Energy conversion at the nanoscale

Exploiting nonthermal resources

Henning Kirchberg

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WPC Theoretical Physics Symposium 2025, U Hamburg, 14th May 2025

"La Bête humaine", comic after Emile Zola in 1890, Hachette 2018

Task: Transporting heavy goods

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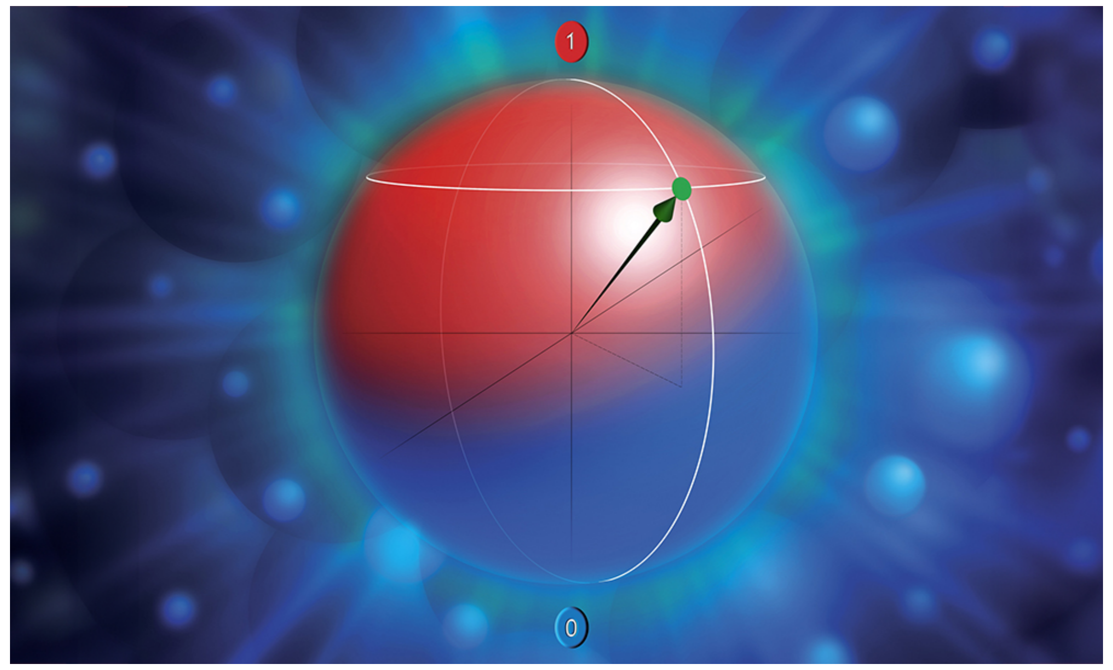
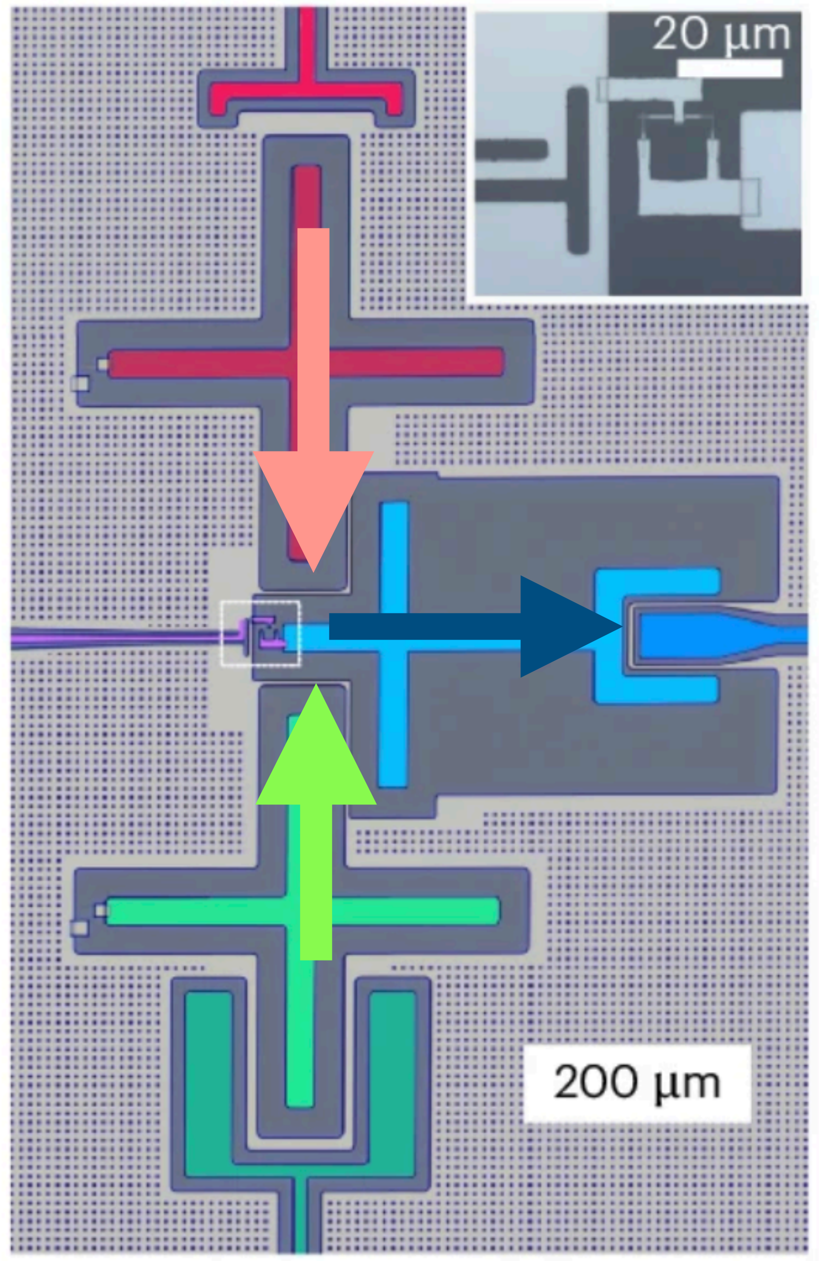


Mark Garlick / Getty Images Science Photo Library



Aamir, M. A. et al. Nat. Phys. 21, 318-323 (2025)

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Task: Transporting heavy goods

Resource: Heat, easy to have

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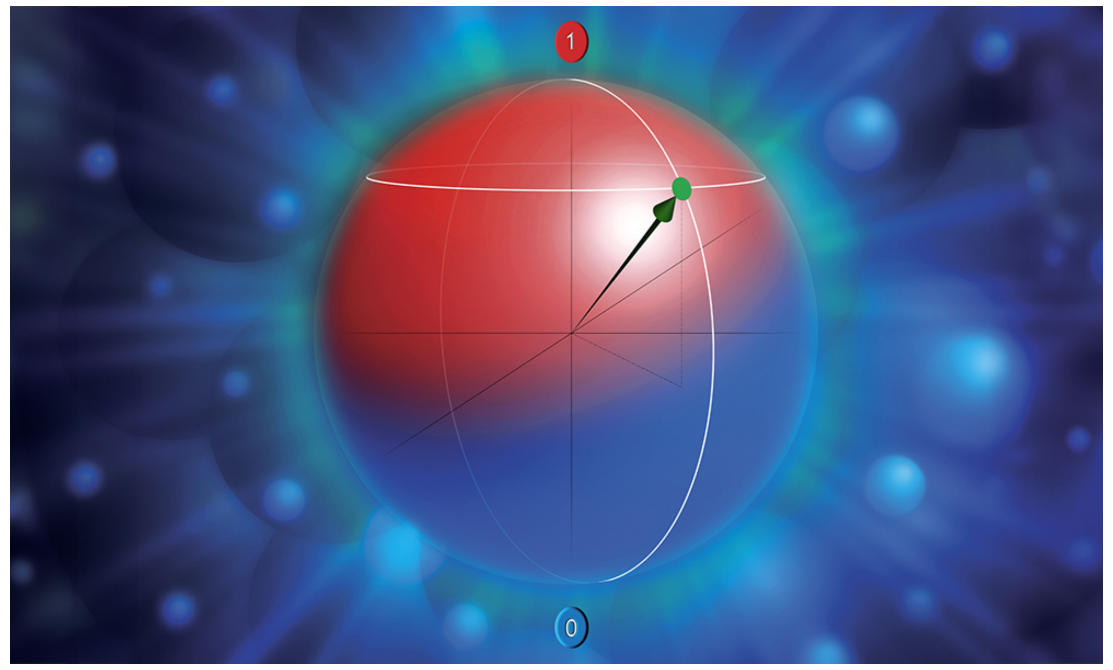
Task: Cooling qubits

Resource: Heat flow, evacuate heat by absorption

Goal: Maximal cooling power



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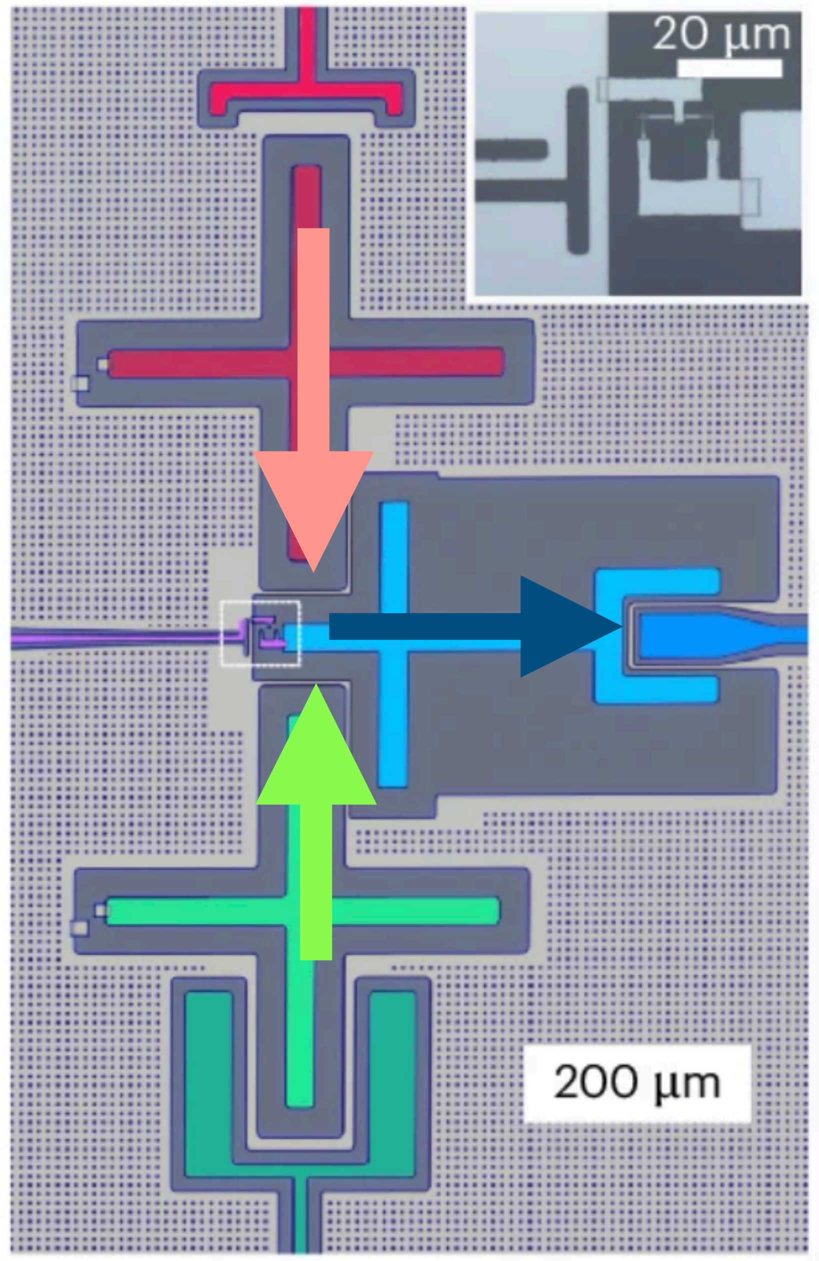

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New challenges - new opportunities

Control energy transduction at the nanoscale → **Measurement & information**

- **K. H. & Nitzan, A. Quantum information engines. Bounds on performance metrics by measurement time, arXiv:2505.00686 (2025)**
- **Hagman, R.; Berx, J.; Splettstoesser, J.; K. H. Optimizing performance metrics of quantum information engines with Pareto fronts, *in preparation***

