Quantum Optomechanical Heat Engine

~Ando-Lab Seminar on Sep. 2nd~

Kentaro Komori

Optomechanics ⇔ Thermodynamics

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Quantum Optomechanical Heat Engine

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We investigate theoretically a quantum optomechanical realization of a heat engine. In a generic optomechanical arrangement the optomechanical coupling between the cavity field and the oscillating end mirror results in polariton normal mode excitations whose character depends on the pump detuning and the coupling strength. By varying that detuning it is possible to transform their character from phononlike to photonlike, so that they are predominantly coupled to the thermal reservoir of phonons or photons, respectively. We exploit the fact that the effective temperatures of these two reservoirs are different to produce an Otto cycle along one of the polariton branches. We discuss the basic properties of the system in two different regimes: in the optical domain it is possible to extract work from the thermal energy of a mechanical resonator at finite temperature, while in the microwave range one can in principle exploit the cycle to extract work from the blackbody radiation background coupled to an ultracold atomic ensemble.

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Contents

Contents

- What is the heat engine?
- Hamiltonian and polaritons
- Otto cycle
- Work and efficiency
- Cosmic blackbody radiation

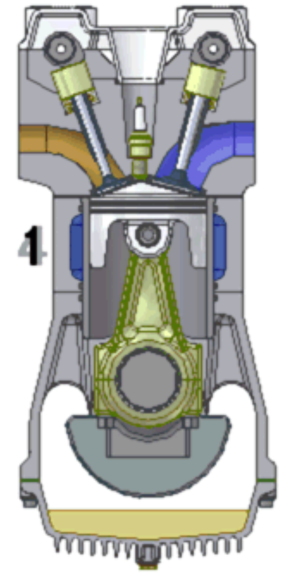
What is the heat engine?

✓ The machine producing work from heat

For example …

✧ Car engine (a kind of otto cycle)

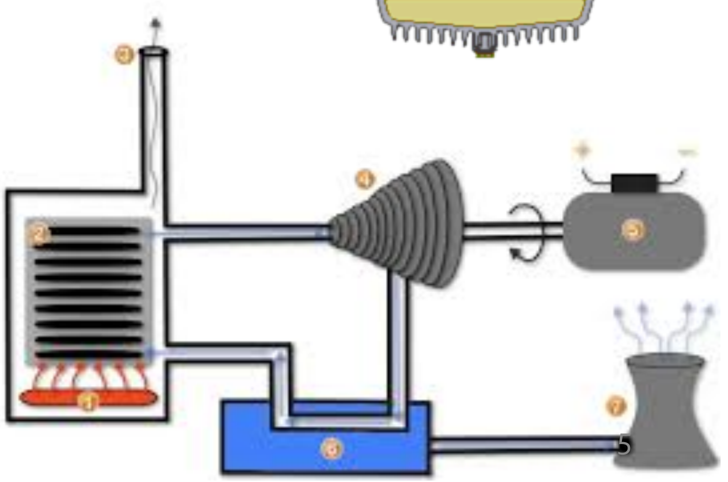
1. Intake, 2. Compression,
3. Power, 4. Exhaust



