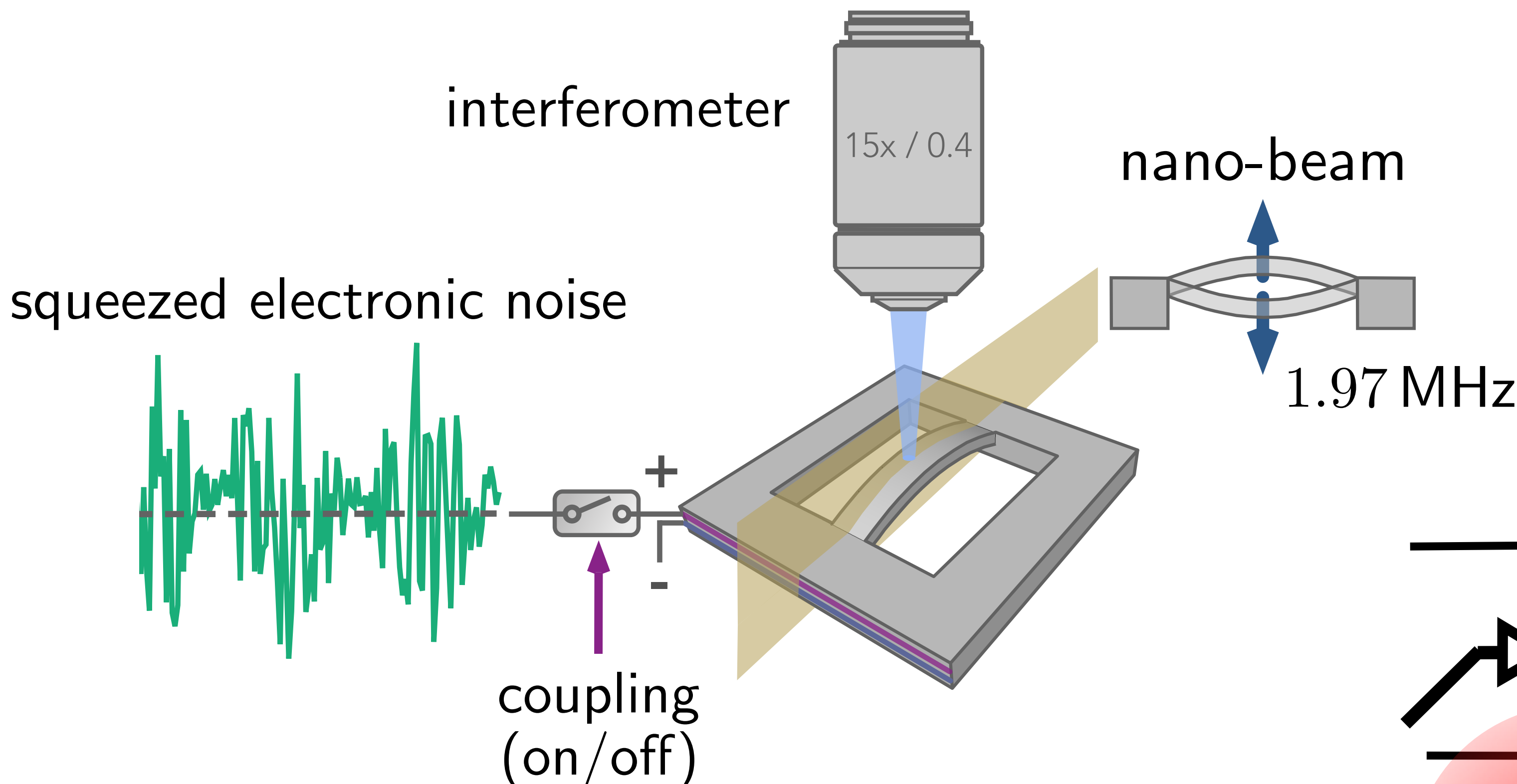
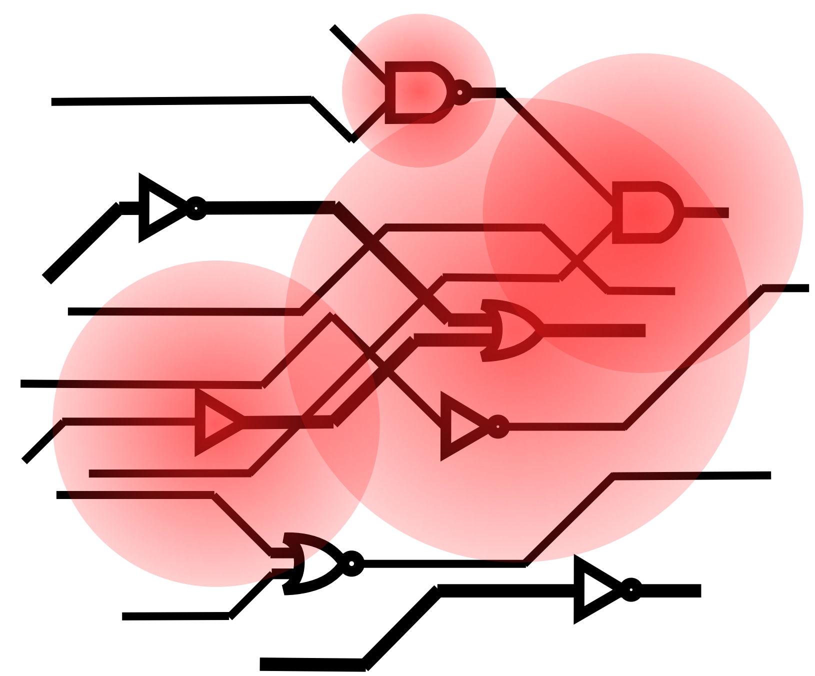
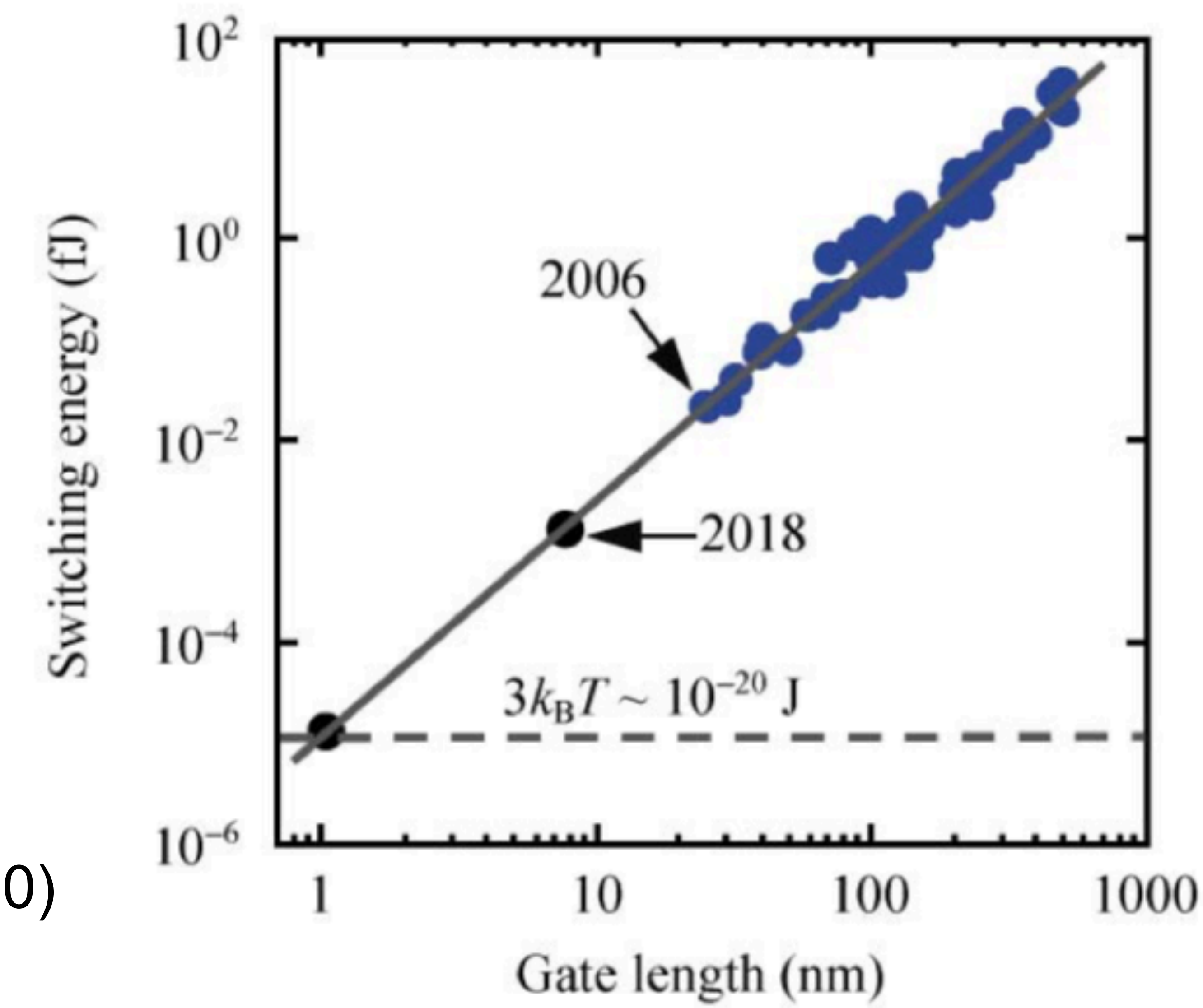