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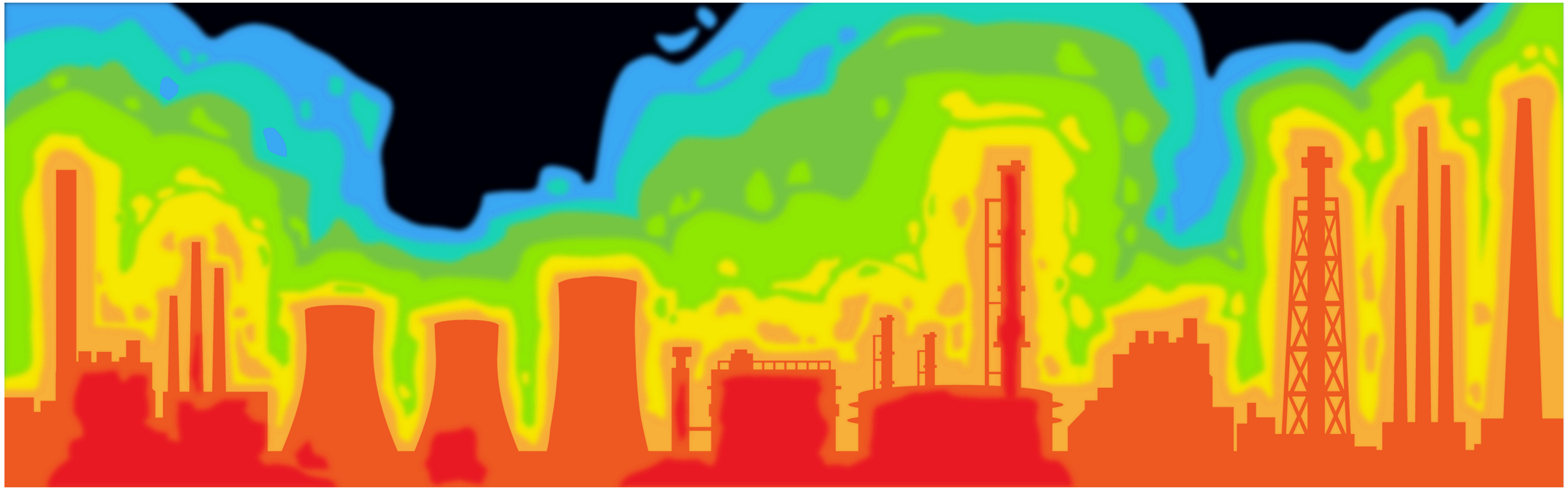
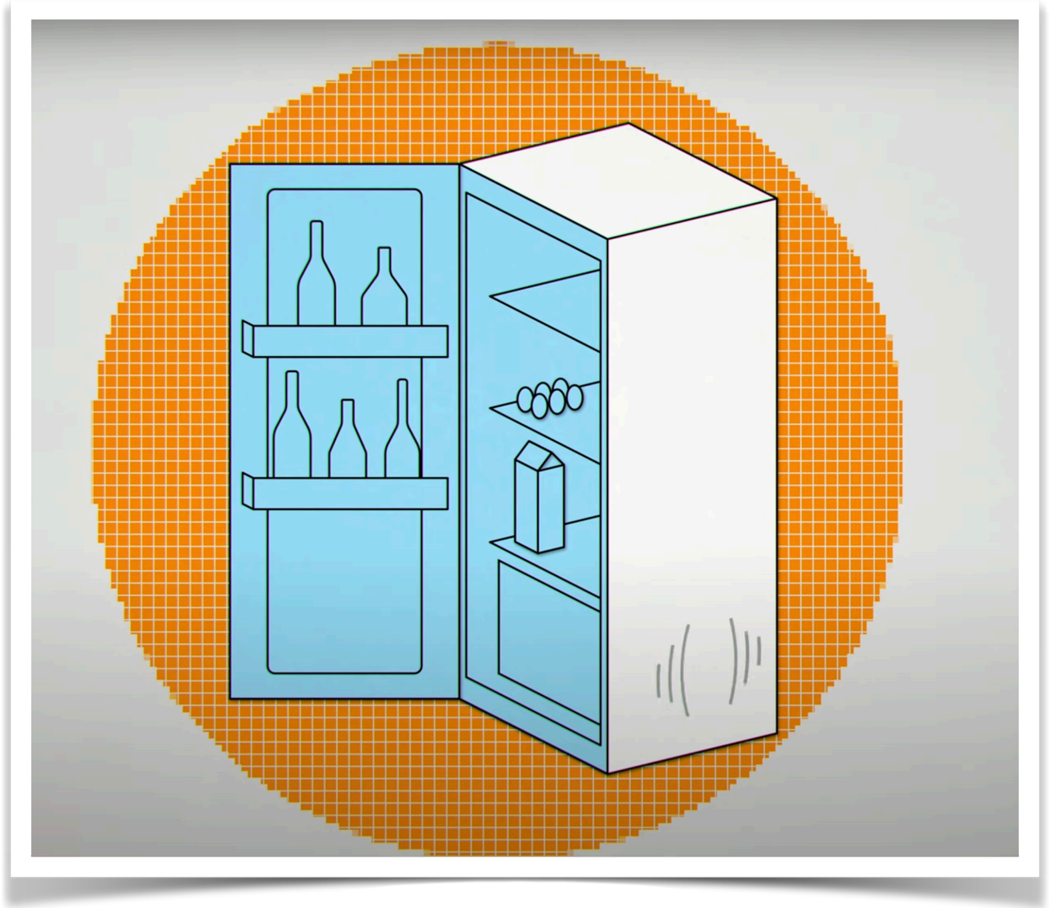
Devices smaller than thermalization length → **Nonthermal resources**



Outline

- Introduction
    - Refrigerator: Energy conversion for cooling
    - Thermoelectric cooling at the nanoscale
- Nonthermal resources?
- Optimizing thermoelectric cooling exploiting nonthermal resources
- Open questions

Refrigerator: Energy conversion for cooling



- **Task:** Cool the inside of the fridge

1. QPlayLearn: QuantumPills #3

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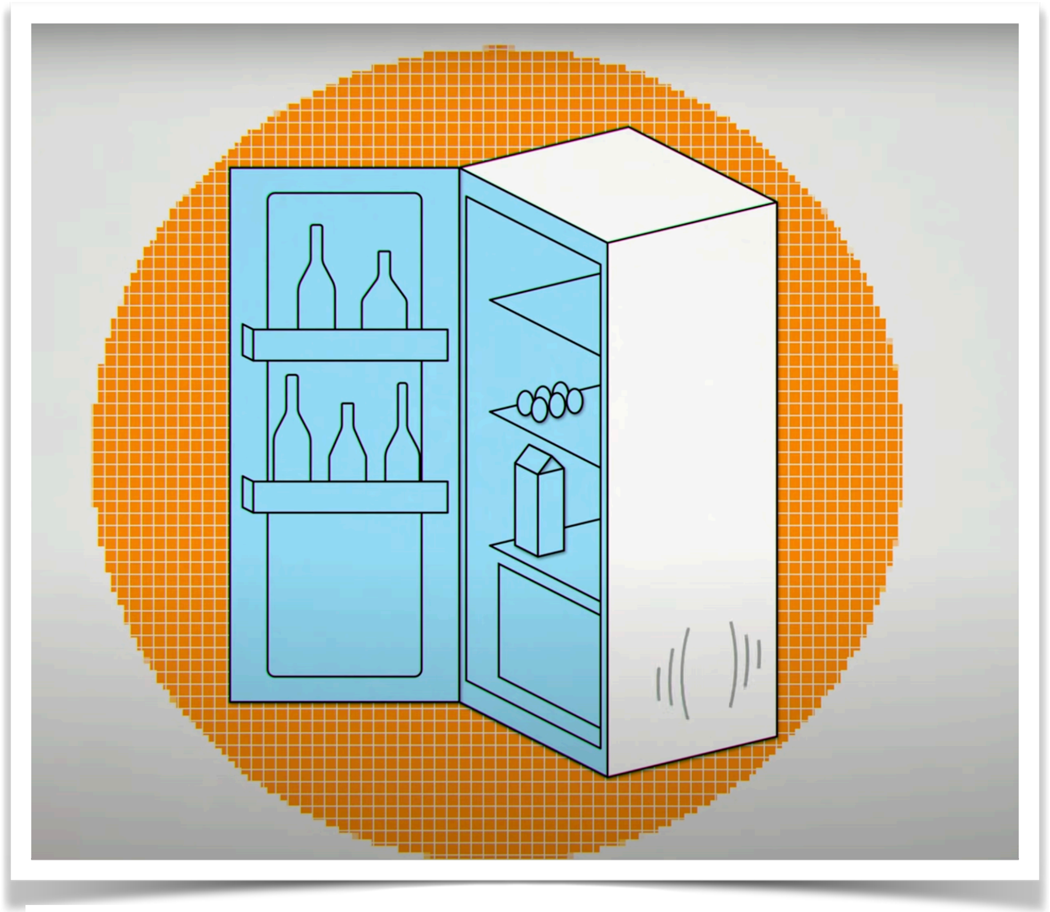

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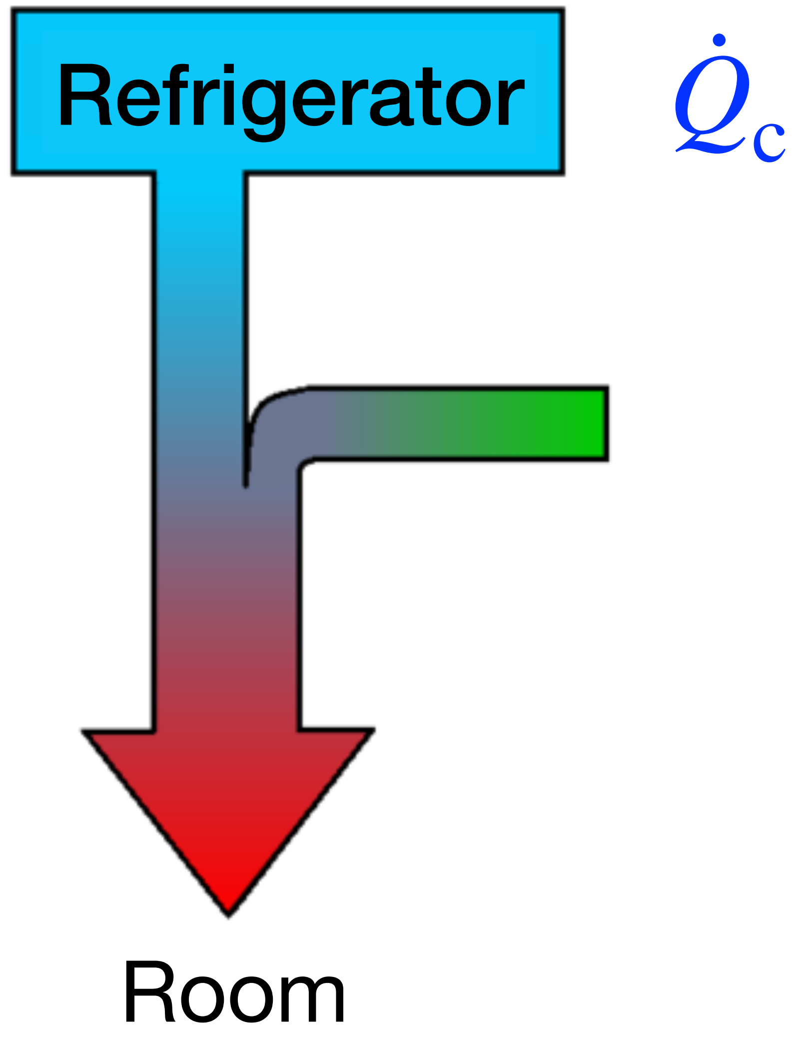
- **Goal:** large cooling power