✧ Steam turbine

Fuel ⟶ Gas

Heat ⇧   ⇨ Work

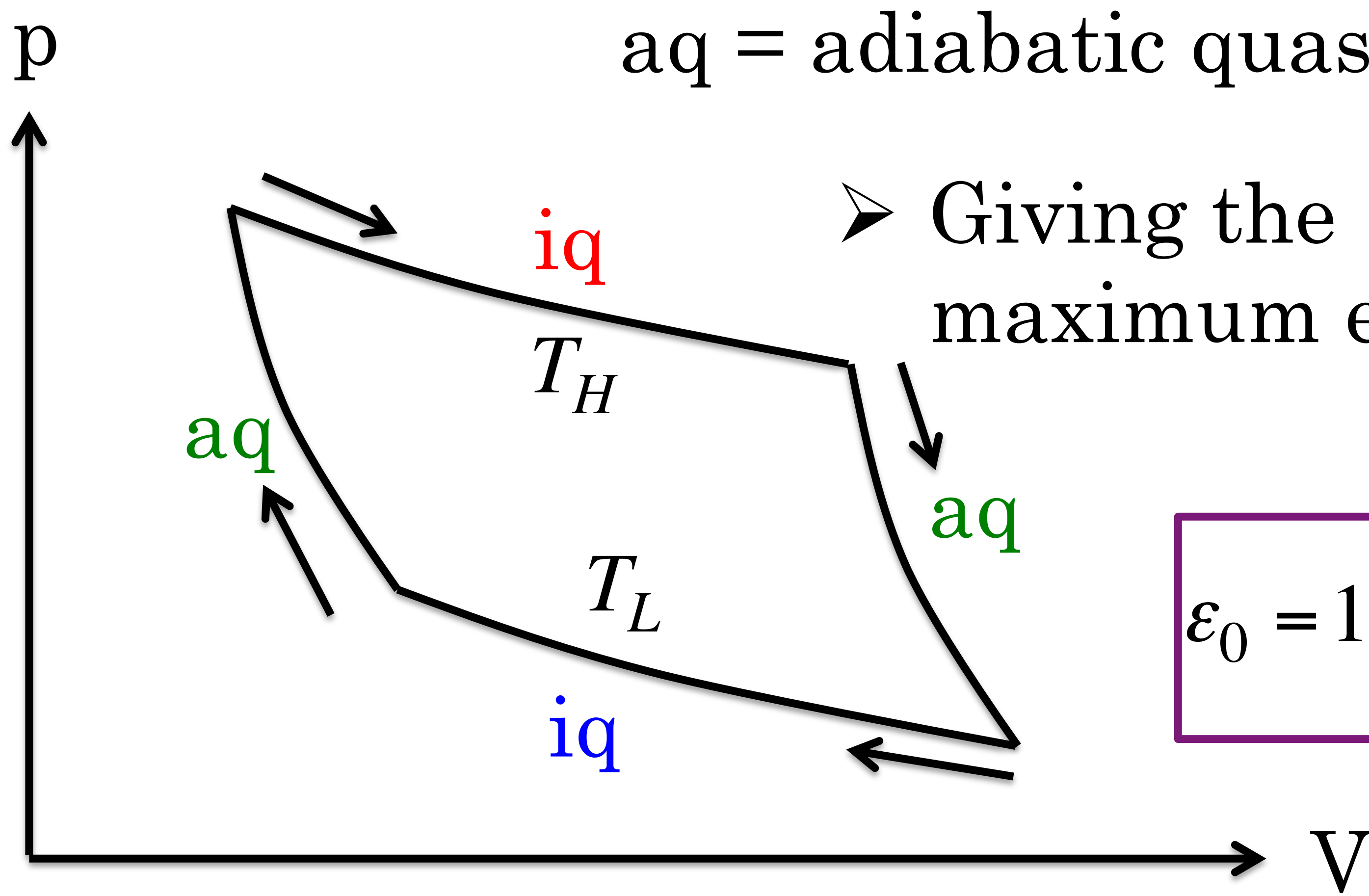


Cycles at thermodynamics

- Carnot cycle

iq = isothermal quasistatic

aq = adiabatic quasistatic

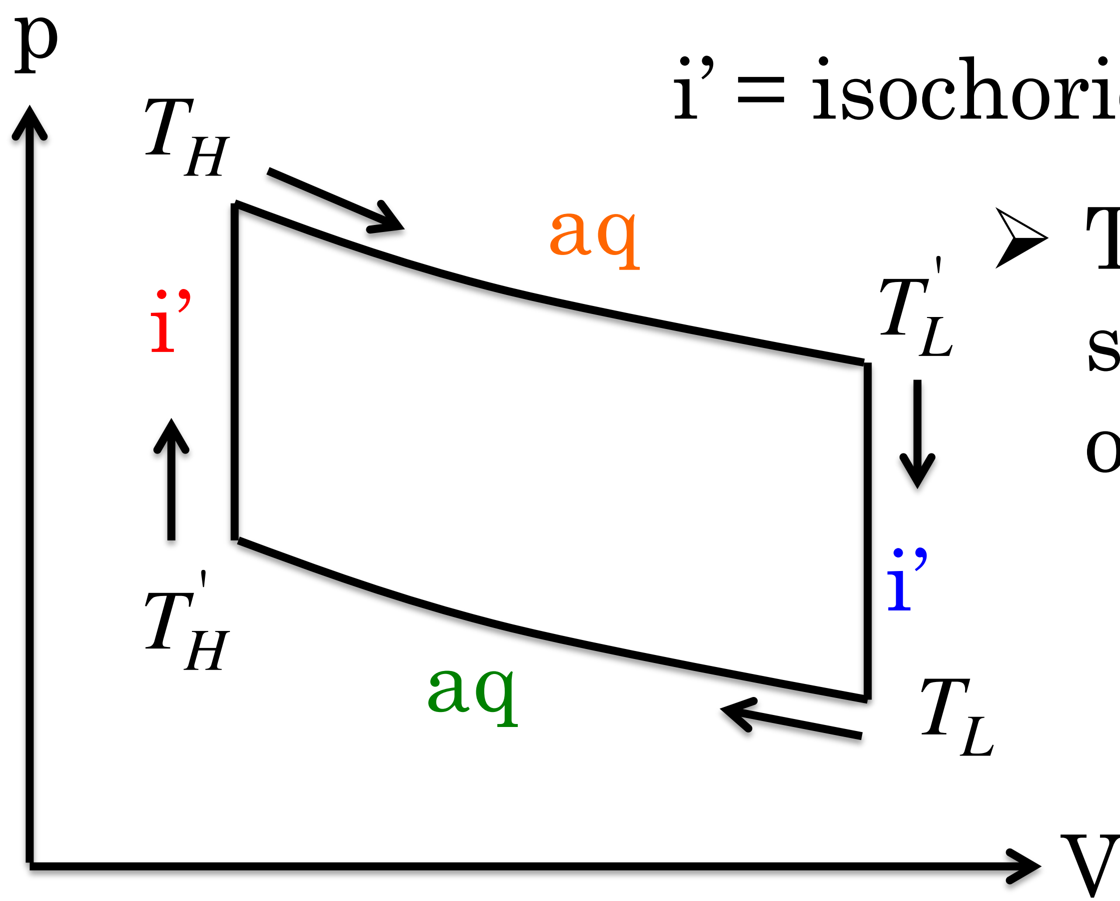


- Giving the maximum efficient

$$\varepsilon_0 = 1 - \frac{T_L}{T_H}$$

Cycles at thermodynamics

- Otto cycle (considered at this seminar)



i' = isochoric

- The efficient is smaller than one of carnot

$$\varepsilon = 1 - \frac{T_L}{T_H^{'}} < \varepsilon_0$$

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Hamiltonian

- Linearized optomechanical coupling

$$H = \underbrace{-\hbar\Delta\hat{a}^{\dagger}\hat{a}}_{\text{optical}} + \underbrace{\hbar\omega_m\hat{b}^{\dagger}\hat{b}}_{\text{mechanical}} + \underbrace{\hbar G(\hat{b}+\hat{b}^{\dagger})(\hat{a}+\hat{a}^{\dagger})}_{\text{optomechanical}}$$

$\bar{\alpha}+\hat{a}$: average + photon annihilation

$\hat{b}$: phonon annihilation

Δ : cavity detuning

ω_m : mechanical resonant frequency

Hamiltonian

- Linearized optomechanical coupling

$$\mathrm{H} = -\hbar\Delta\hat{a}^\dagger\hat{a} + \hbar\omega_m\hat{b}^\dagger\hat{b} + \hbar G(\hat{b}+\hat{b}^\dagger)(\hat{a}+\hat{a}^\dagger)$$

$$= -\hbar\Delta\frac{X_c^2+P_c^2}{2} + \hbar\omega_m\frac{X_m^2+P_m^2}{2} + 2\hbar G X_m X_c$$

$$X_c = \frac{\hat{a}+\hat{a}^\dagger}{\sqrt{2}}, P_c = \frac{\hat{a}-\hat{a}^\dagger}{\sqrt{2}i}$$ ：optical quadrature

$$X_m = \frac{\hat{b}+\hat{b}^\dagger}{\sqrt{2}}, P_m = \frac{\hat{b}-\hat{b}^\dagger}{\sqrt{2}i}$$ ：mechanical quadrature

Hamiltonian

- Linearized optomechanical coupling

$$
\begin{aligned}
\mathrm{H} &= -\hbar\Delta\hat{a}^{\dagger}\hat{a} + \hbar\omega_m\hat{b}^{\dagger}\hat{b} + \hbar G(\hat{b}+\hat{b}^{\dagger})(\hat{a}+\hat{a}^{\dagger}) \\
&= -\hbar\Delta\frac{X_c^2+P_c^2}{2} + \hbar\omega_m\frac{X_m^2+P_m^2}{2} + 2\hbar G X_m X_c \\
&= \hbar\omega_+\frac{X_+^2+P_+^2}{2} + \hbar\omega_-\frac{X_-^2+P_-^2}{2} \\
&= \hbar\omega_+\underline{\hat{A}^{\dagger}\hat{A}} + \hbar\omega_-\underline{\hat{B}^{\dagger}\hat{B}}
\end{aligned}
$$

diagonalization

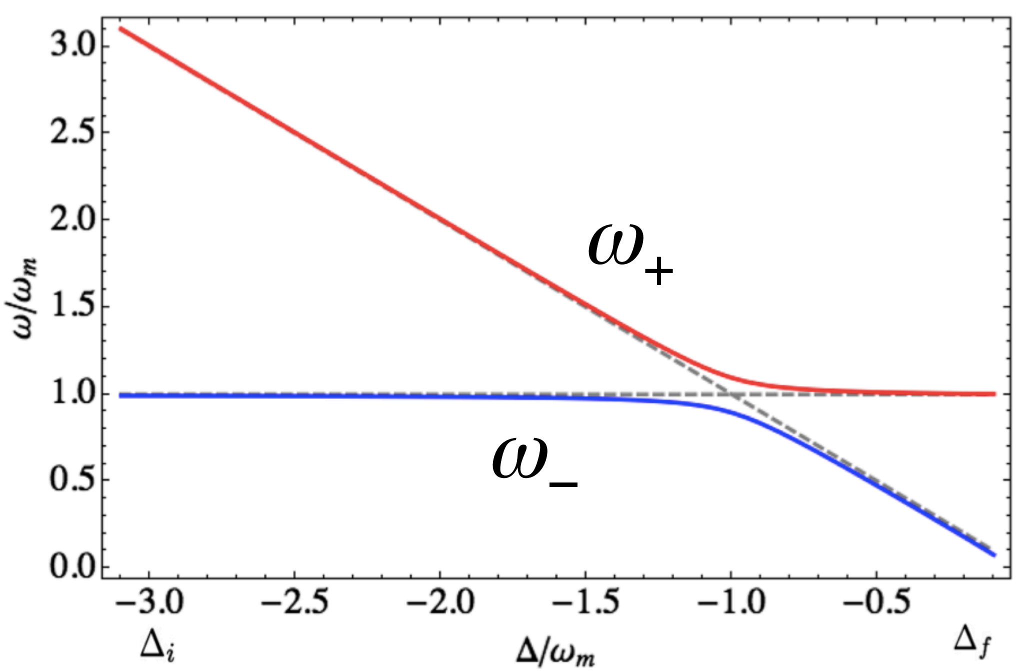
new bosonic annihilation operators

(linear combinations of $\hat{a},\hat{a}^{\dagger},\hat{b},\hat{b}^{\dagger}$)

Hamiltonian

- the frequency of polaritons

$$\omega_{\pm} = \sqrt{\frac{\Delta^2 + \omega_m^2 \pm \sqrt{(\Delta^2 - \omega_m^2)^2 - 16G^2\Delta\omega_m}}{2}}$$