Landauer's erasure principle

Logically irreversible operations are associated with energetic costs of at least $W = (\ln 2)\, k_{\mathrm{B}} T$.

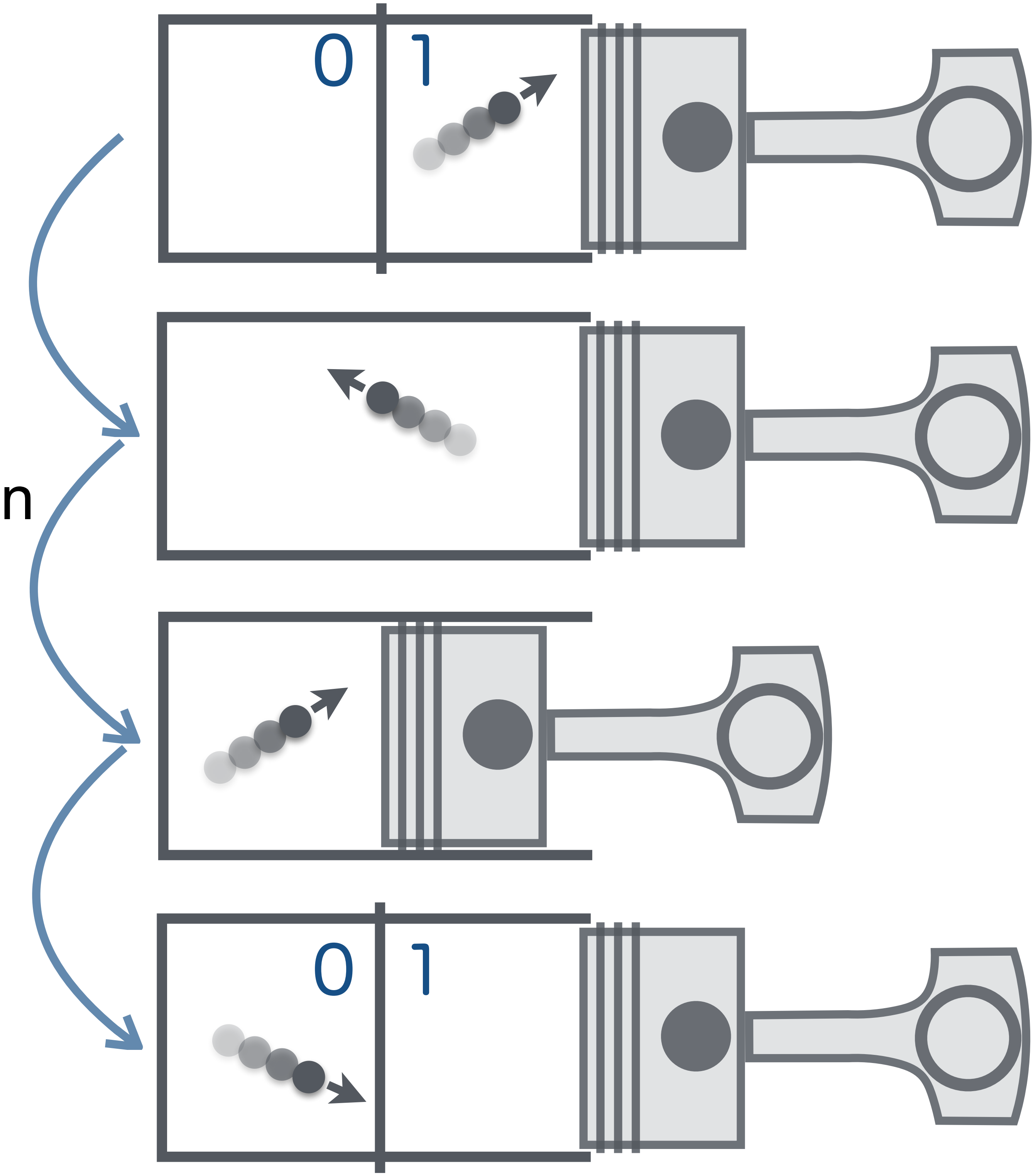
Energy dissipation in CPUs



Pop, Nano Res. 3, 147 (2010)