$\dot{Q}_c$



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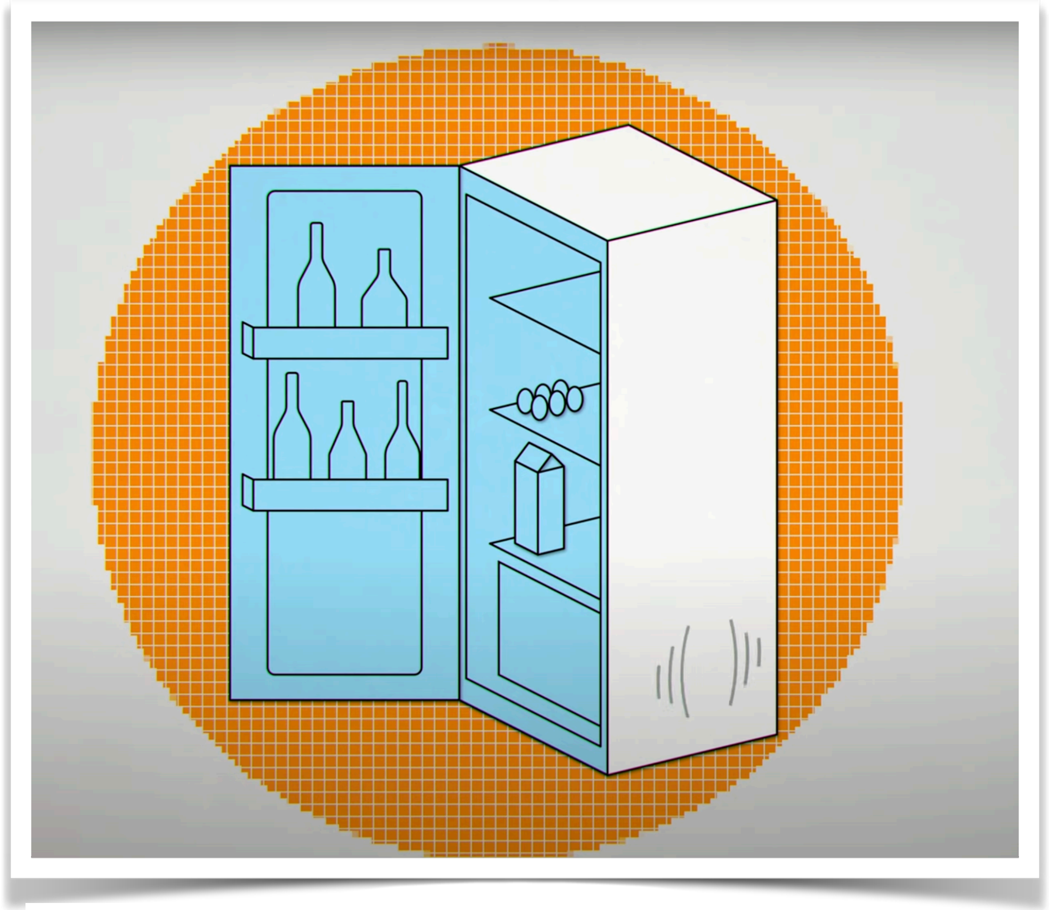

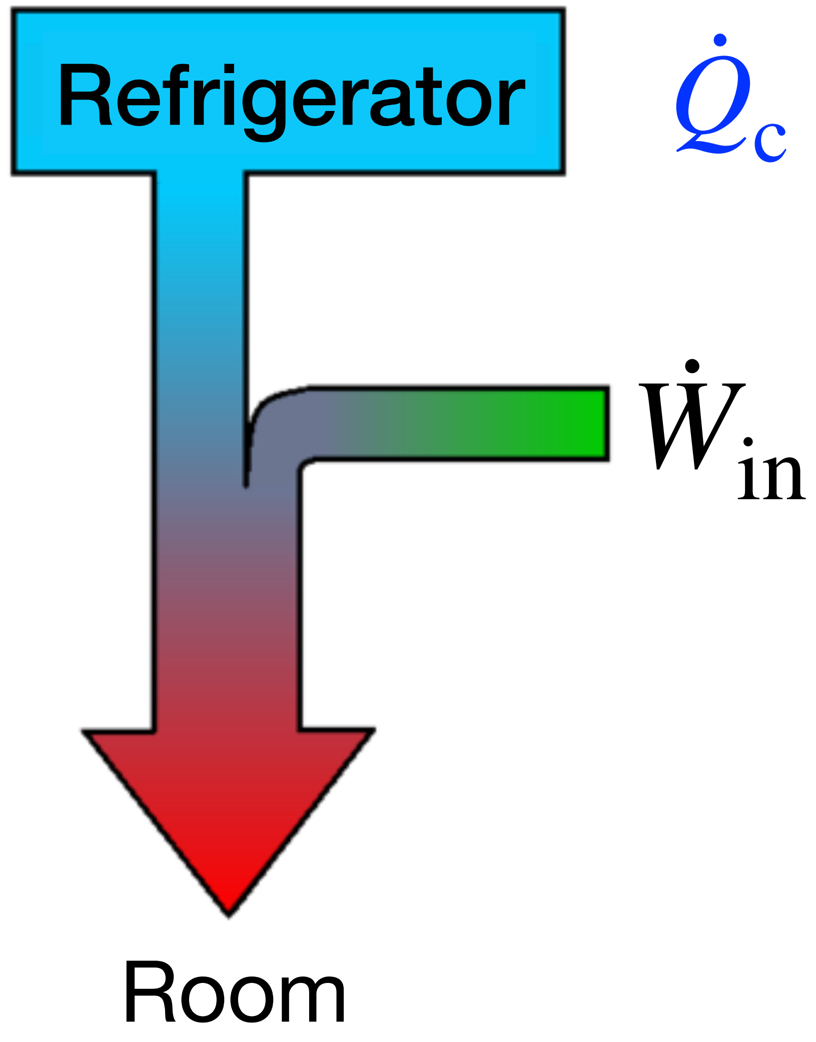

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$$\dot{Q}_c$$

- Using work **resource**

$$\dot{W}_{in}$$

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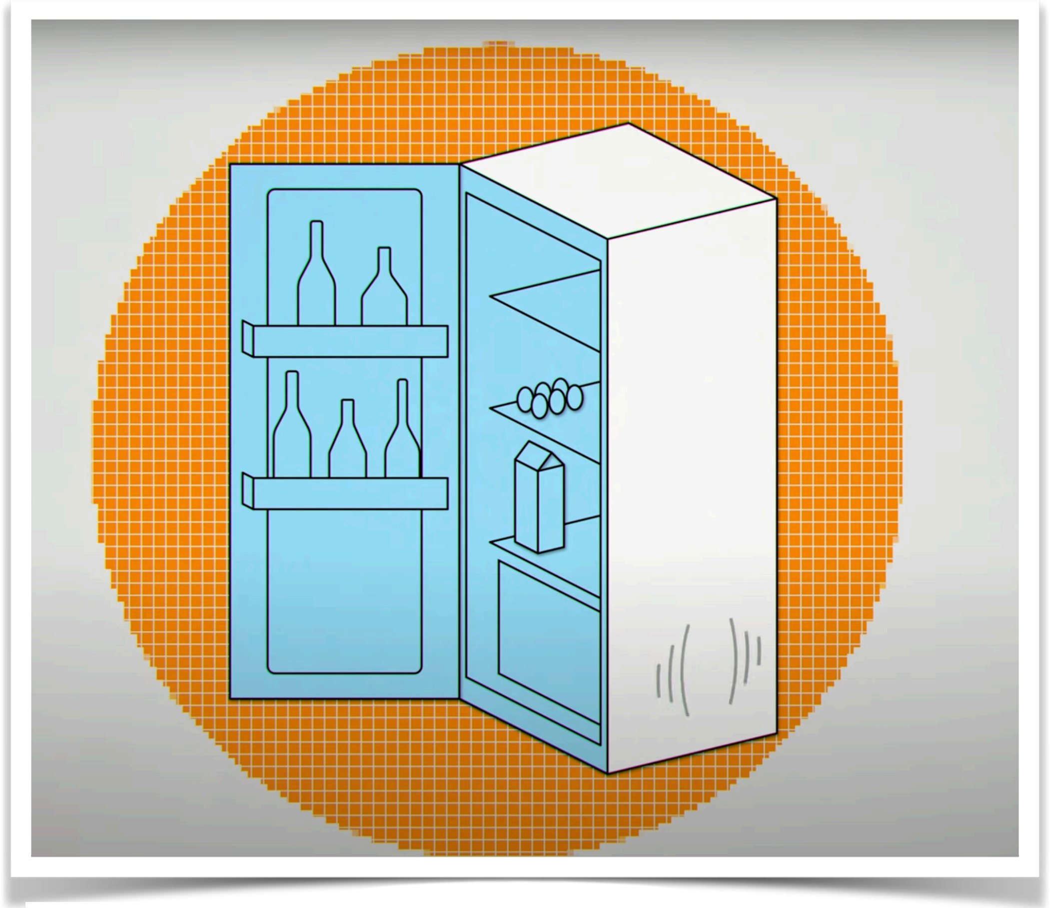

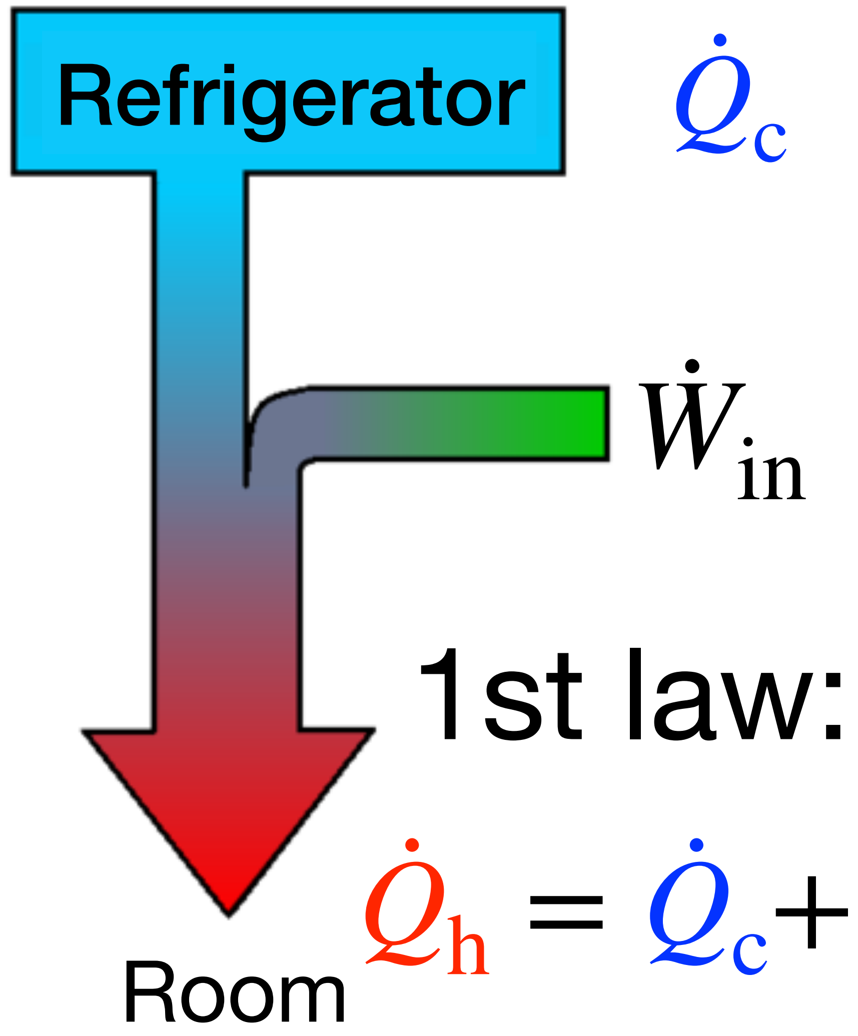

1st law:

$$\dot{Q}_\mathrm{h} = \dot{Q}_\mathrm{c} + \dot{W}_\mathrm{in}$$

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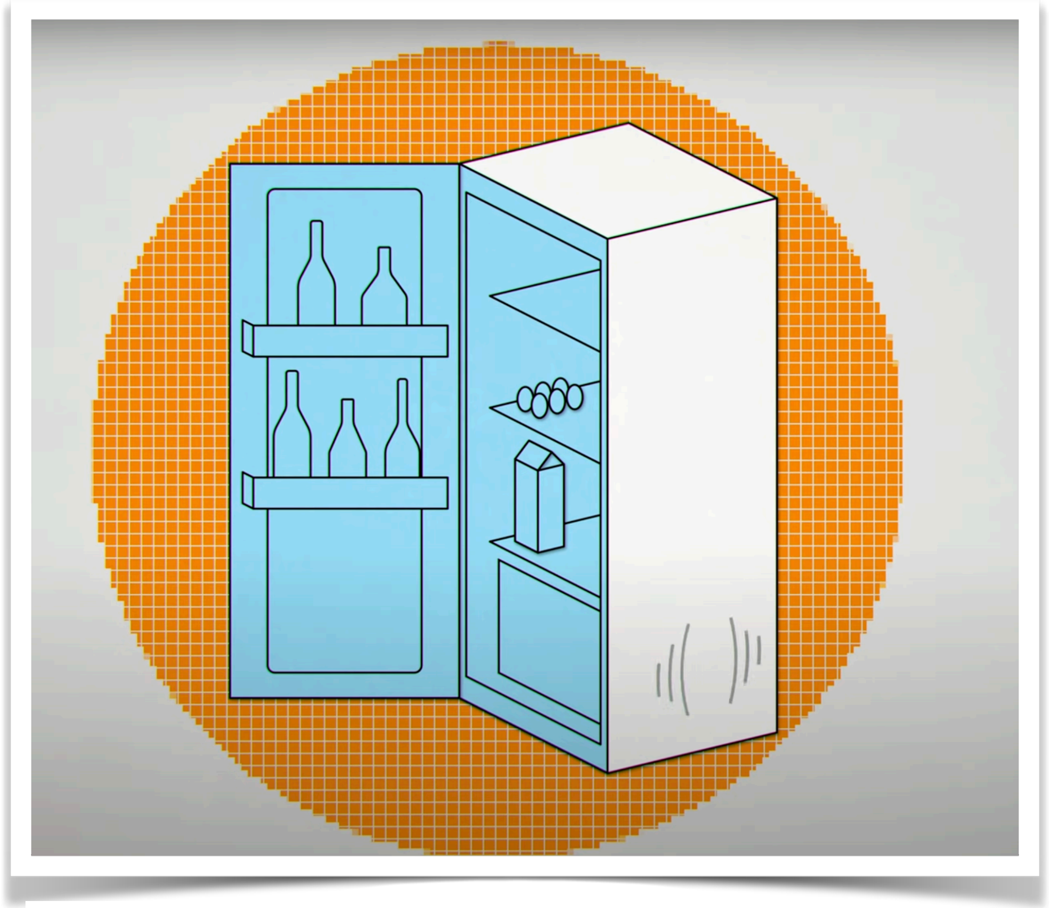