Focusing on the normal-mode $\hat{B}$

$\omega_- \sim \omega_m (\Delta < -\omega_m)$

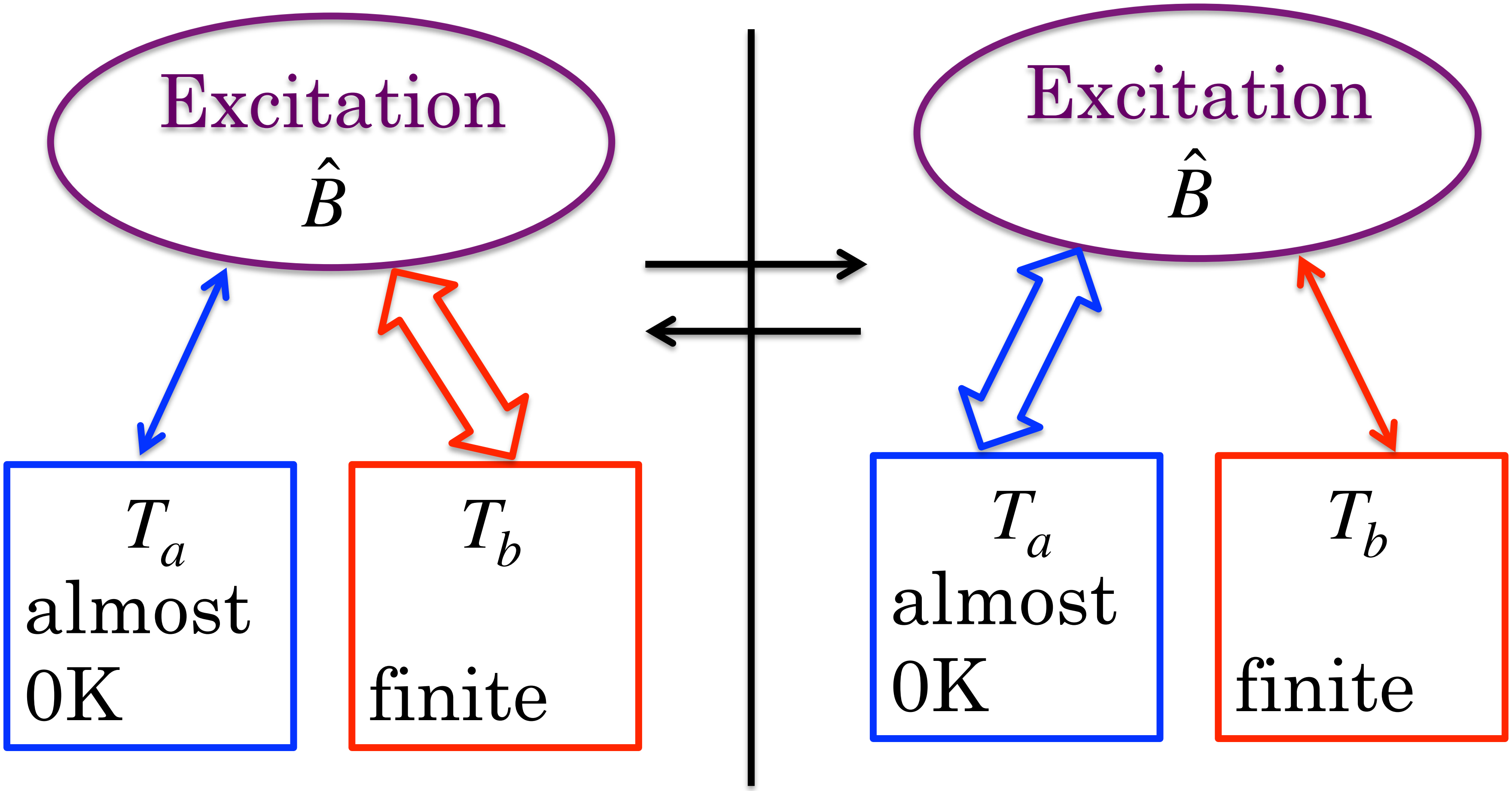
phononlike

⇕

$\omega_- \sim -\Delta(-\omega_m < \Delta < 0)$

photonlike

Situation



$\omega_- \sim \omega_m (\Delta < -\omega_m)$
phononlike

$\omega_- \sim -\Delta(-\omega_m < \Delta < 0)$
photonlike

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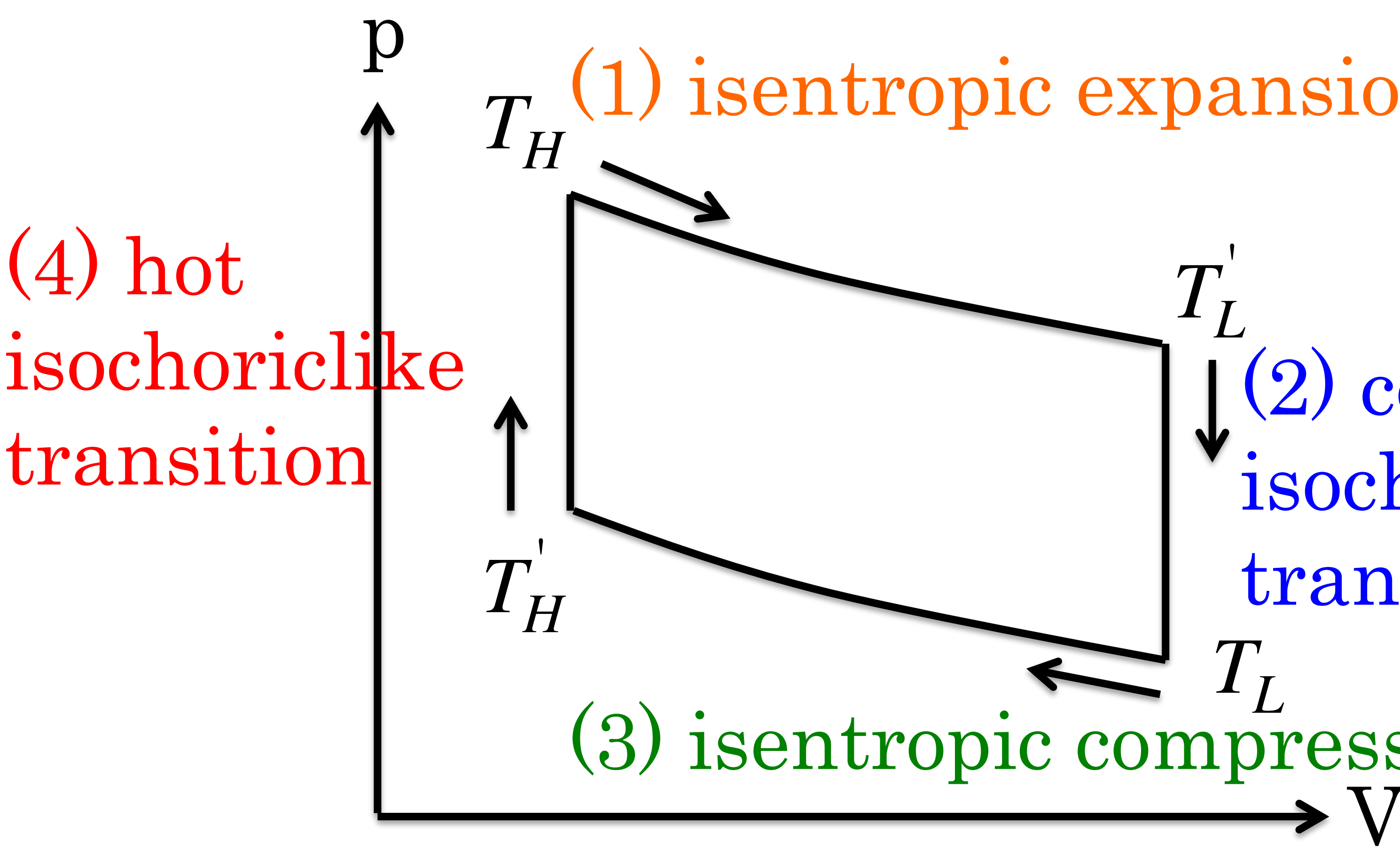
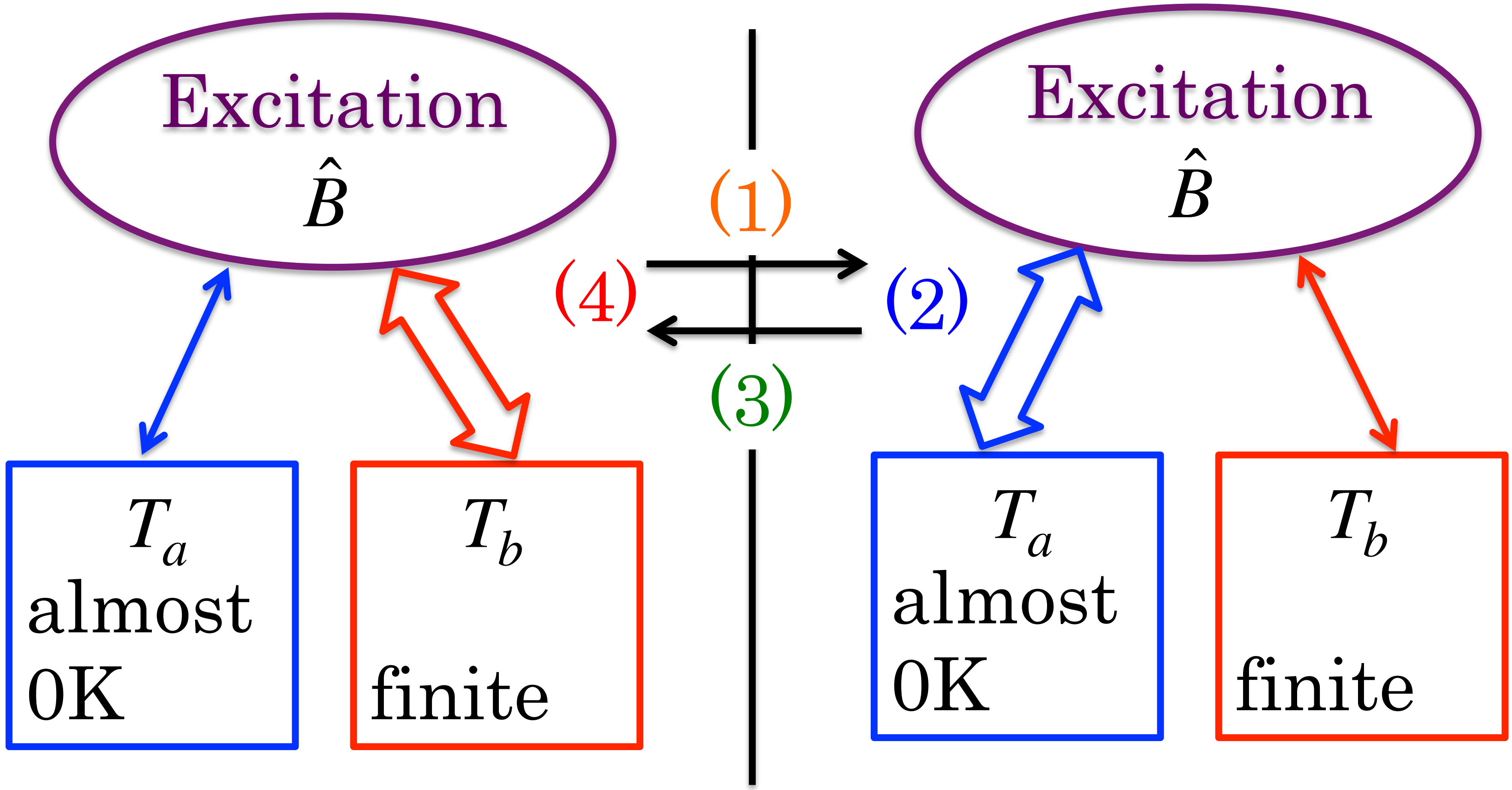
Otto cycle