Erasing/resetting 1 bit of information

1. remove partition
   (free expansion)
   $$\Delta S = k_{\mathrm{B}} \ln 2$$
2. isothermal compression
   $$W = T\Delta S$$
   $$= (\ln 2)\, k_{\mathrm{B}} T$$
3. insert partition

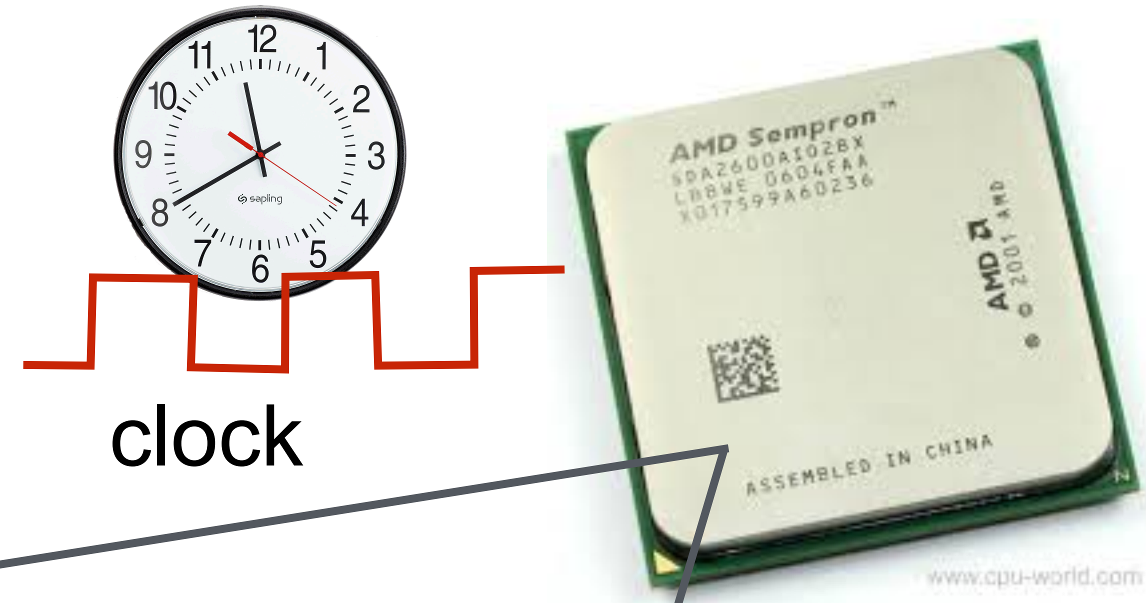


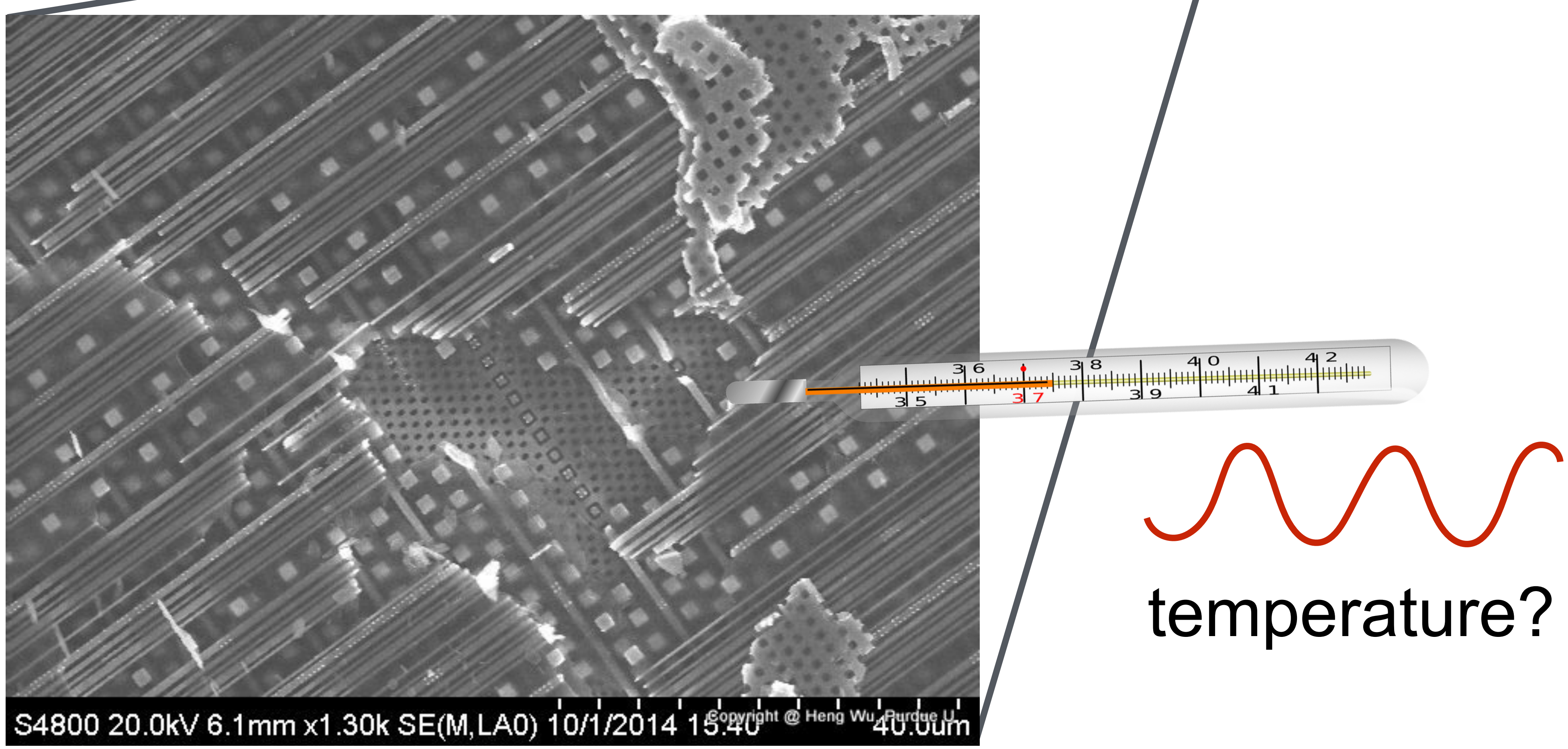
Experimental verification: Berut et al., Nature 483, 183 (2012)

Assumption of thermal equilibrium?

energy dissipation in CPU:
≈50% static
≈50% dynamic (switching)