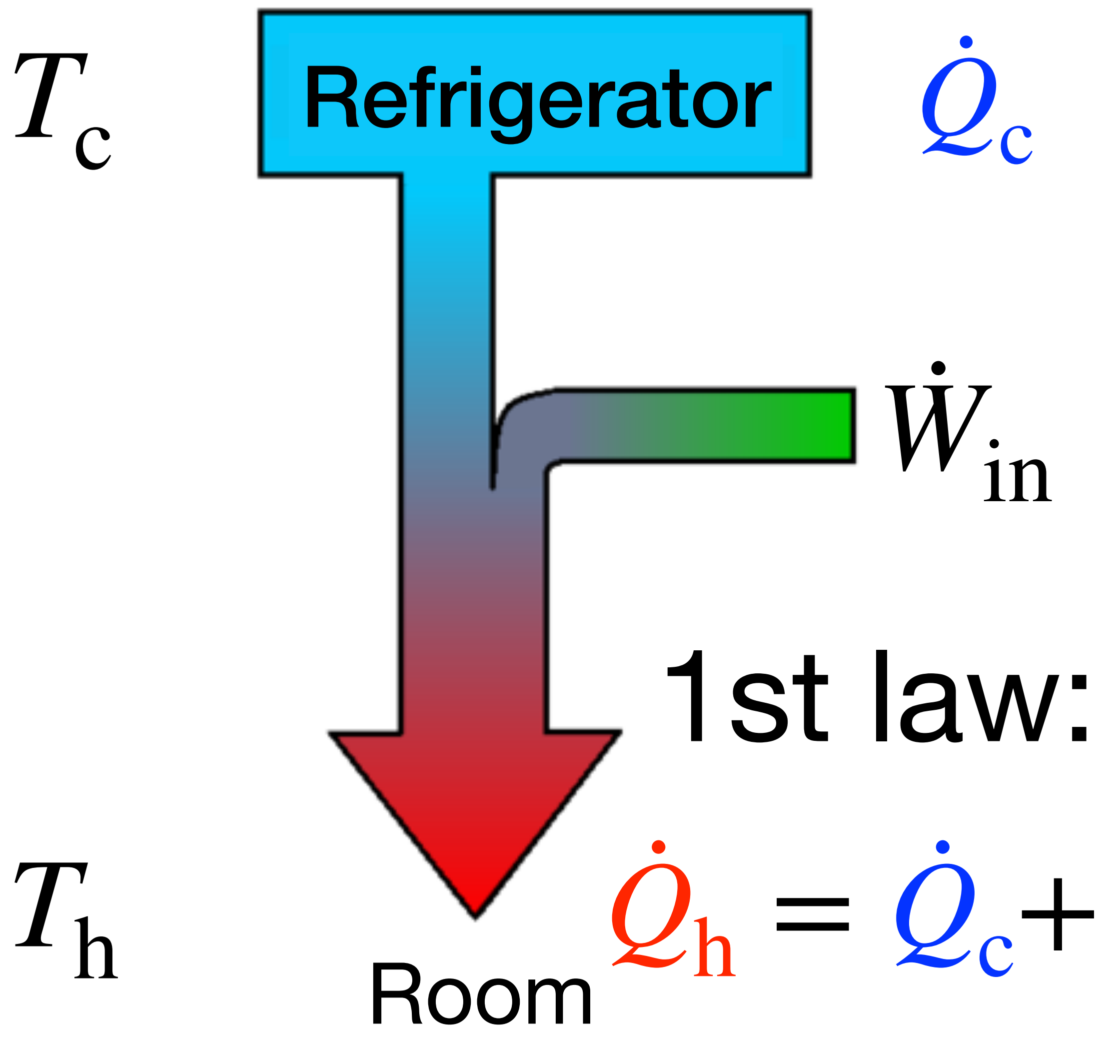

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$$\dot{W}_{in}$$

- **Alternative goal:** Maximize coefficient of performance

$$\mathrm{COP} = \frac{\dot{Q}_c}{\dot{W}_{in}}$$

- **Upper bound:** $\leq \frac{T_c}{T_h - T_c}$

2nd law:

$$\dot{\Sigma} = -\frac{\dot{Q}_c}{T_c} + \frac{\dot{Q}_h}{T_h} \geq 0$$

1824-2024: 200 years of 2nd law

Carnot (1796-1832)

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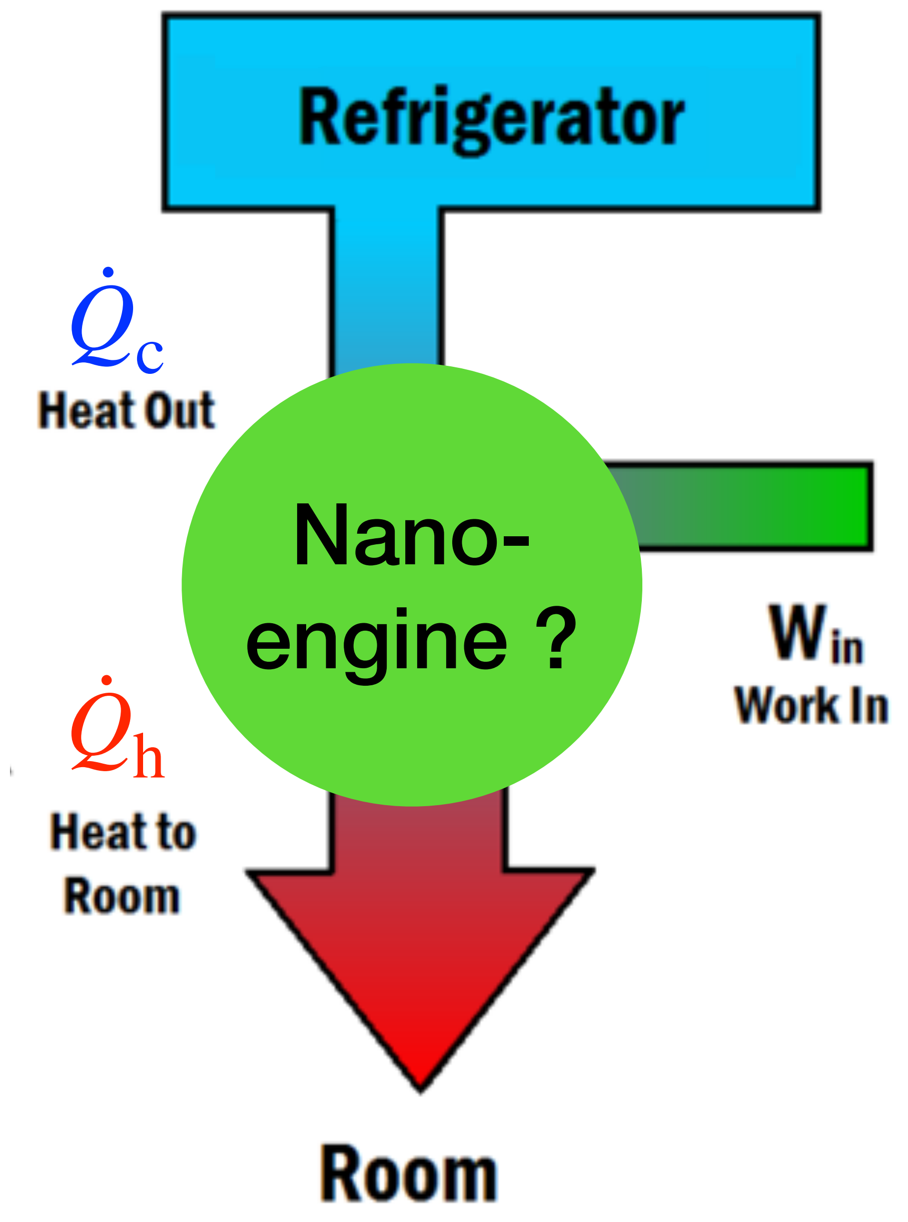
Energy transmission at the nanoscale

- What if we replace the engine by a **quantum/nanosystem**?



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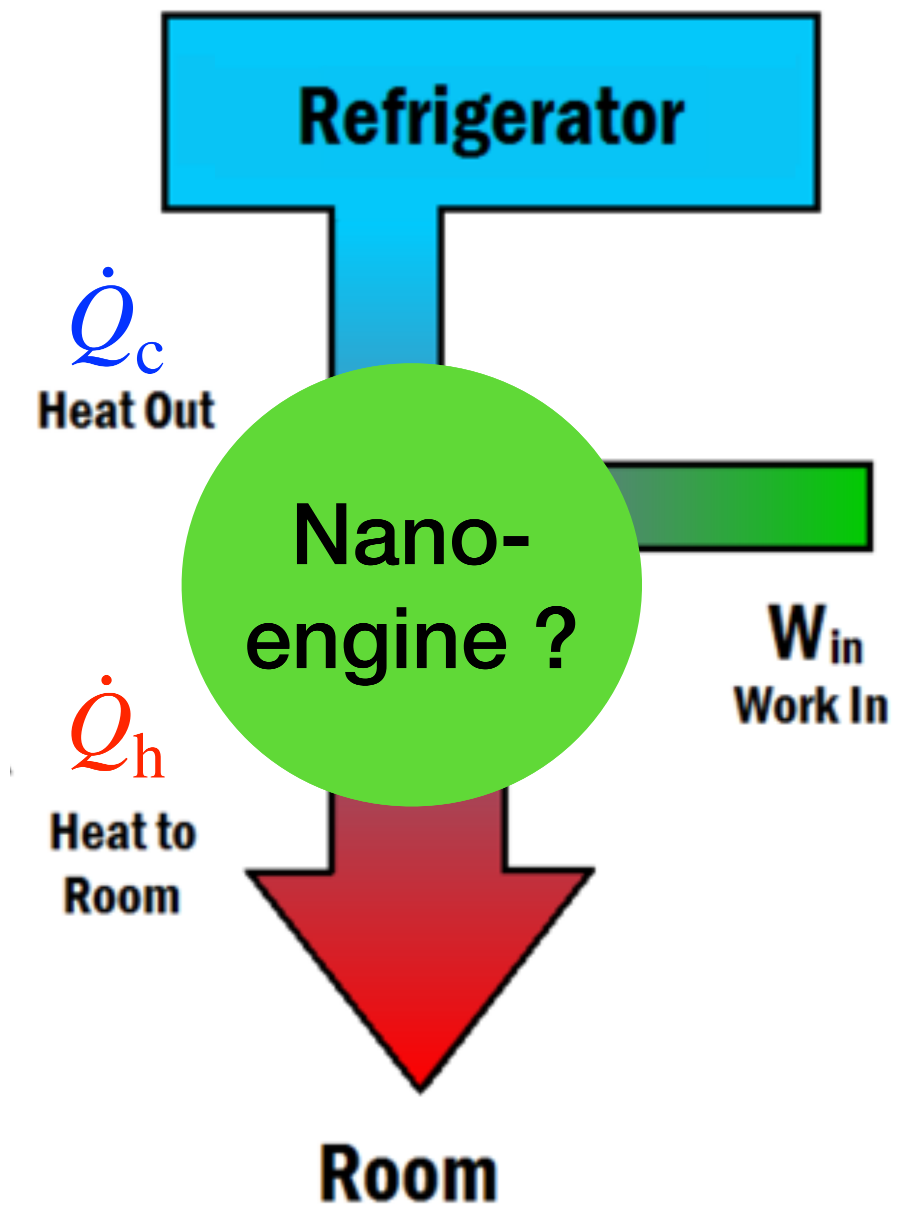