(1),(3) changing detuning (laser frequency)

Situation



$\omega_{-} \sim \omega_m (\Delta < -\omega_m)$
phononlike

$\omega_{-} \sim -\Delta (-\omega_m < \Delta < 0)$
photonlike

(1) Isentropic expansion

$\omega_i \sim \omega_m (\Delta < -\omega_m)$

phononlike

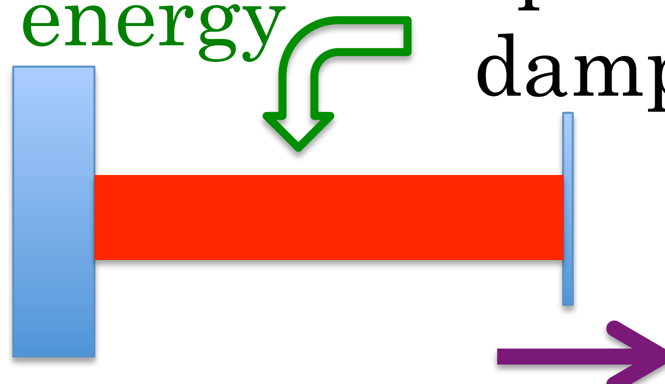
$$N_i = \left\langle \hat{B}^\dagger \hat{B} \right\rangle_{\omega_i, T_i}$$ remains unchanged

$\omega_f \sim -\Delta(-\omega_m < \Delta < 0)$

photonlike

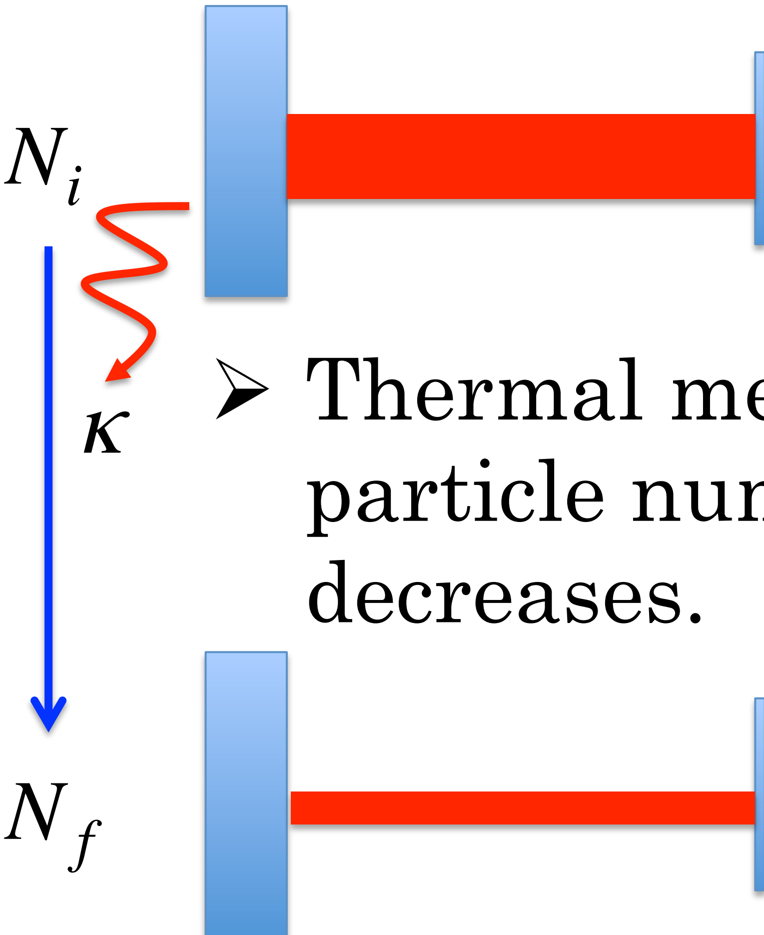
energy

optical damping

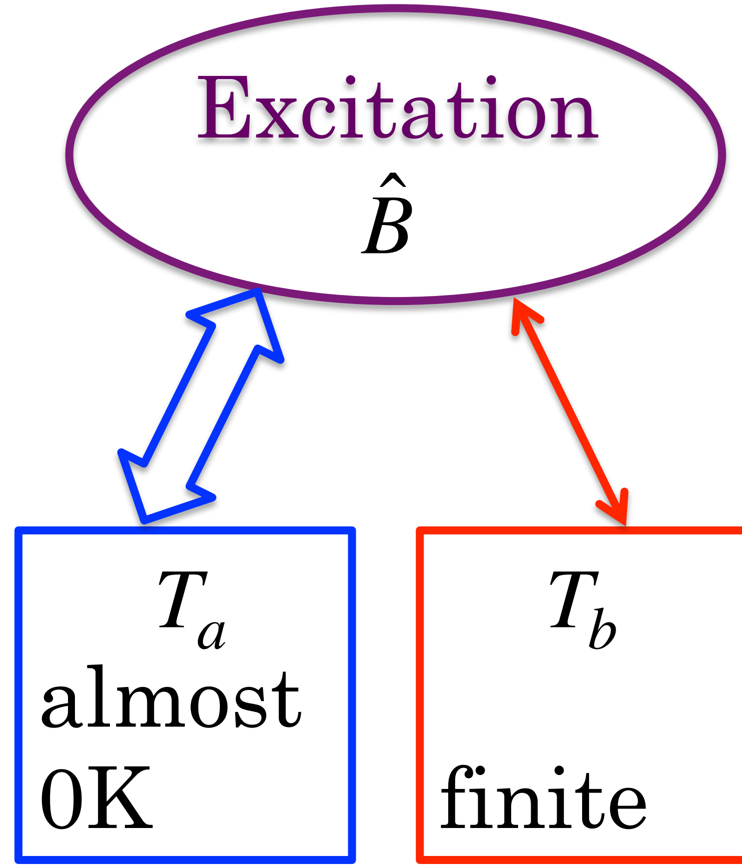


increased radiation pressure = work

(2) Cold Isochoriclike transition



- Thermal mean particle number decreases.