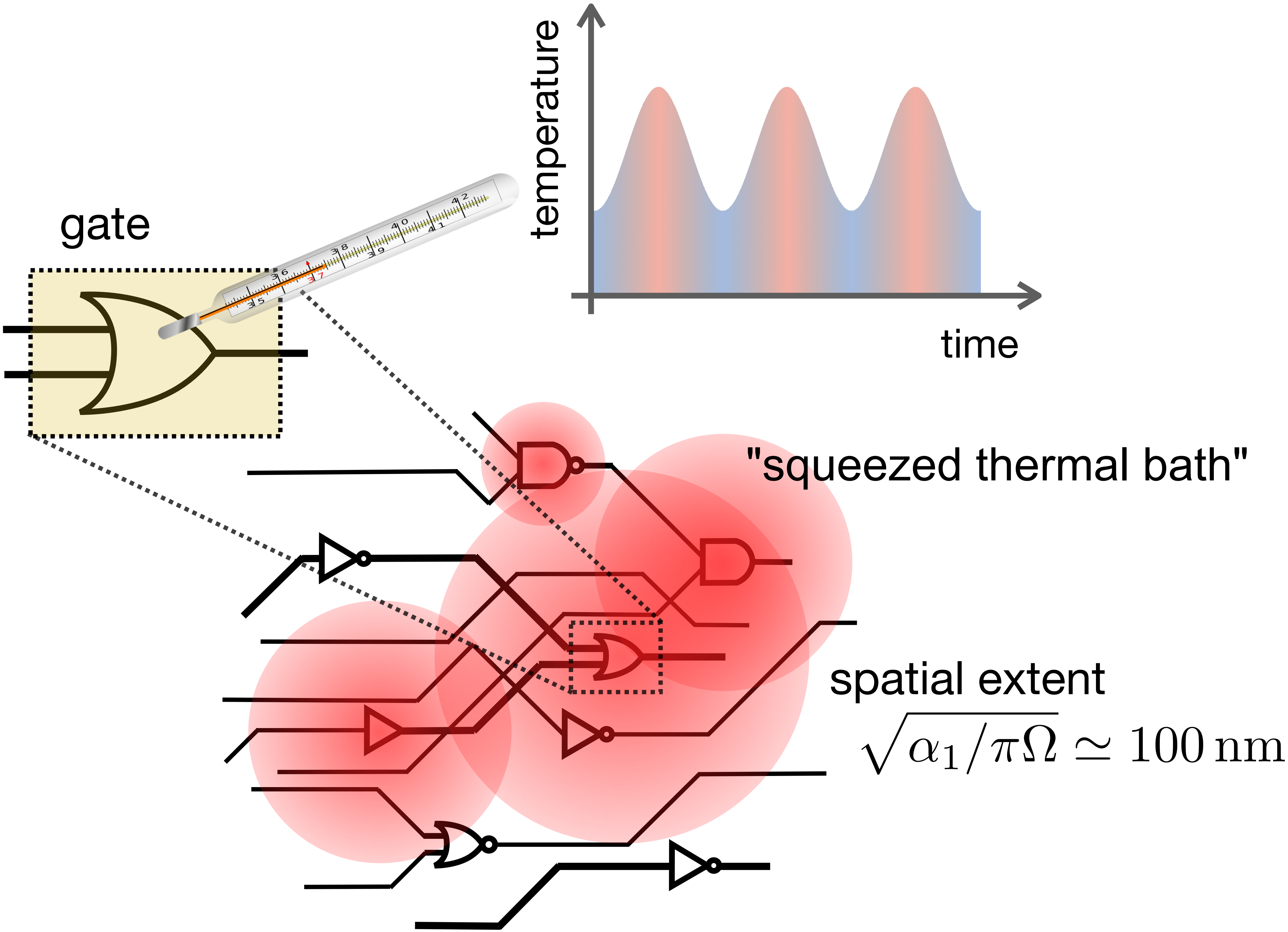
Pop, Nano Res. 3, 147 (2010)





Heng Wu (Purdue University)

Logical gates as periodic heat source

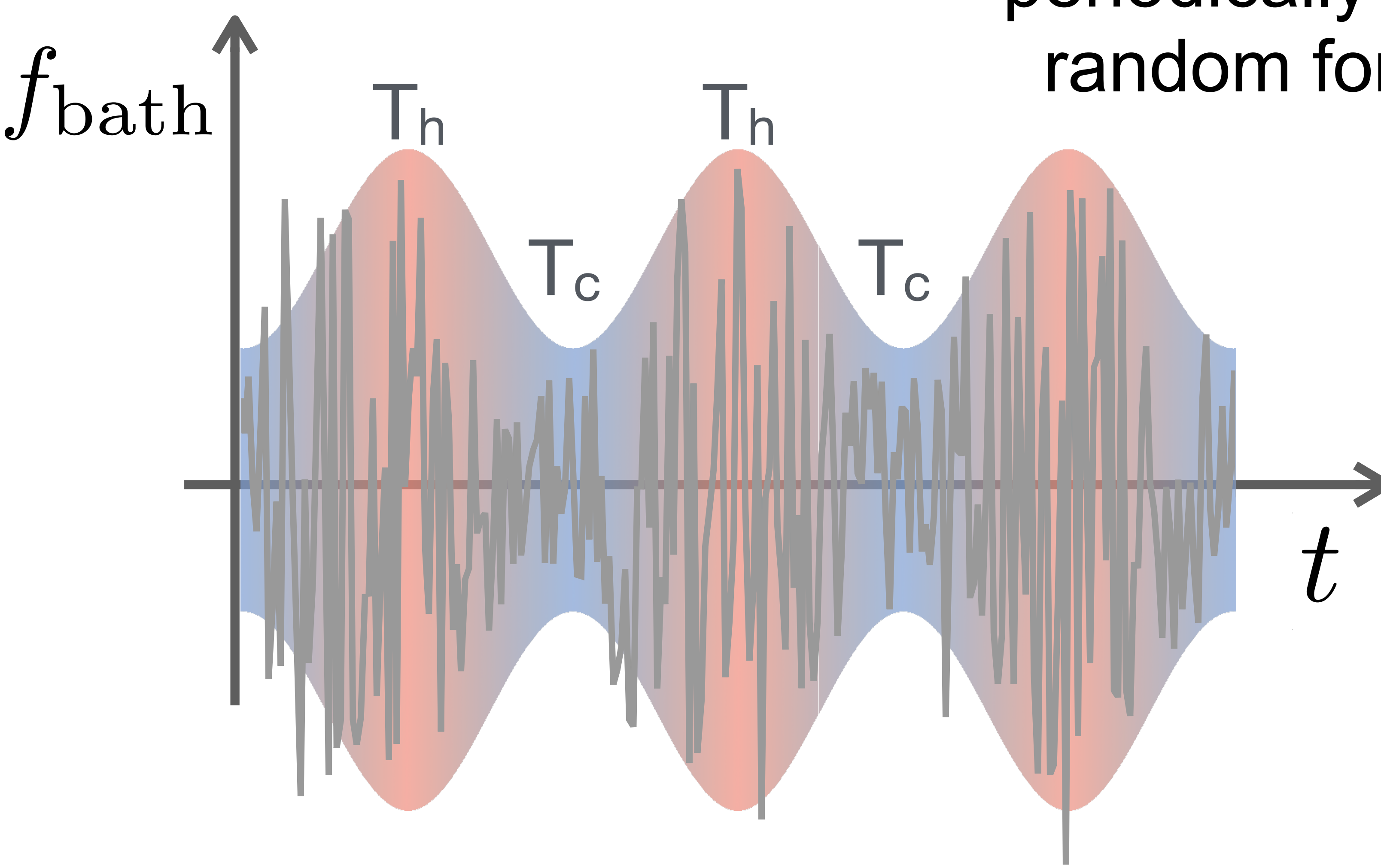


Squeezed thermal bath

A thermal environment can be characterized by random forces it exerts on a physical system.