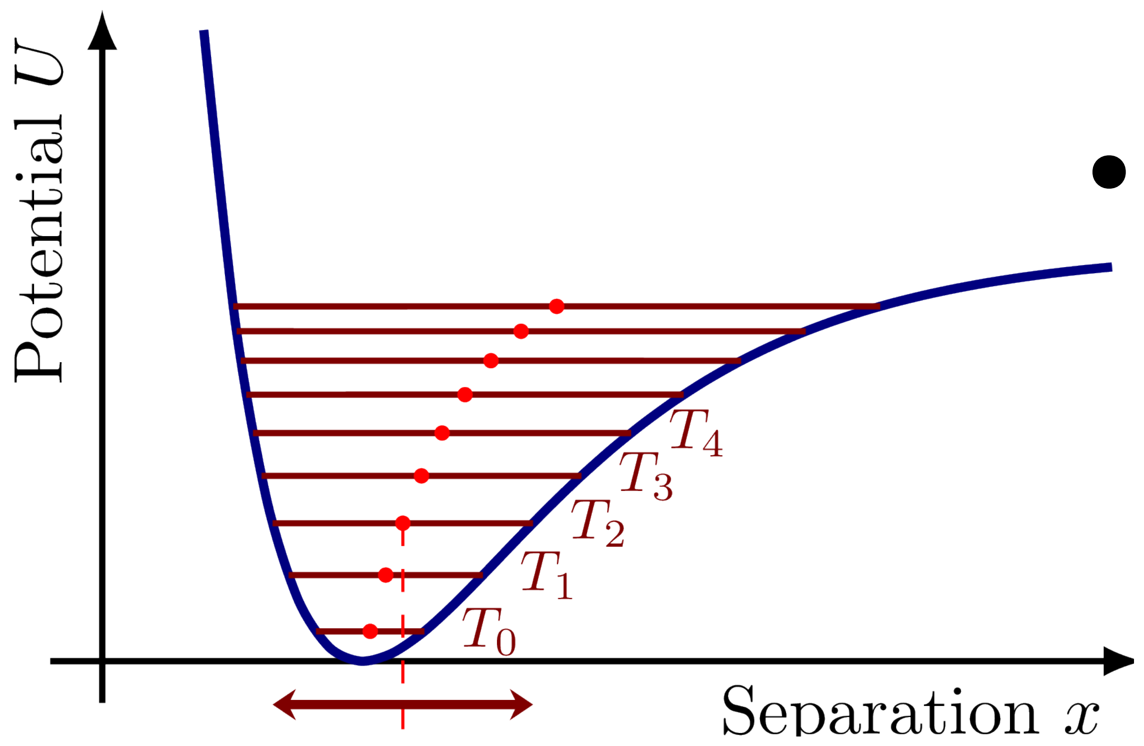

- **Discrete energy levels**, occupied by few electrons

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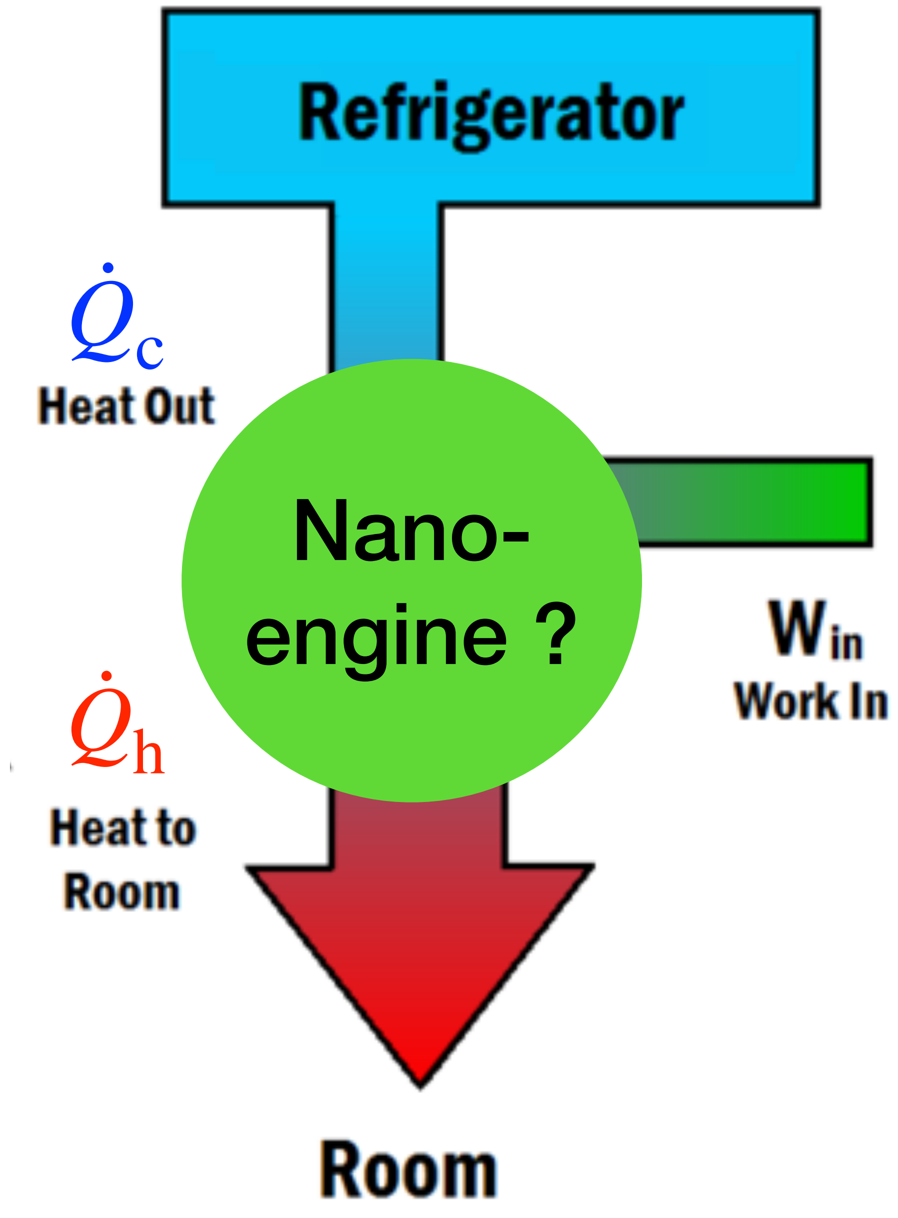

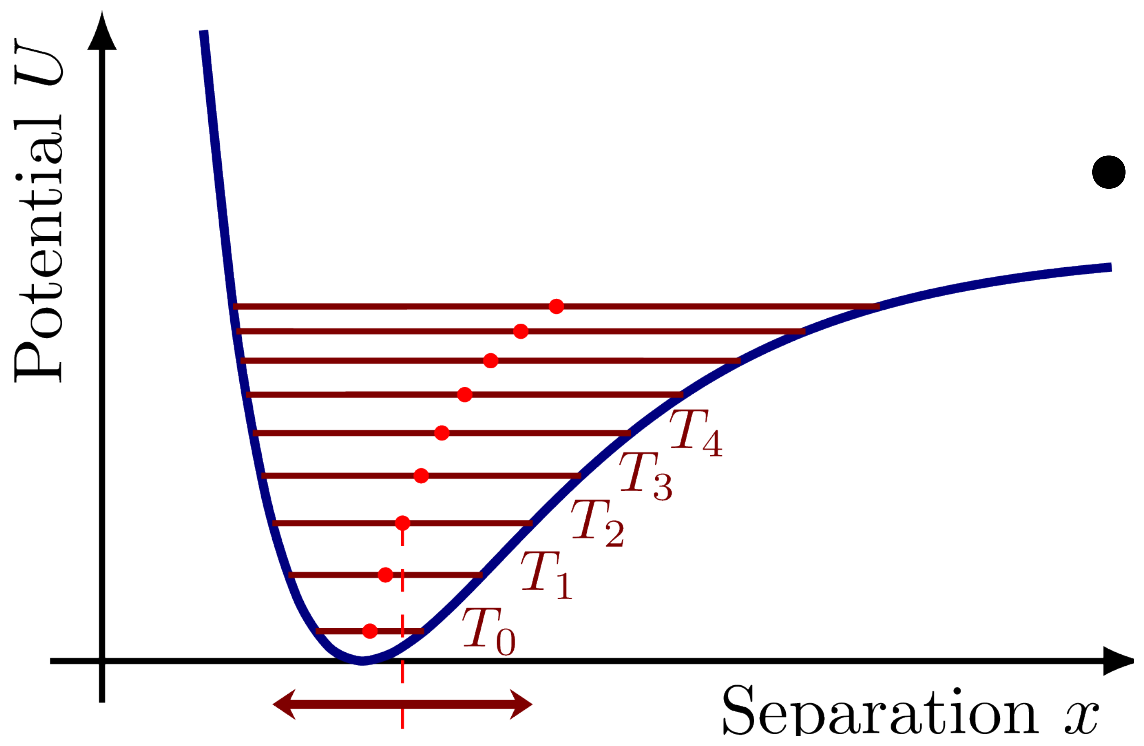

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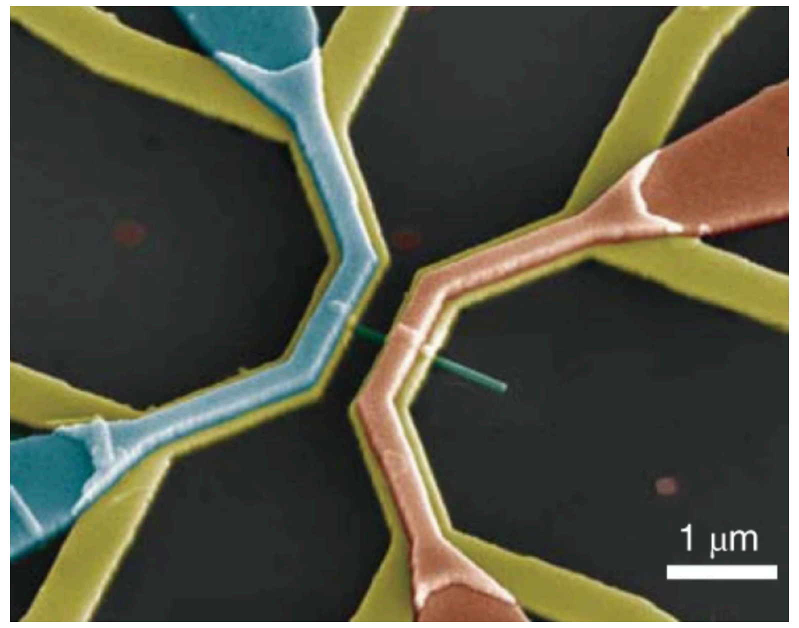
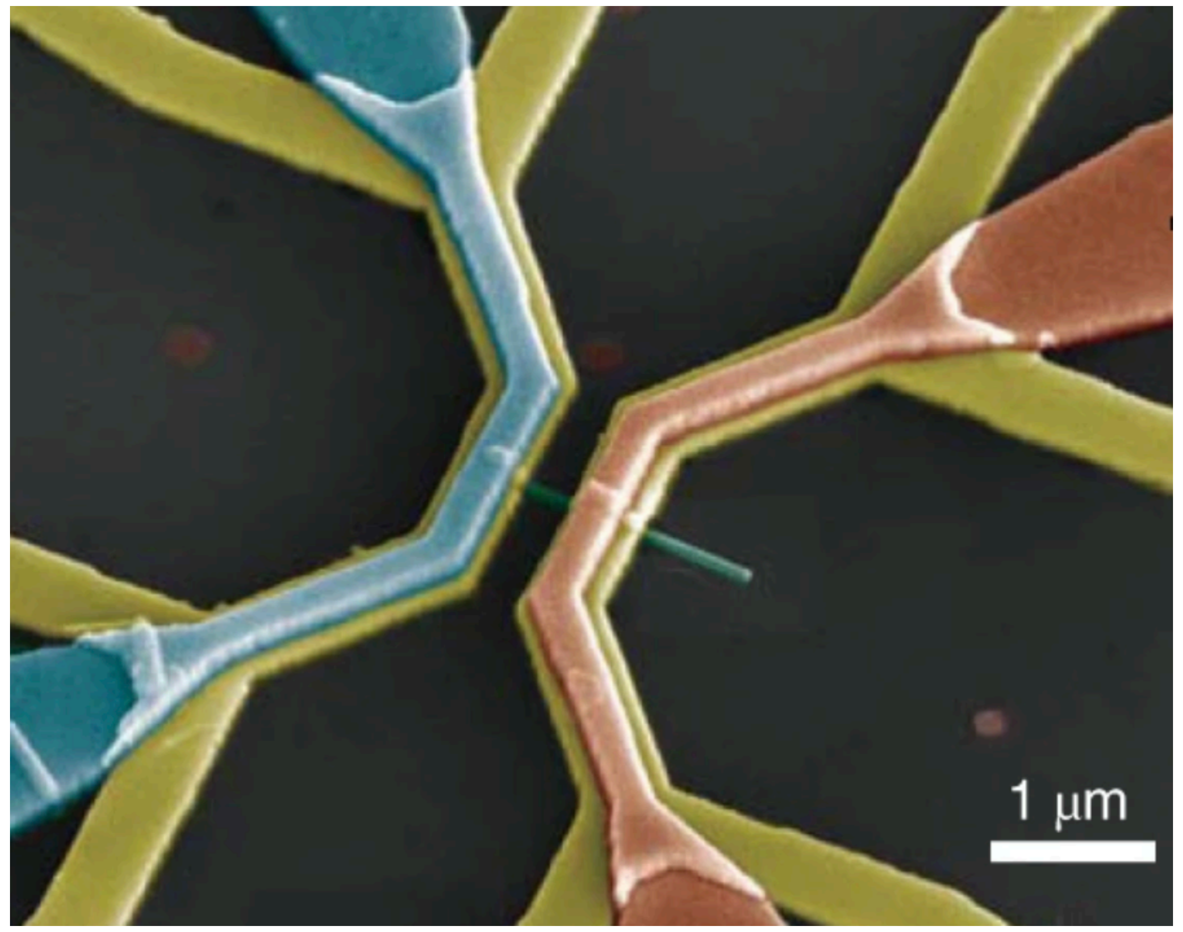