$$\omega_f \sim -\Delta(-\omega_m < \Delta < 0)$$

photonlike

(3) Isentropic compression

$$\omega_f \sim -\Delta(-\omega_m < \Delta < 0)$$

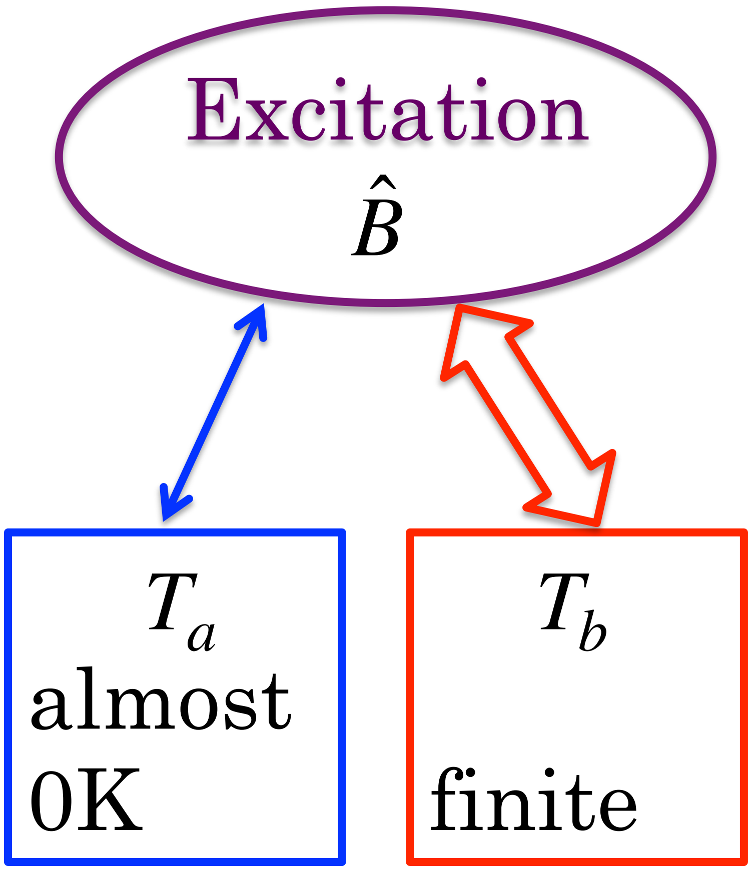
photonlike

$N_f = \left\langle \hat{B}^\dagger \hat{B} \right\rangle_{\omega_f, T_f}$ remains unchanged

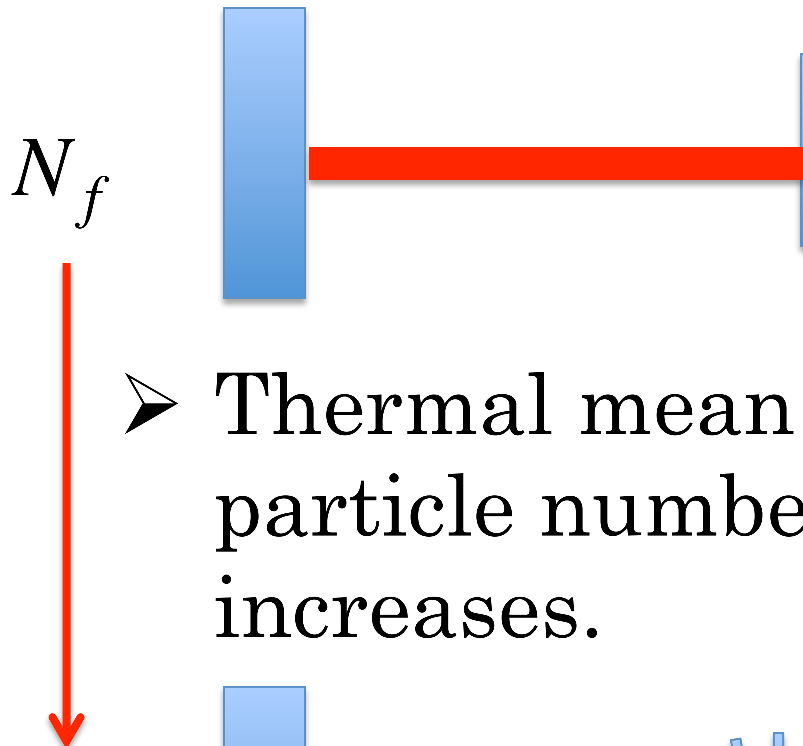
$$\omega_i \sim \omega_m(\Delta < -\omega_m)$$

phononlike

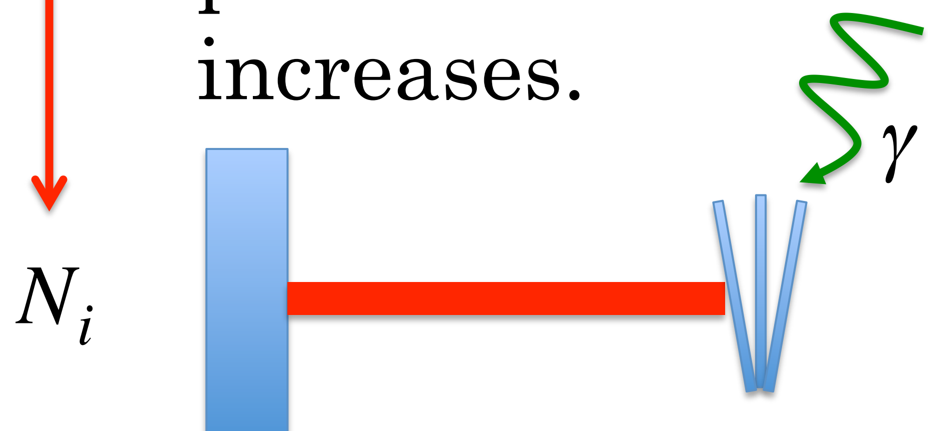
(4) Hot Isochoriclike transition



$\omega_i \sim \omega_m (\Delta < -\omega_m)$
phononlike



- Thermal mean particle number increases.