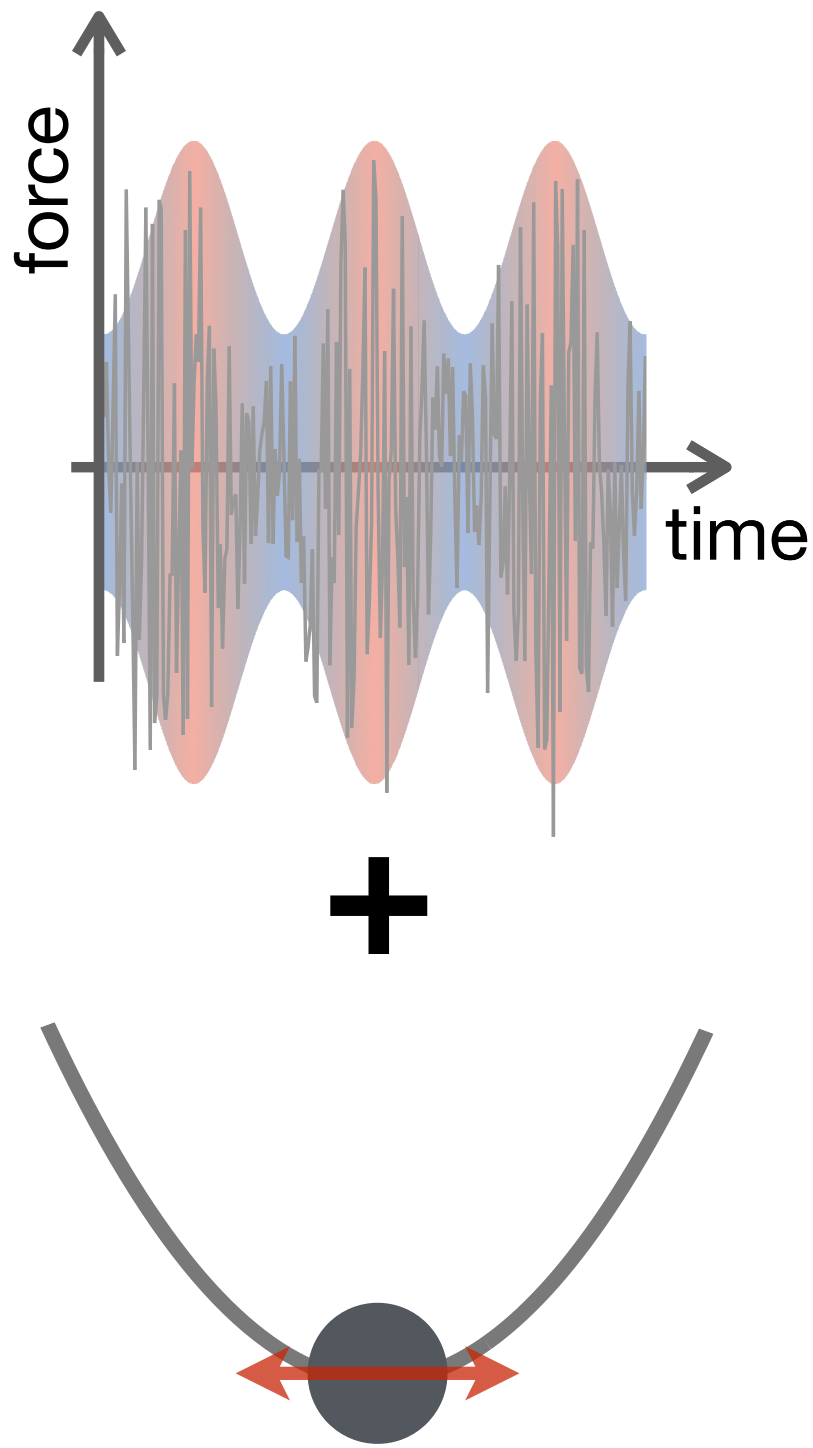
Squeezed thermal bath:

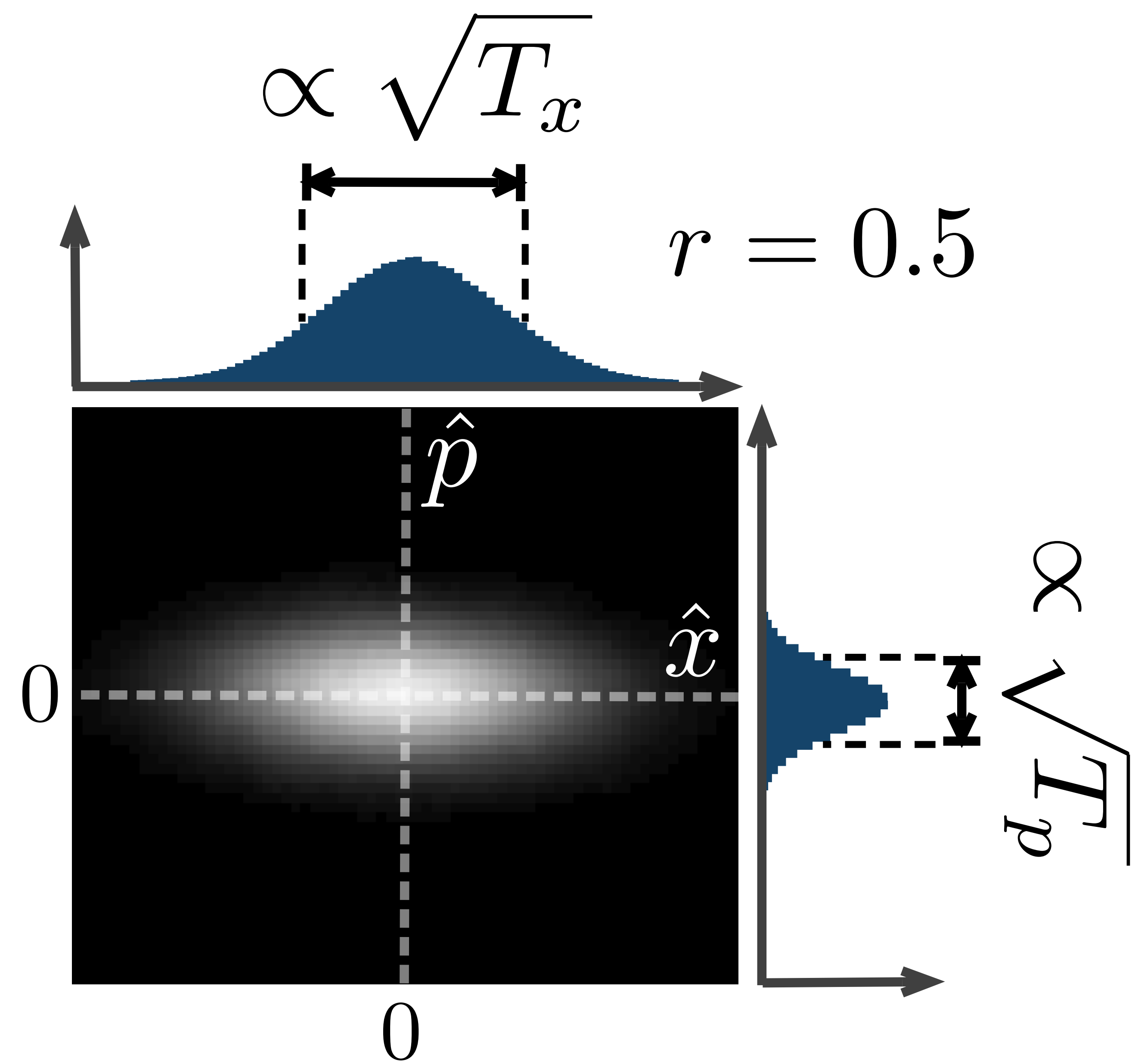
periodically modulated random force



$$f_{\mathrm{bath}}(t) = a_0 \left[\mathrm{e}^{+r}\xi_1(t)\,\cos(\omega t) + \mathrm{e}^{-r}\xi_2(t)\,\sin(\omega t)\right]$$

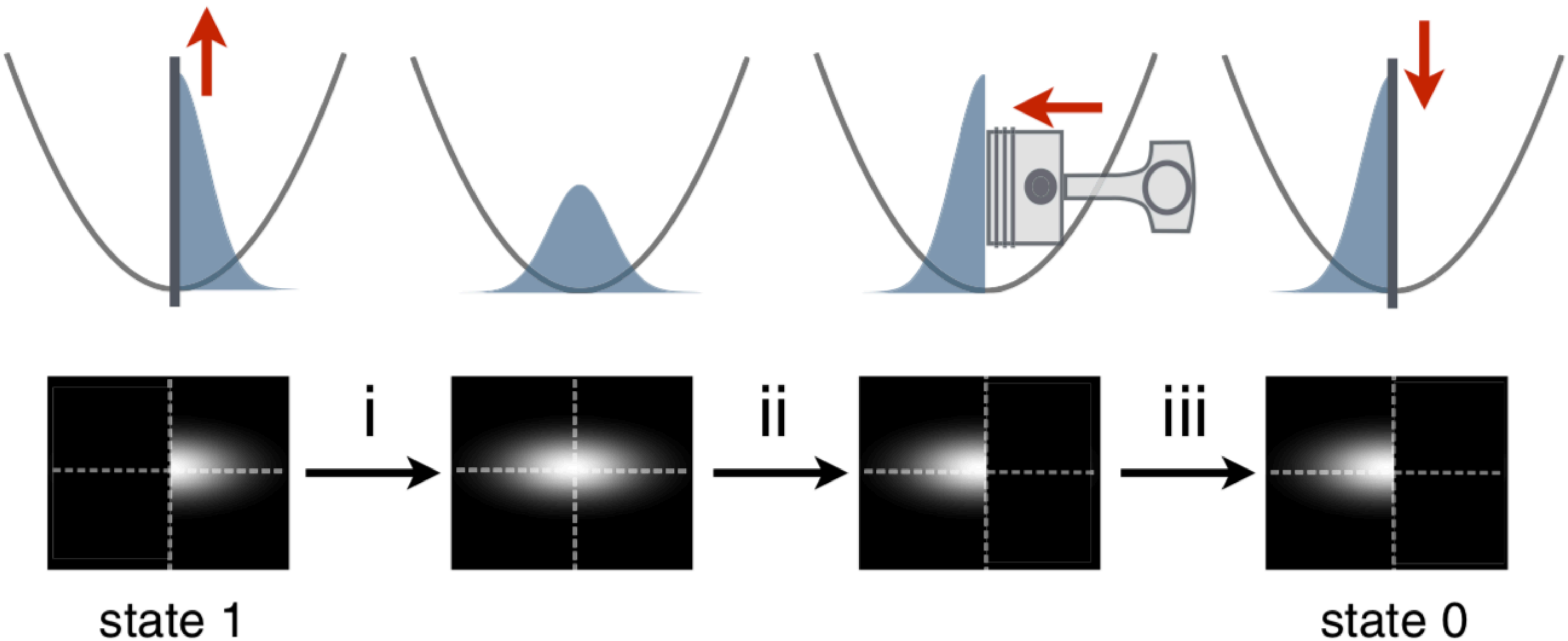
Single particle subject to squeezed noise