- Quantum dot - ‘artificial atom’, tunable energy levels, part of an electric circuit
  → **energy filtering between reservoirs**

1. EnergyEducation, U of Calgary
2. TikZ.net

Josefsson, M. et al. Nat. Nanotechnol. 13, 920 (2018)
Giazotto, F. et al. Rev. Mod. Phys. 78, 217 (2006)

Thermoelectric cooling by energy filtering



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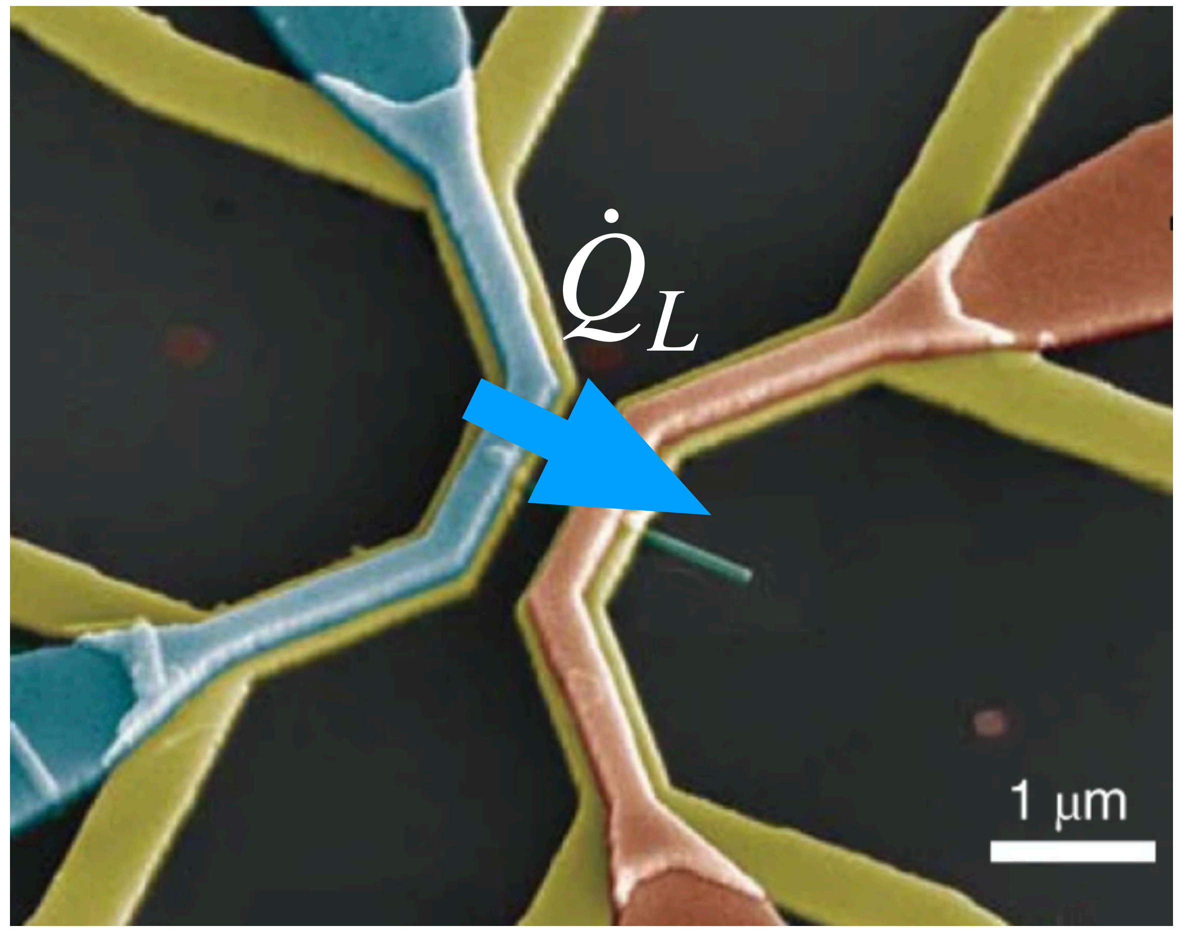
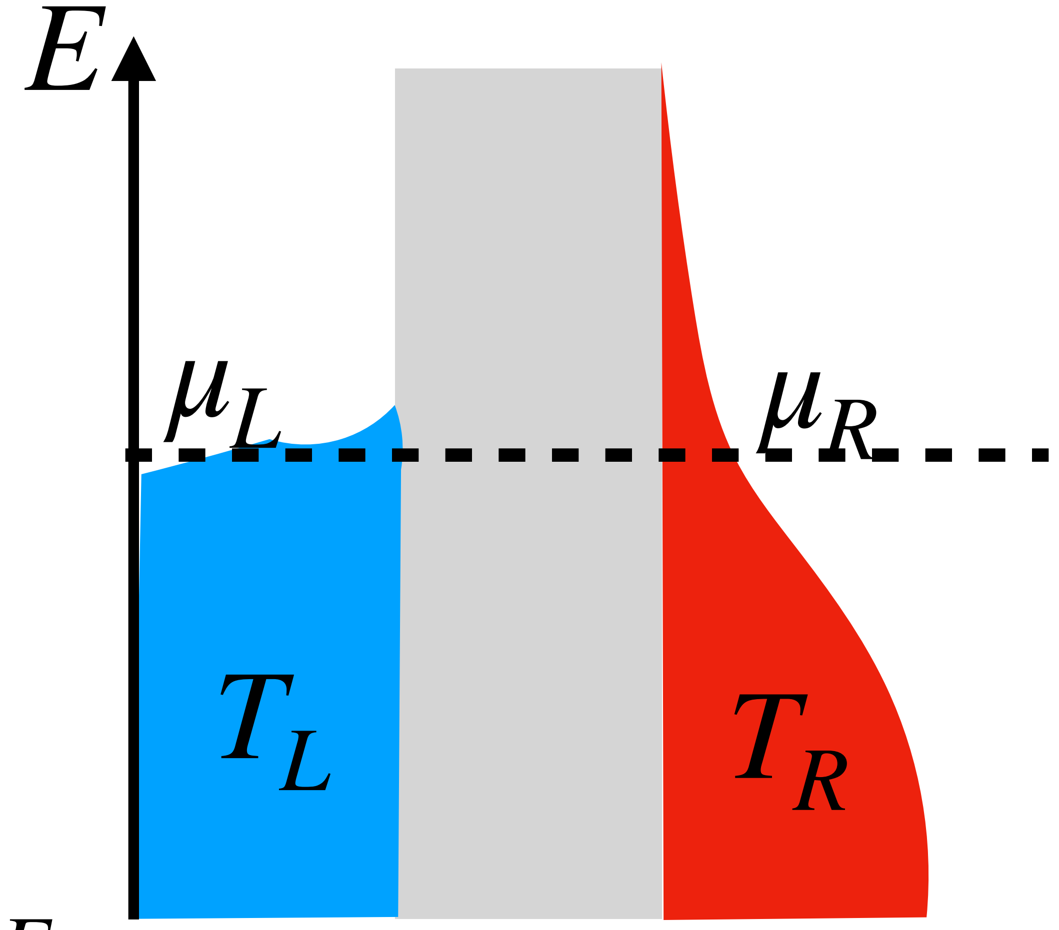
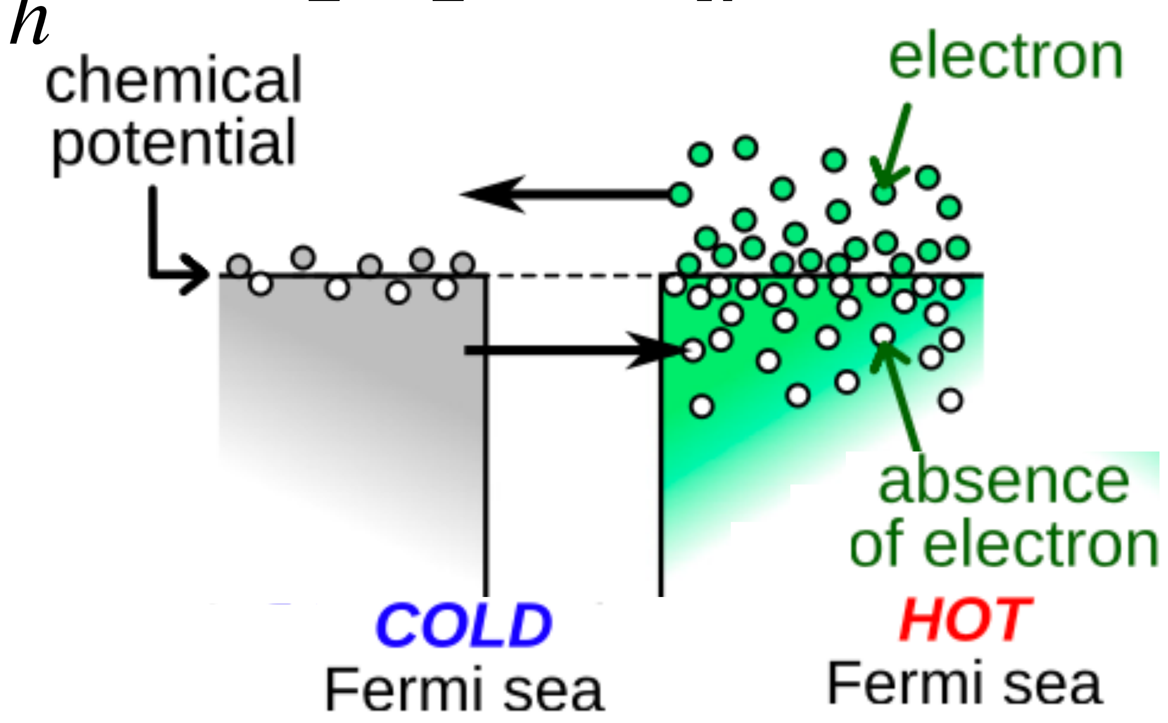




$$\dot{Q}_L = \int \frac{dE}{h}(E-\mu_L)[f_L(E) - f_R(E)]$$



Direct contact – no energy filter.