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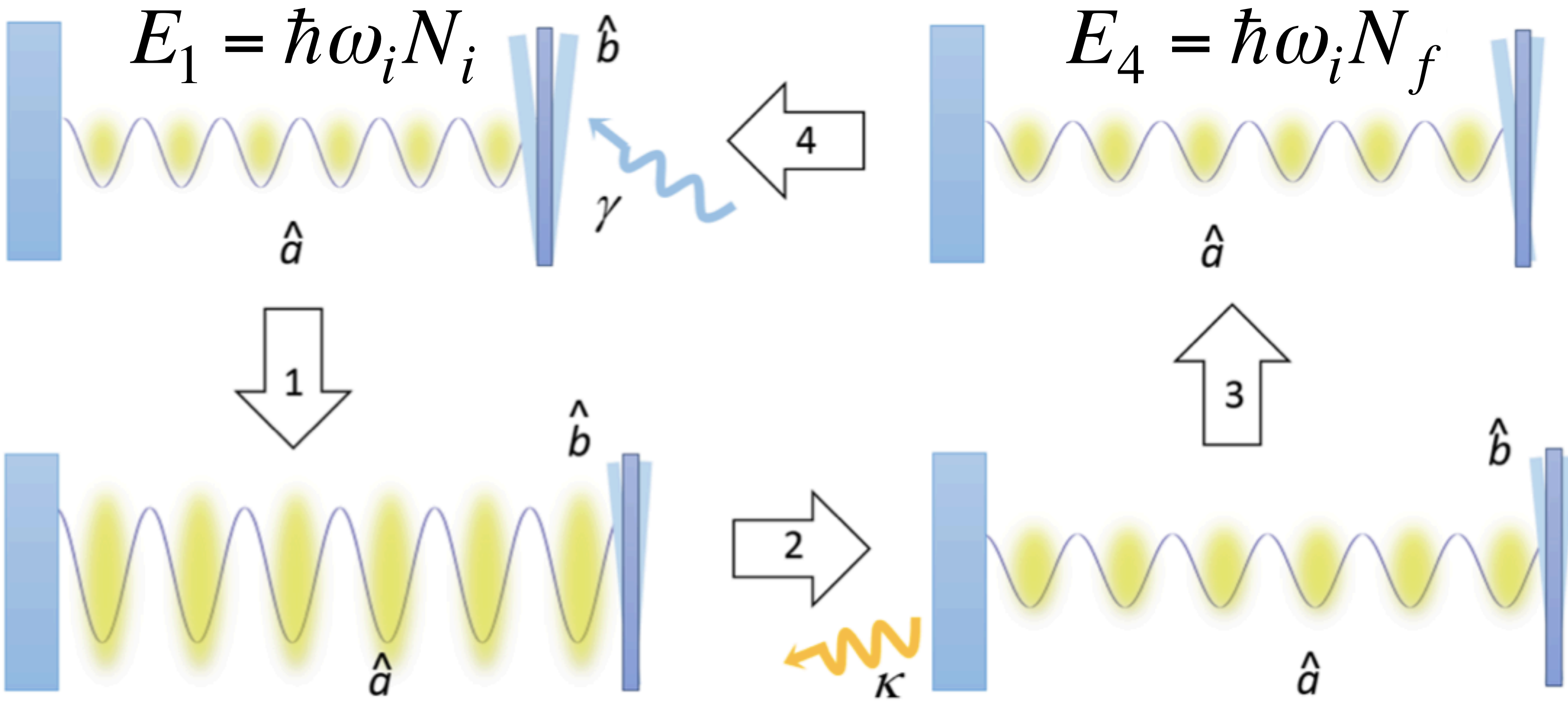
Work and efficiency



$$E_2 = \hbar\omega_f N_i$$

$$E_3 = \hbar\omega_f N_f$$

- total work

$$W = E_1 - E_2 + E_3 - E_4$$

- received heat

$$Q = E_1 - E_4$$

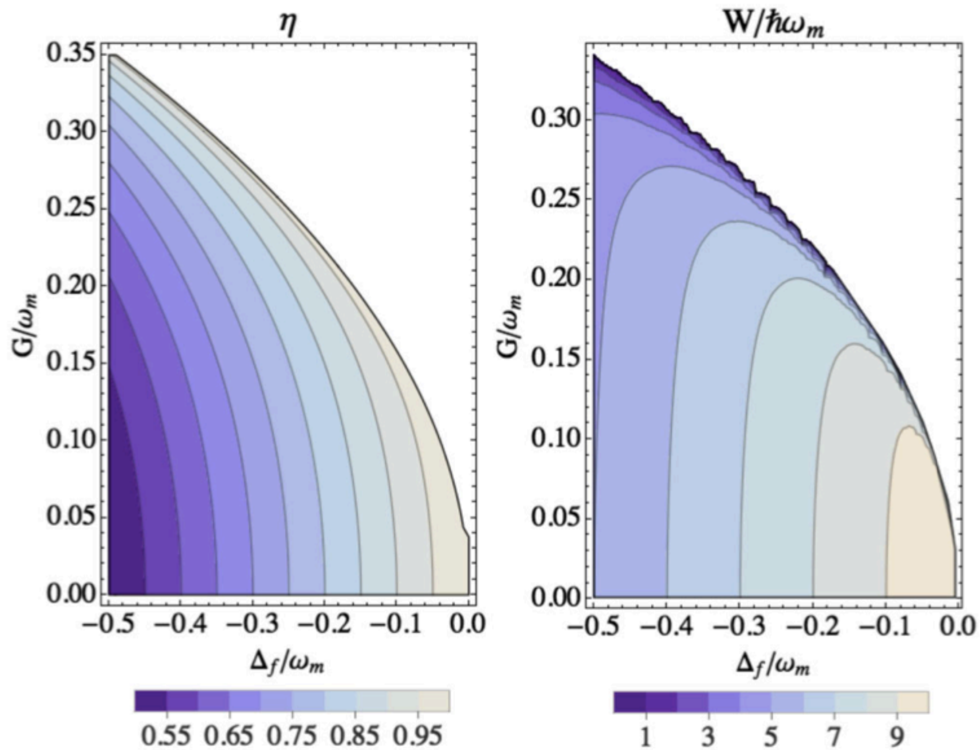
Work and efficiency

- efficiency

$$\eta = \frac{W}{Q} = 1 - \frac{\omega_f}{\omega_i}$$

$$W = \hbar(\omega_i - \omega_f)(N_i - N_f)$$

$$Q = \hbar\omega_i(N_i - N_f)$$



$$\Delta_i = -3\omega_m$$

$$T_a = 0, T_b = 0.1$$

Work and efficiency

When $\frac{G}{\omega_m} << 1$ (weak coupling)

and $-\frac{\Delta_f}{\omega_m} << 1$,the approximate values are

$$\omega_i = \omega_m \qquad N_i = n_b$$

$$\omega_f = -\Delta_f - \frac{2G^2}{\omega_m} \qquad N_f = \left(1 + \frac{4\Delta_f G^2}{\omega_m^3}\right) n_a + \frac{2G^2}{\omega_m^2} n_b$$

$$\frac{W}{\hbar\omega_m} = \left(\frac{\Delta_f}{\omega_m} + \frac{2G^2}{\omega_m^2} + 1\right)\left[\left(1 - \frac{2G^2}{\omega_m^2}\right) n_b - \frac{G^2}{\omega_m^2}\right]$$

Work and efficiency

In the high temperature limit of phonon bath,

$\frac{k_B T_b}{\hbar \omega_m} >> 1$, the efficiency at maximum work is

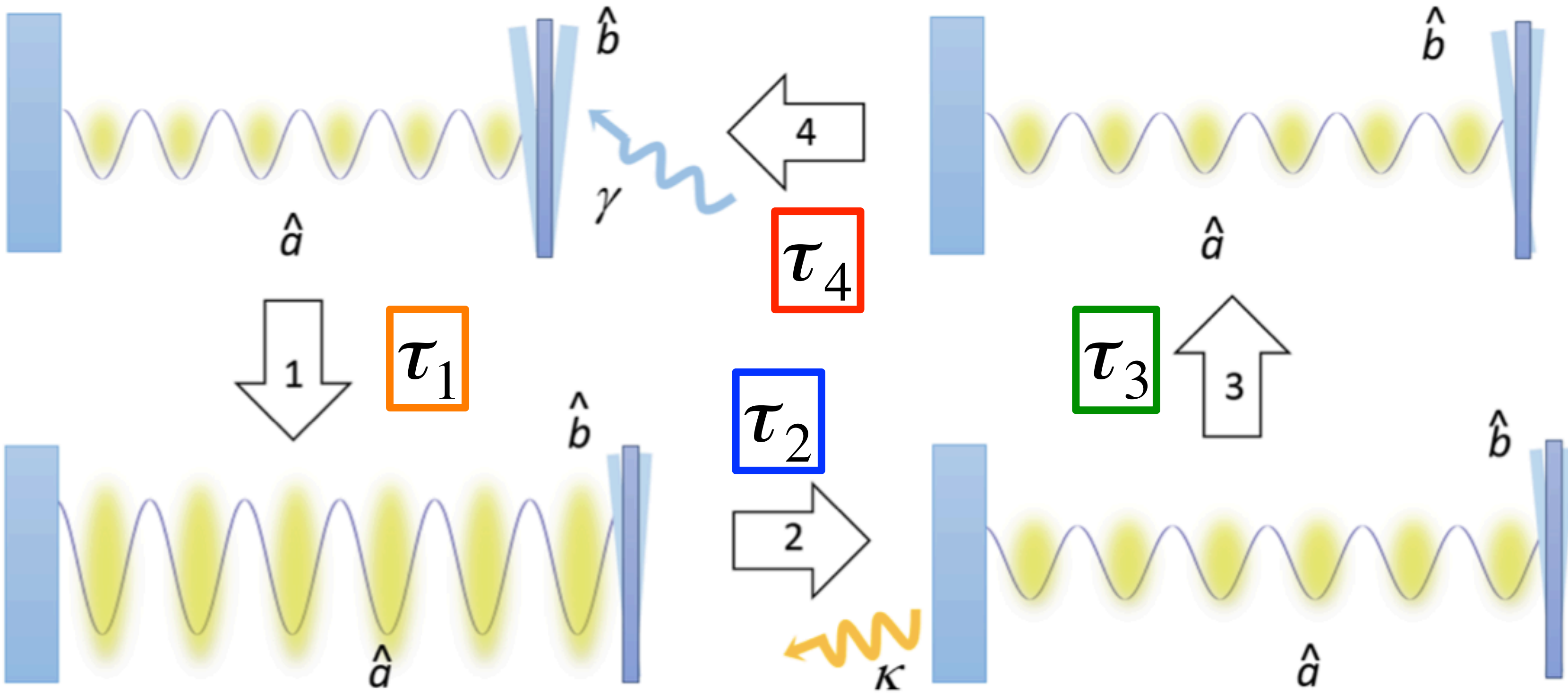
$$\eta_W = 1 - \left(\frac{-\Delta_f}{\omega_m} + \frac{\hbar \omega_m}{4 k_B T_b} \right)$$