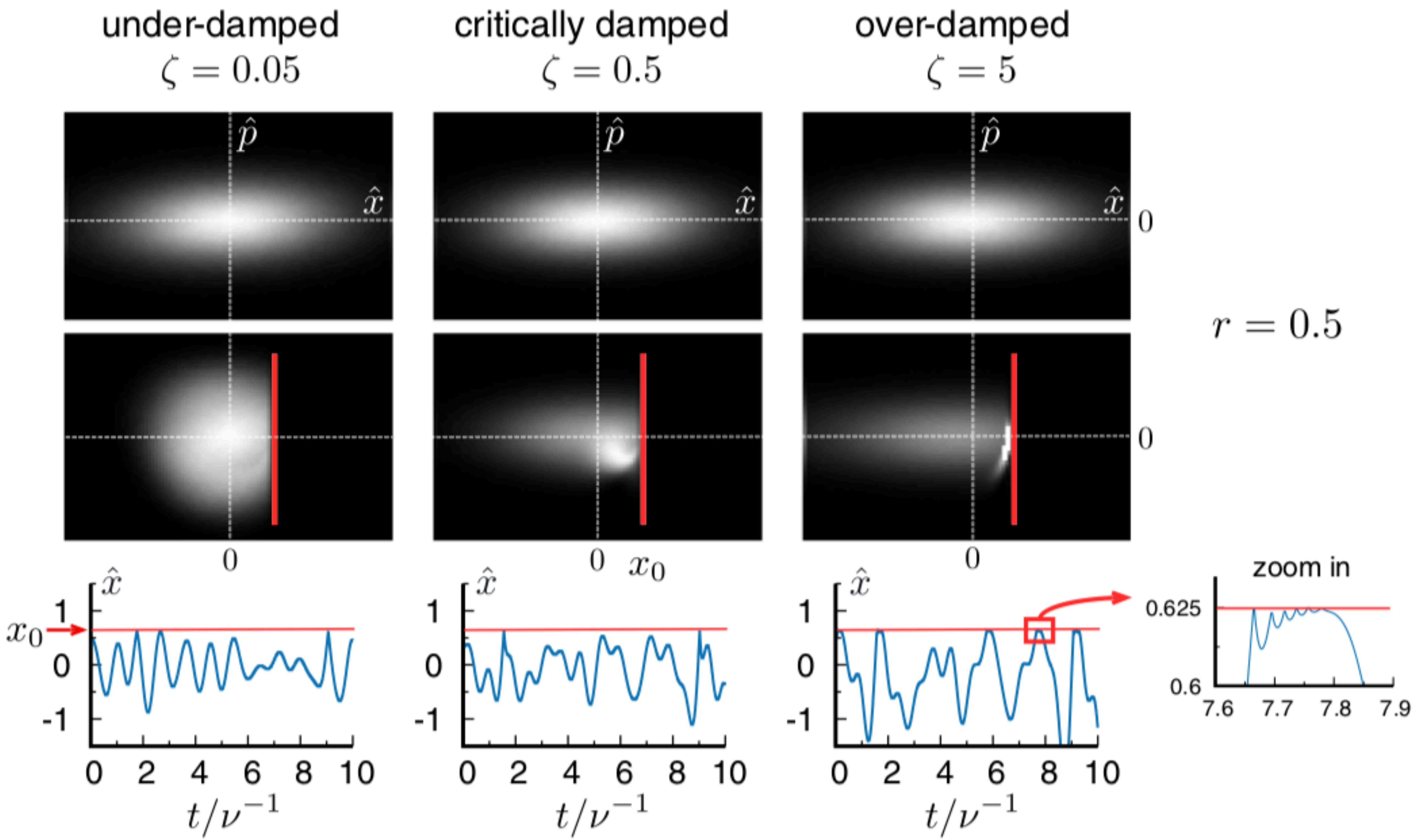
stroboscopic phase space picture

Erasing 1 bit in a squeezed thermal memory



i. remove partition (free expansion)
ii. isothermal & iso-squeezed compression
iii. insert partition

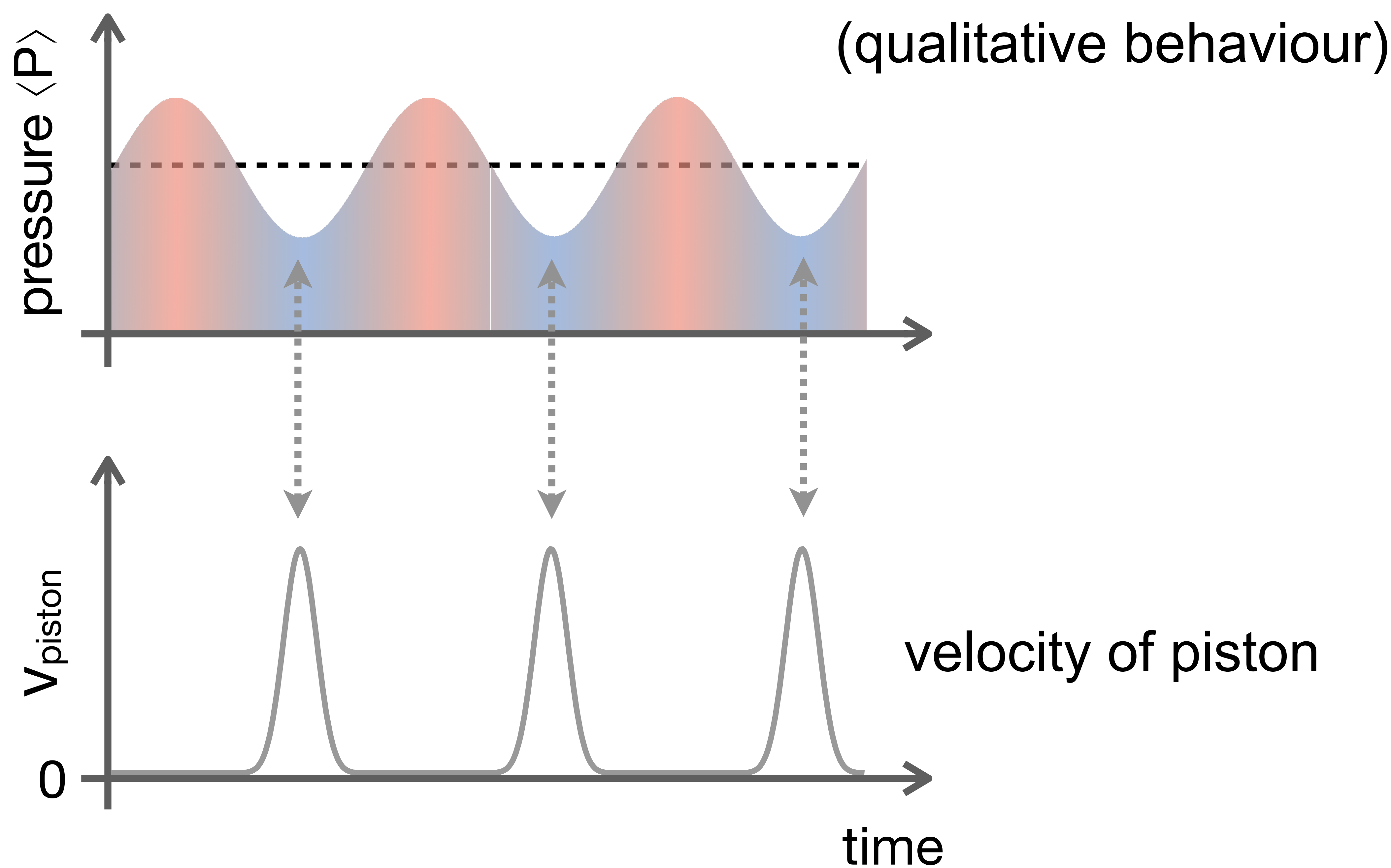
Spatially compressed squeezed thermal state