Josefsson, M. et al. Nat. Nanotechnol. 13, 920 (2018)

Reviews: A. Beneti, G.; Casati, K.; Whitney, R. S. Phys. Rep. 694,1 (2017)
B. Whitney, R.S.; Sánchez, R.; Splettstoesser, J. In: Binder, F. et al. Thermodynamics in the Quantum Regime. Fundamental Theories of Physics, vol 195. Springer (2018)

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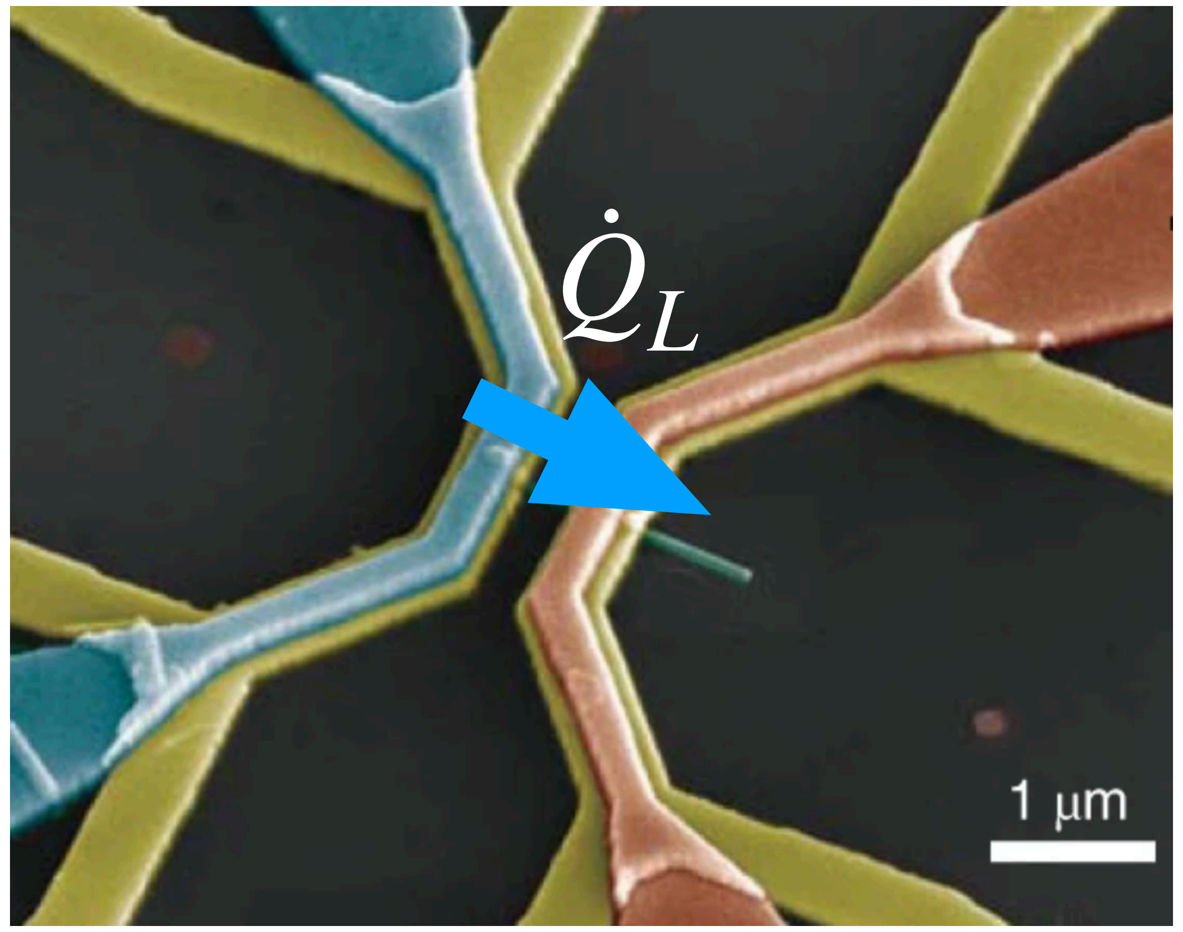
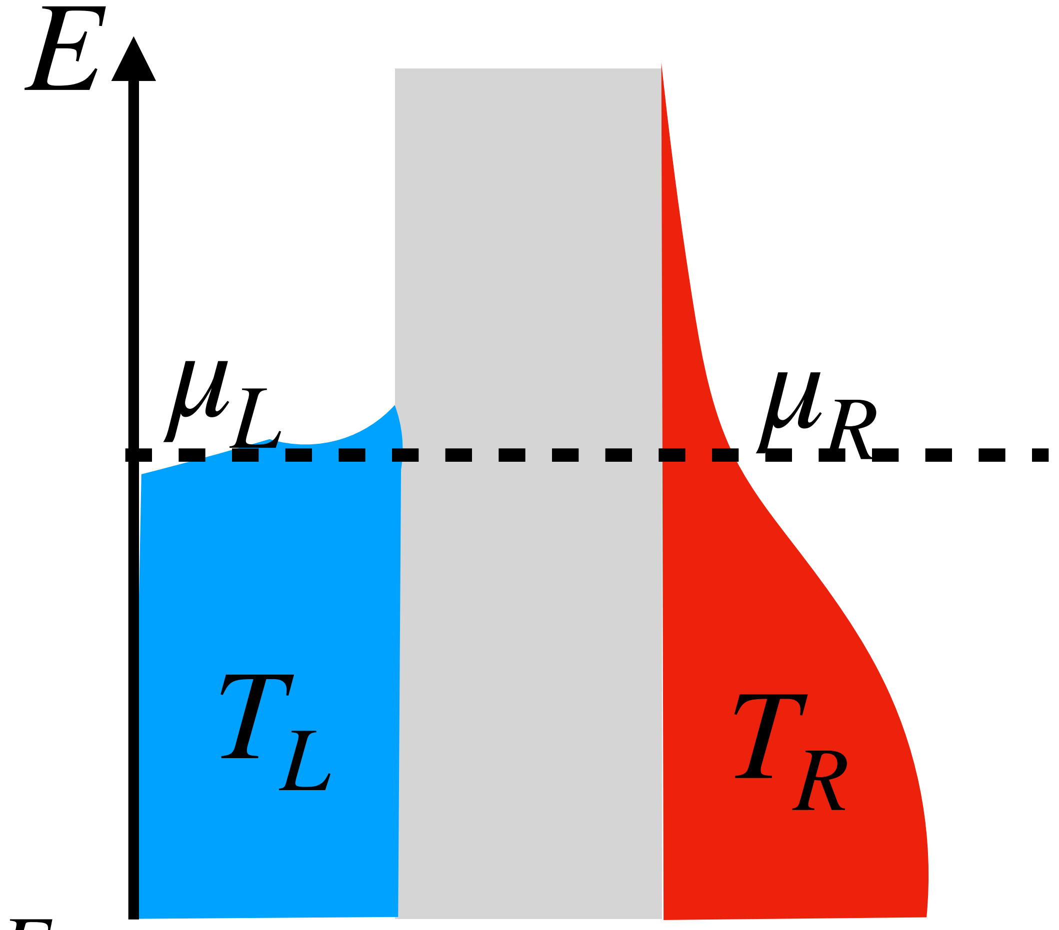


Design optimal energy filter $D(E)$ for specific thermoelectric task.

E.g. Quantum dot at E_d

$$D(E) \propto \frac{\Gamma^2}{(E - E_d)^2 + \Gamma^2}$$

Josefsson, M. et al. Nat. Nanotechnol. 13, 920 (2018)



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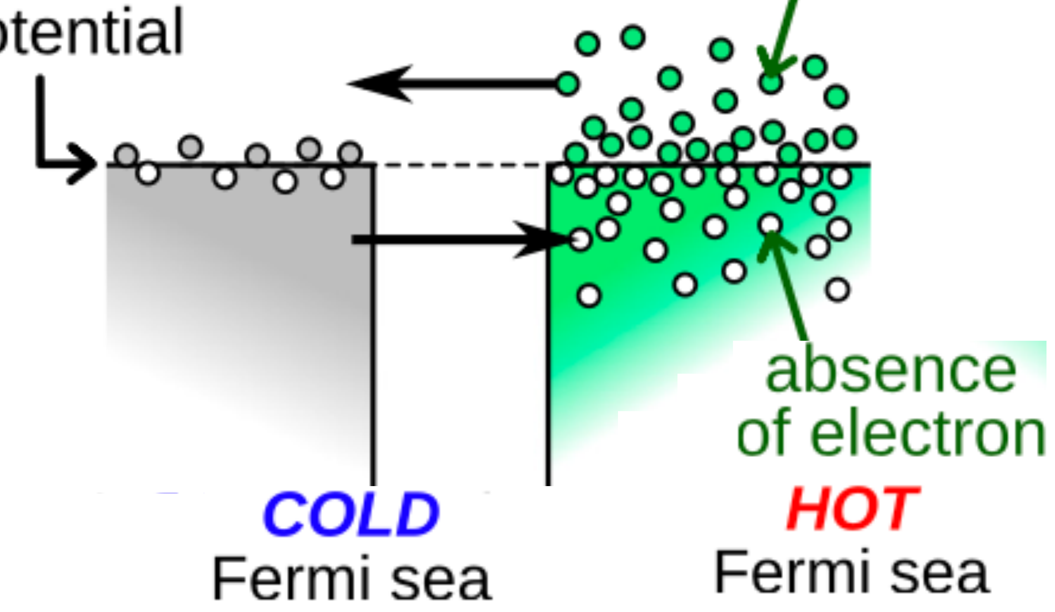

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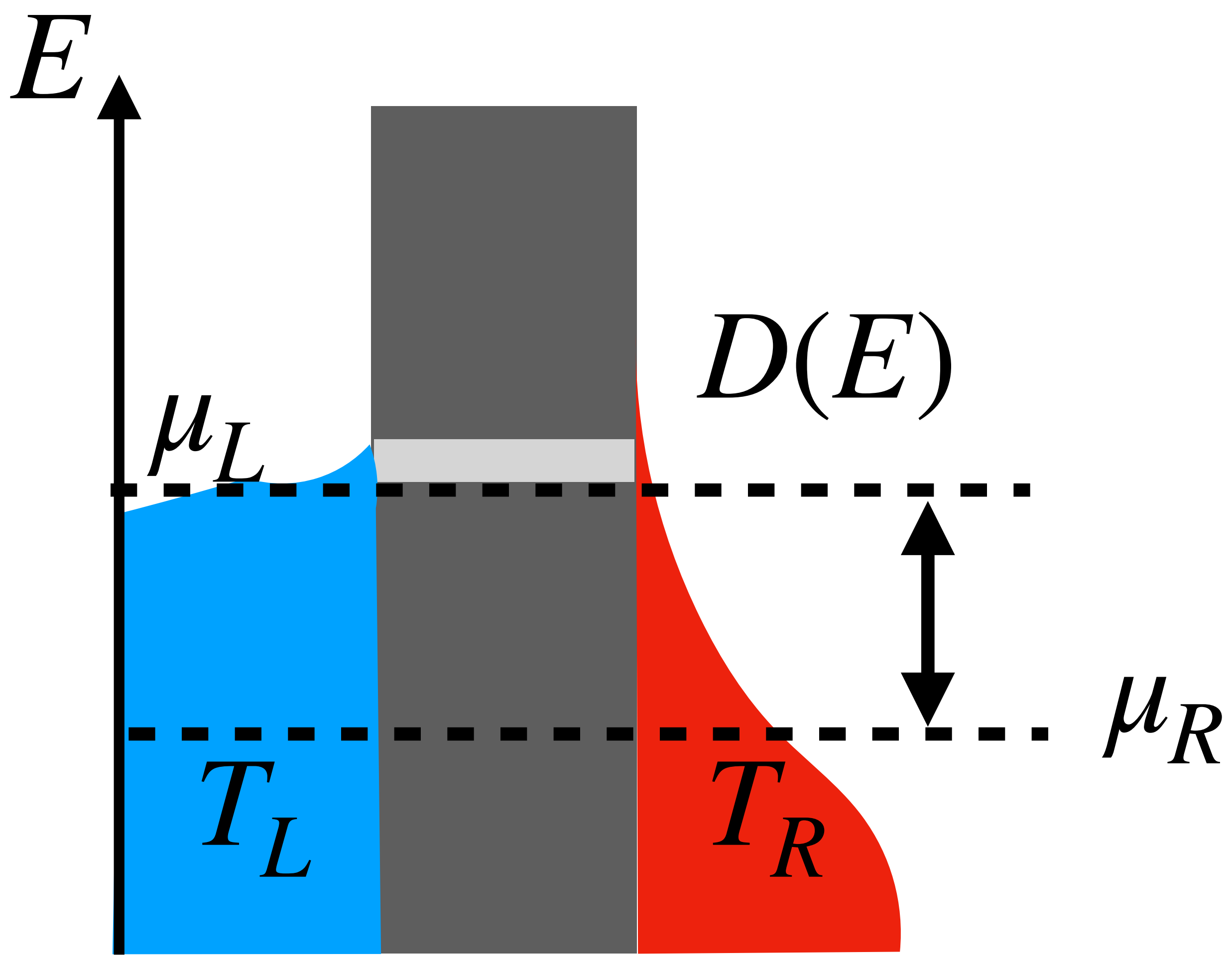

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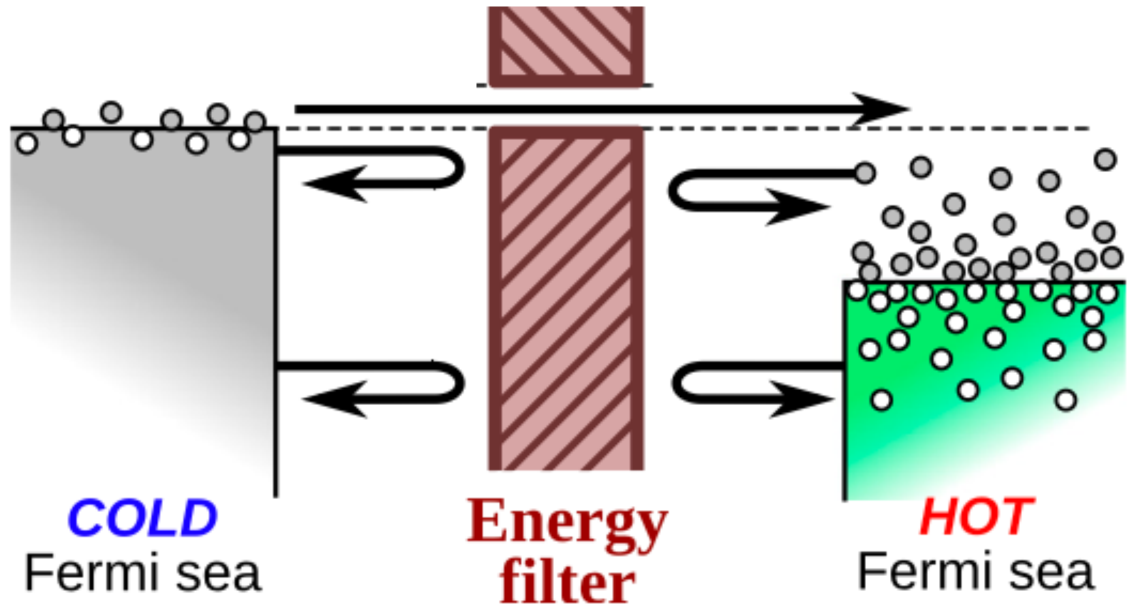

Energy-filter as refrigerator.