$$< 1 - \sqrt{\frac{-\hbar \Delta_f}{2 k_B T_b}}$$

c.f. Carnot limit

$$\eta < 1 + \frac{\hbar \Delta_f}{2 k_B T_b}$$

Timescale

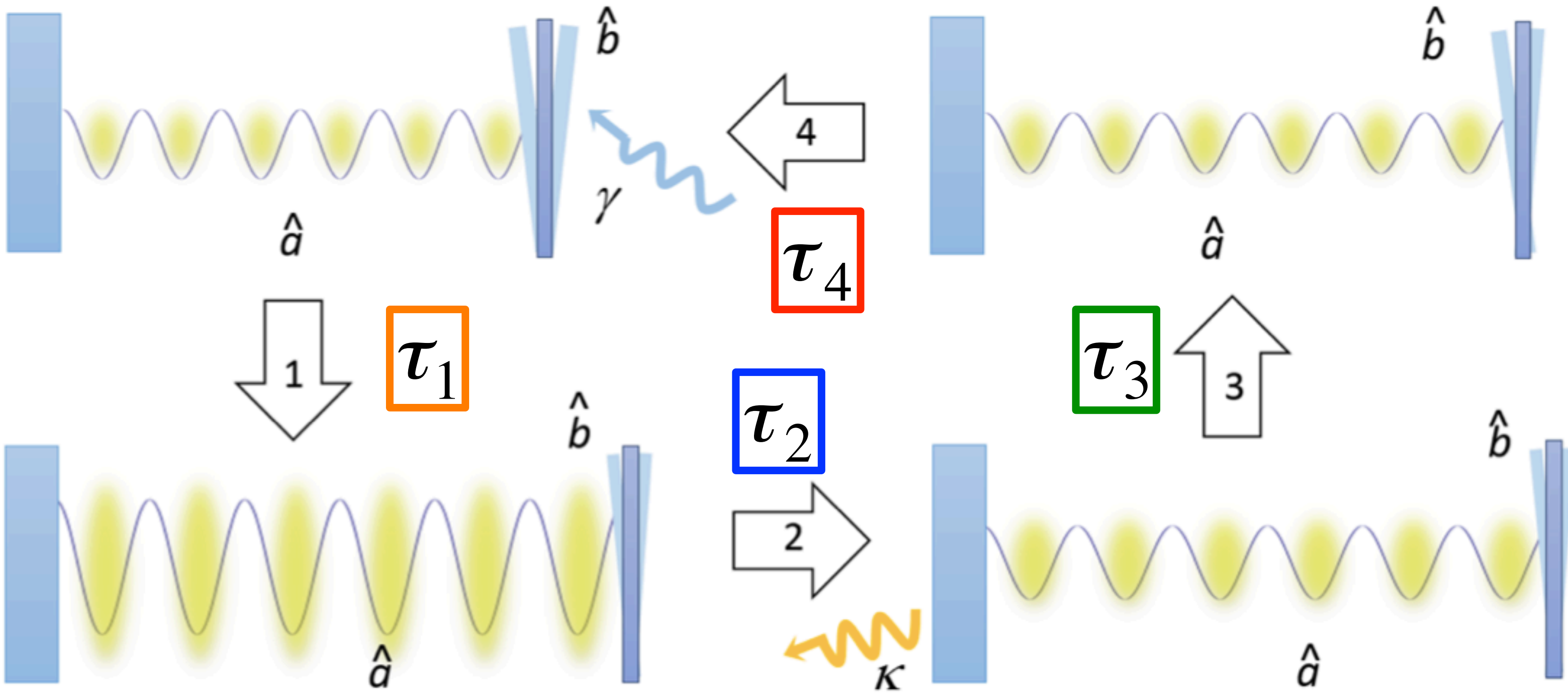


$$1/G << \tau_1, \tau_3 < 1/\kappa$$

preventing transition between $\hat{A}$ and $\hat{B}$

keeping N_i, N_f unchanged

Timescale

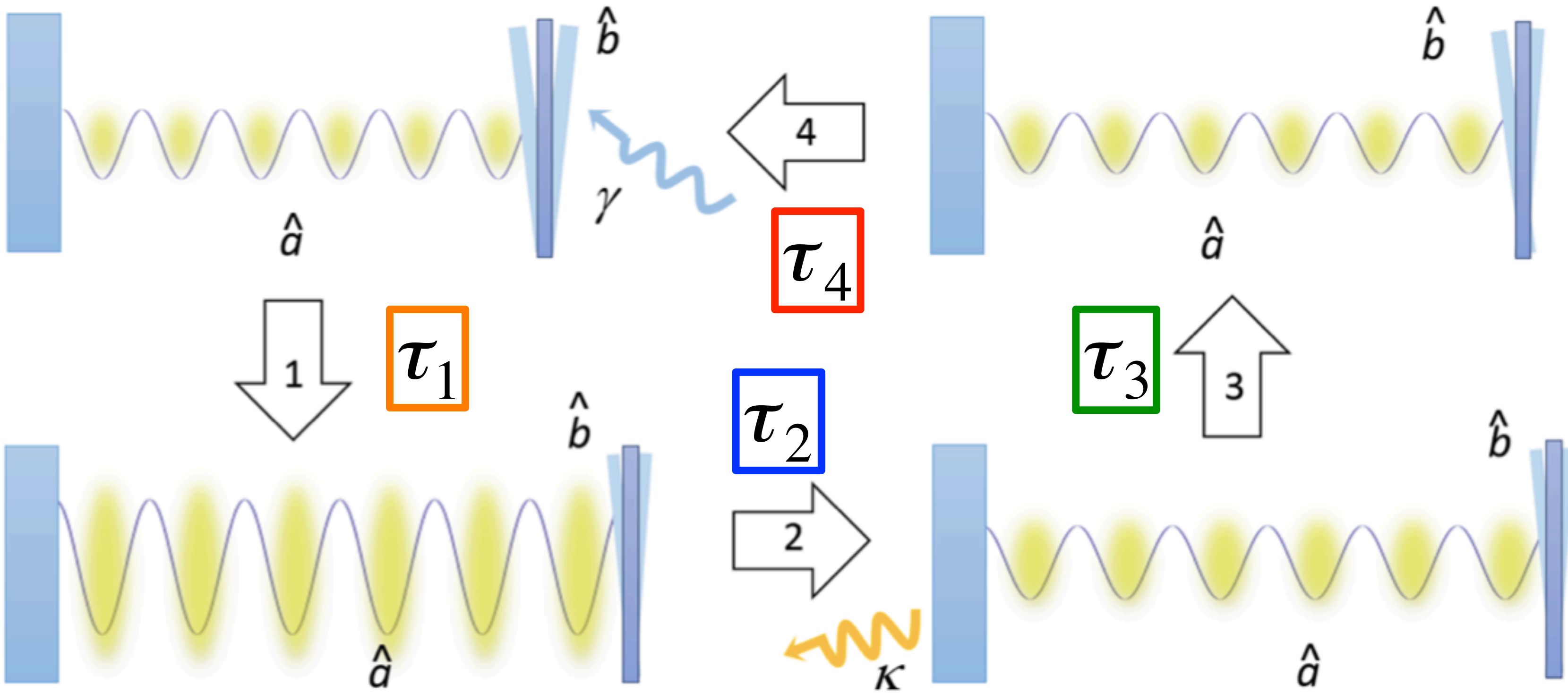


$$1/\kappa < \tau_2 << 1/\gamma$$

waiting thermalization

preventing thermalization of $\hat{A}$

Timescale

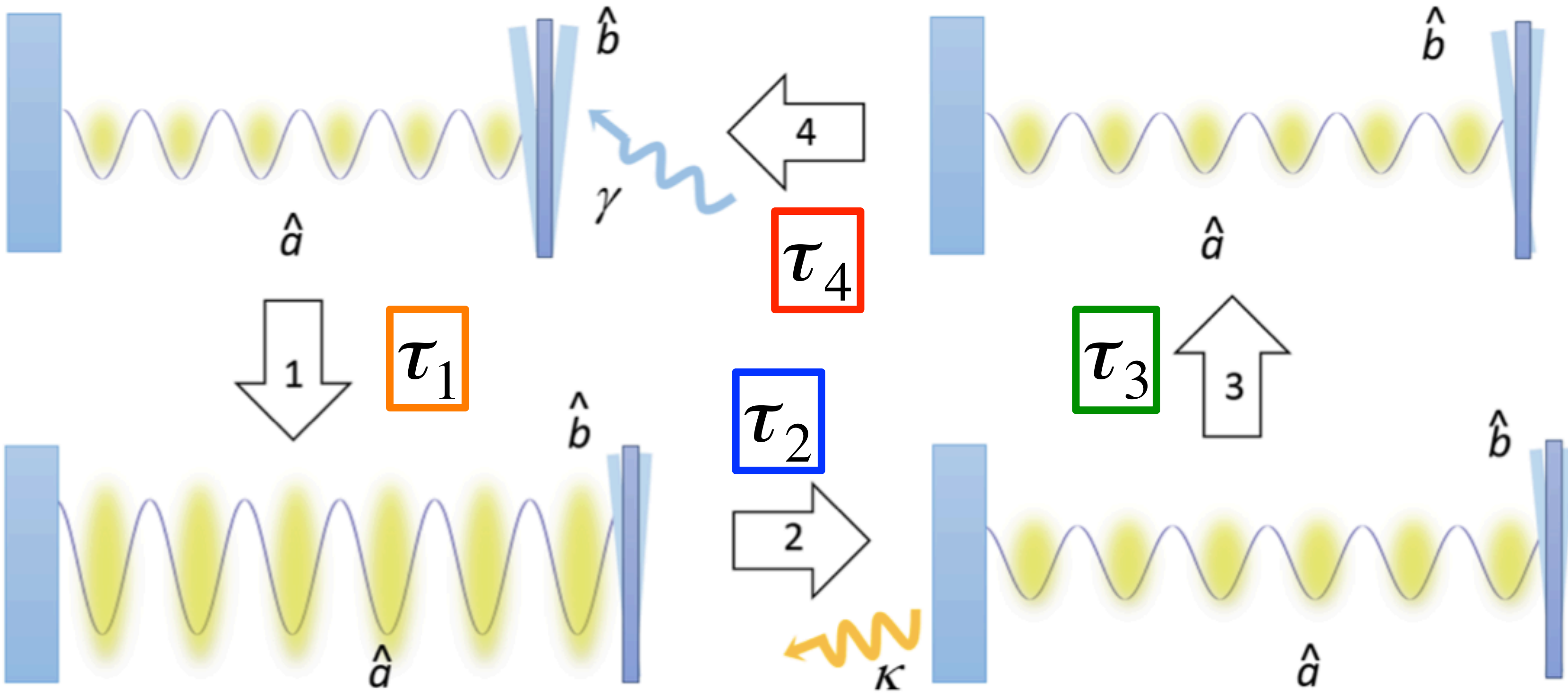


$$1/\gamma < \tau_4$$

waiting

thermalization

Timescale



requirement

$$1/\tau_4 < \gamma << 1/\tau_2 < \kappa < 1/\tau_{1,3} << G << \omega_m$$

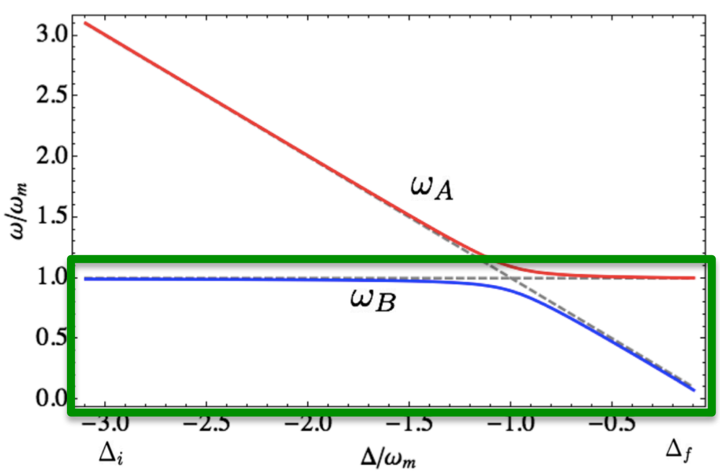
Contents

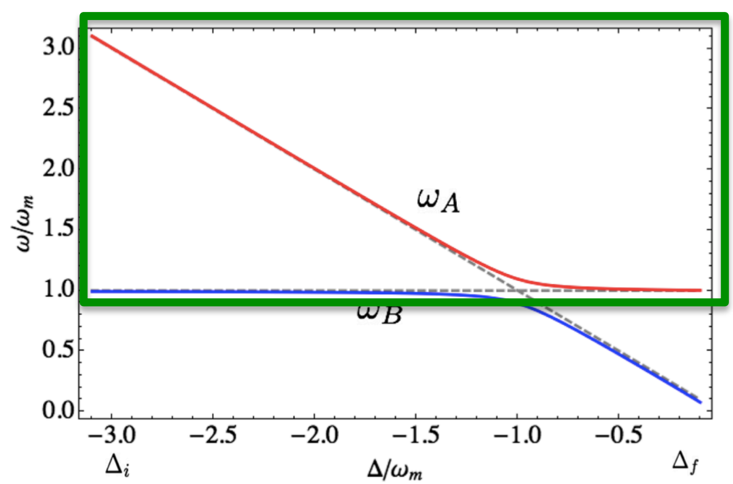
Cosmic blackbody radiation

cold	hot		hot	cold
photon 0K	phonon finite	⇔	CMB 2.7K	cold-atom pK

optical regime

microwave regime