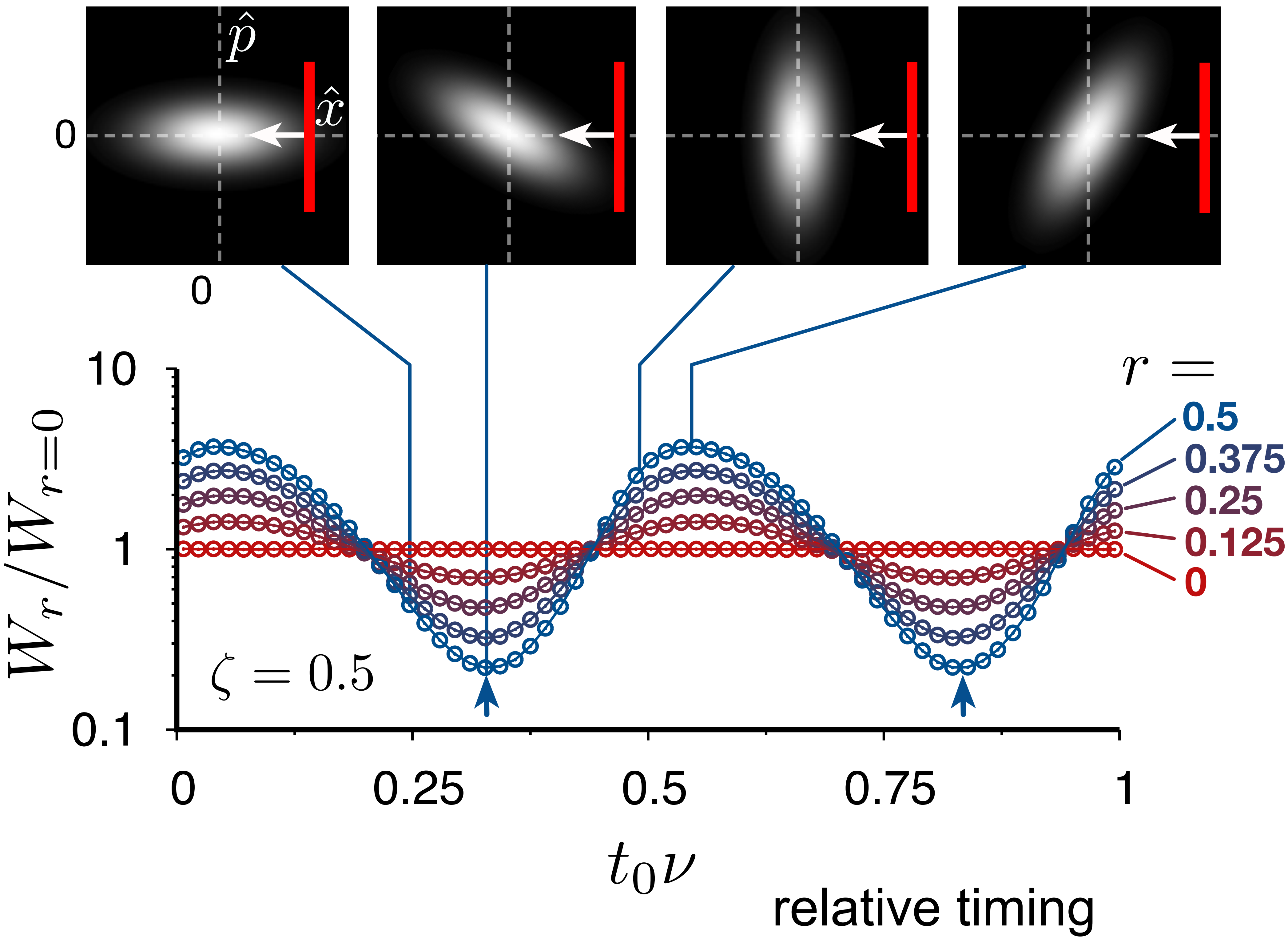
under-damped regime: squeezing canceled by piston

Isothermal compression step

General idea: use squeezing to reduce the pressure on the piston during the compression step.

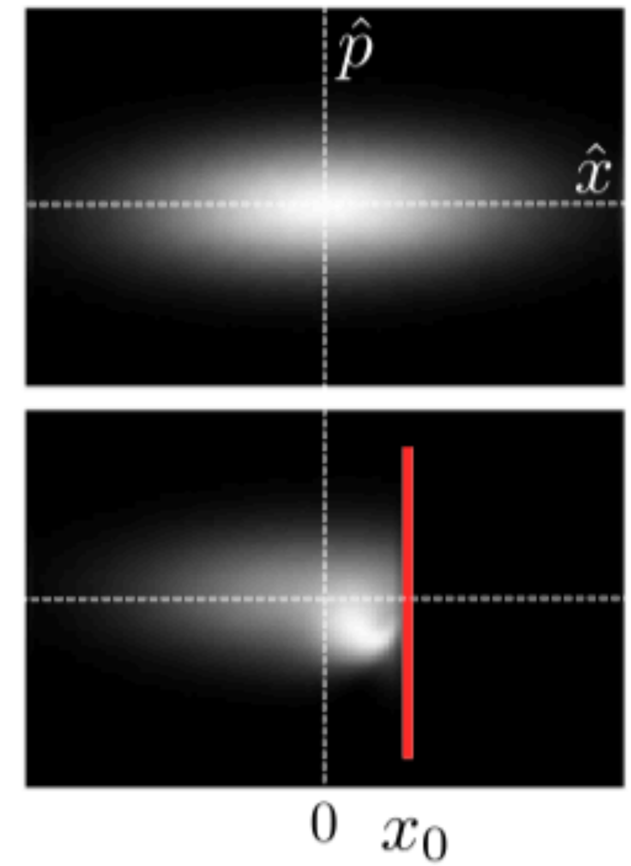


Work for compression step (numerical)



Work for compression step (analytical approx.)

$$\rho_{\mathrm{sq}}(\hat{x},\hat{p}) \;\propto\; \exp\left(-\frac{\hbar\omega\hat{x}^2}{2k_{\mathrm{B}}T_x}-\frac{\hbar\omega\hat{p}^2}{2k_{\mathrm{B}}T_p}\right)$$



$$\rho(\hat{x},\hat{p}) = Z^{-1}\,\rho_{\mathrm{sq}}(\hat{x},\hat{p})\,\Theta(x_0-\hat{x})$$

momentum transfer on piston:

$$P = \int_0^\infty 2\hbar\omega\hat{p}^2\rho(x_0,p)\,d\hat{p}$$ pressure

$$= 2b_0 g(b_0) k_{\mathrm{B}}T_p/x_0$$

$\rightarrow W = \ln 2\, k_{\mathrm{B}}T_p = \ln 2\, k_{\mathrm{B}}T\,\mathrm{e}^{-2r}$ work

Landauer principle in squeezed thermal memory

Entropy production for erasing 1 bit:

$$\Delta S = k_{\mathrm{B}} \ln 2$$

Work required for erasing 1 bit:

$$W = T_x \Delta S = (\ln 2)\, k_{\mathrm{B}} T\, \mathrm{e}^{-r}$$

Further information:

J. Klaers, Phys. Rev. Lett. 122, 040602 (2019).

Nanomechanical heat engine

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- efficiency unbounded by Carnot limit
- work extraction from single reservoir

Squeezed thermal memory

- exponential work cost reduction for erasing operation possible

Further information:

J. Klaers, S. Faelt, A. Imamoglu & E. Togan, Phys. Rev. X 7, 031044 (2017).

J. Klaers, Phys. Rev. Lett. 122, 040602 (2019).

Collaborators:

Emre Togan, Stefan Fält, Atac Imamoglu

»Thank you for your attention«