Cosmic blackbody radiation

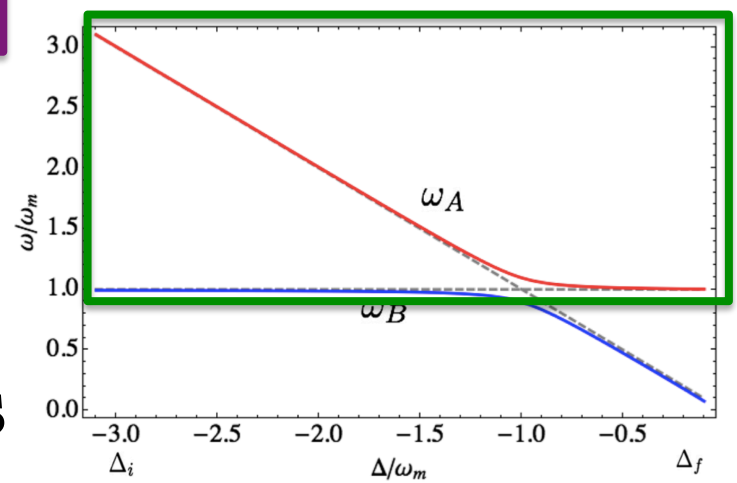
- Can extract energy from CMB !

requirement

thermal motion < coherent momentum recoil $2\hbar k$

hot	cold
CMB 2.7K	cold-atom pK

microwave regime



In a case of lithium atoms, not to exceed a pK for 300 GHz photons

Future work

- Evaluating the role of imperfections due to the coupling to the thermal reservoirs.

- Considering the effects of non-adiabatic transitions between polaritons and non-ideal control of maintaining the intra-cavity power.

- Method to extract work from the cycle actually

Summary

- Heat engine can be realized with opto-mechanical system.

- It is possible to produce an Otto cycle by varying the cavity detuning in terms of two effective reservoirs, which consist phonon and photon.

- In principle, this system can extract work from cosmic microwave background.