Reviews: A. Beneti, G.; Casati, K.; Whitney, R. S. Phys. Rep. 694,1 (2017)
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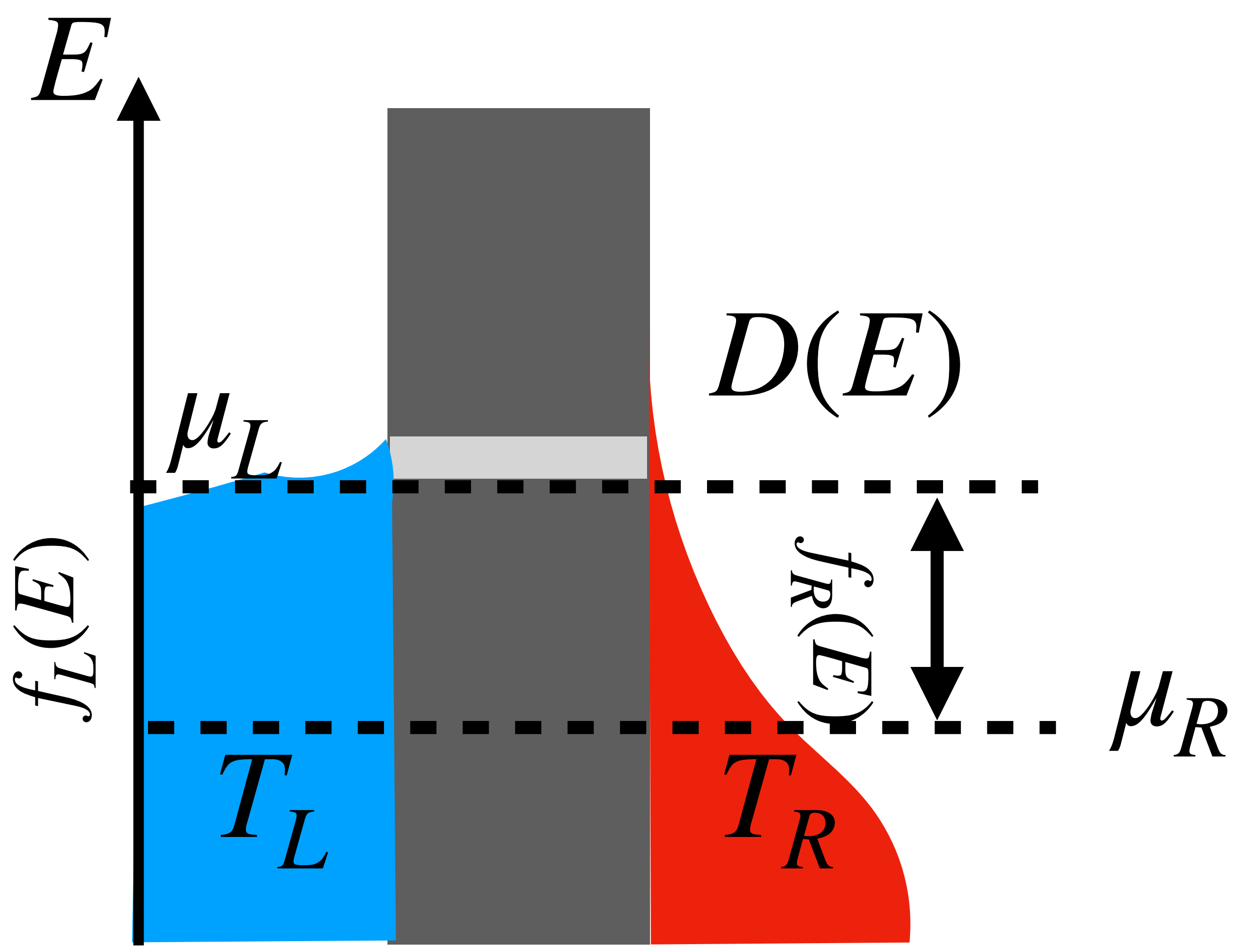
Device performance



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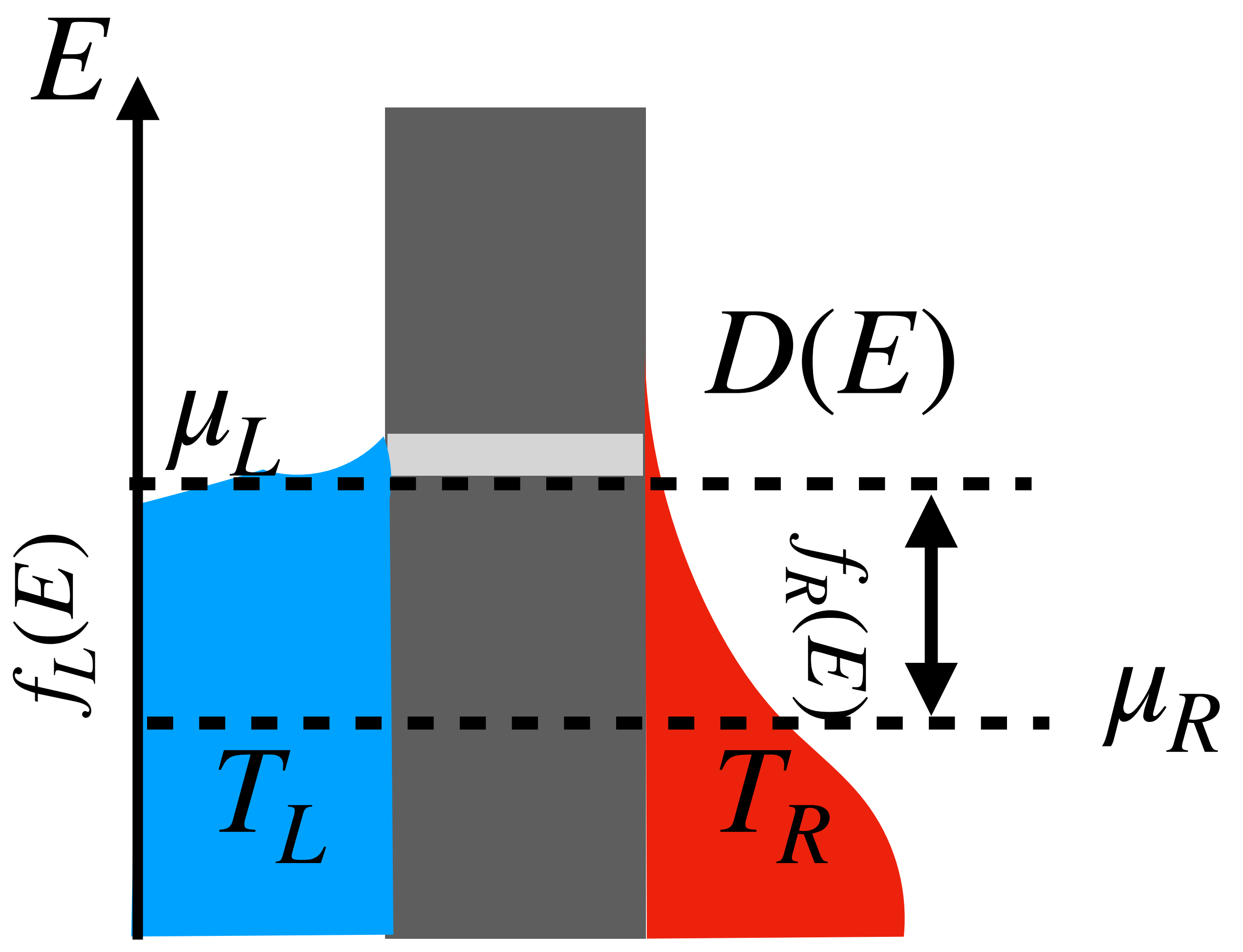

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- **Power** to execute task

$$\dot{Q}_L + \dot{Q}_R = J_{e;L}(\mu_R - \mu_L)/e$$

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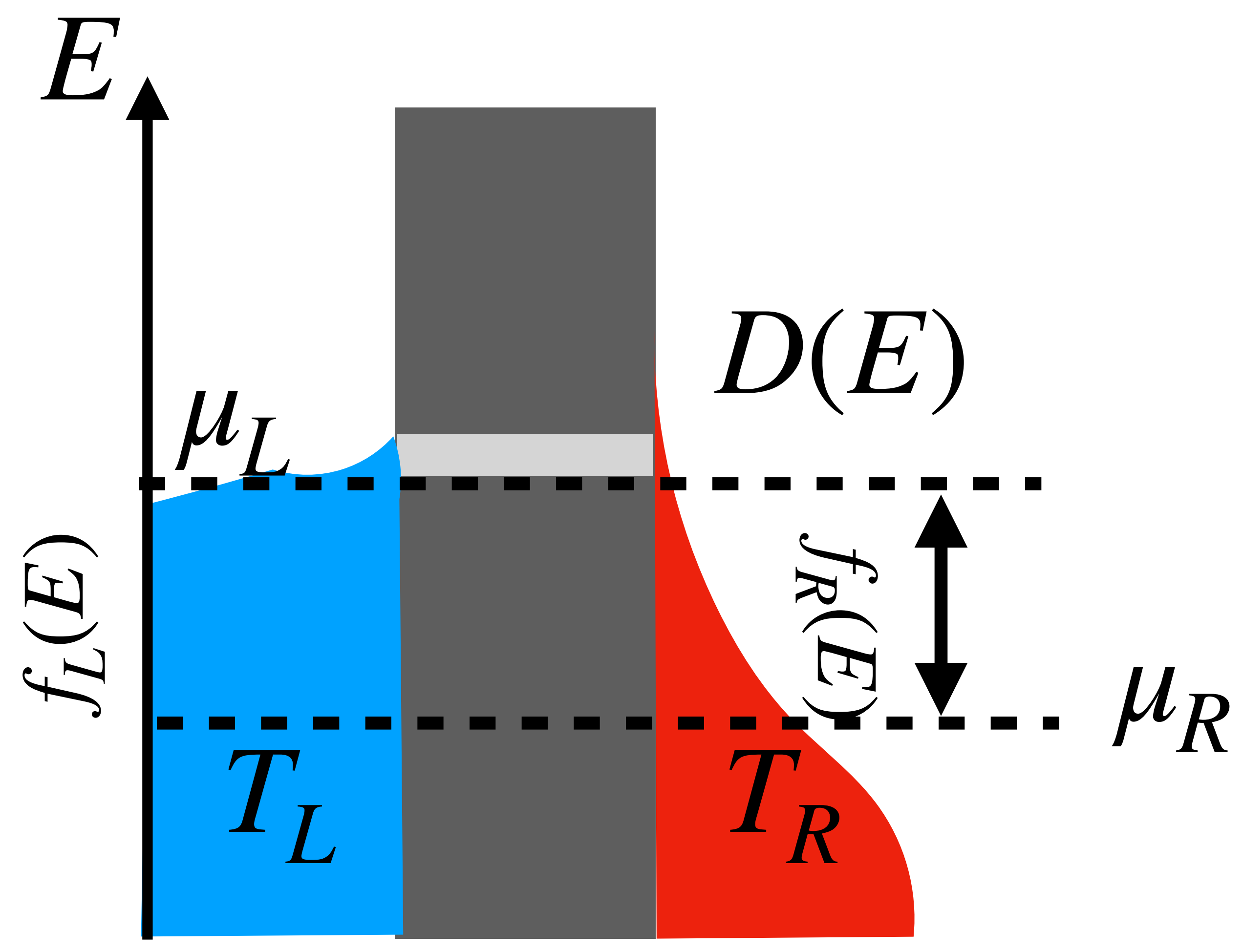

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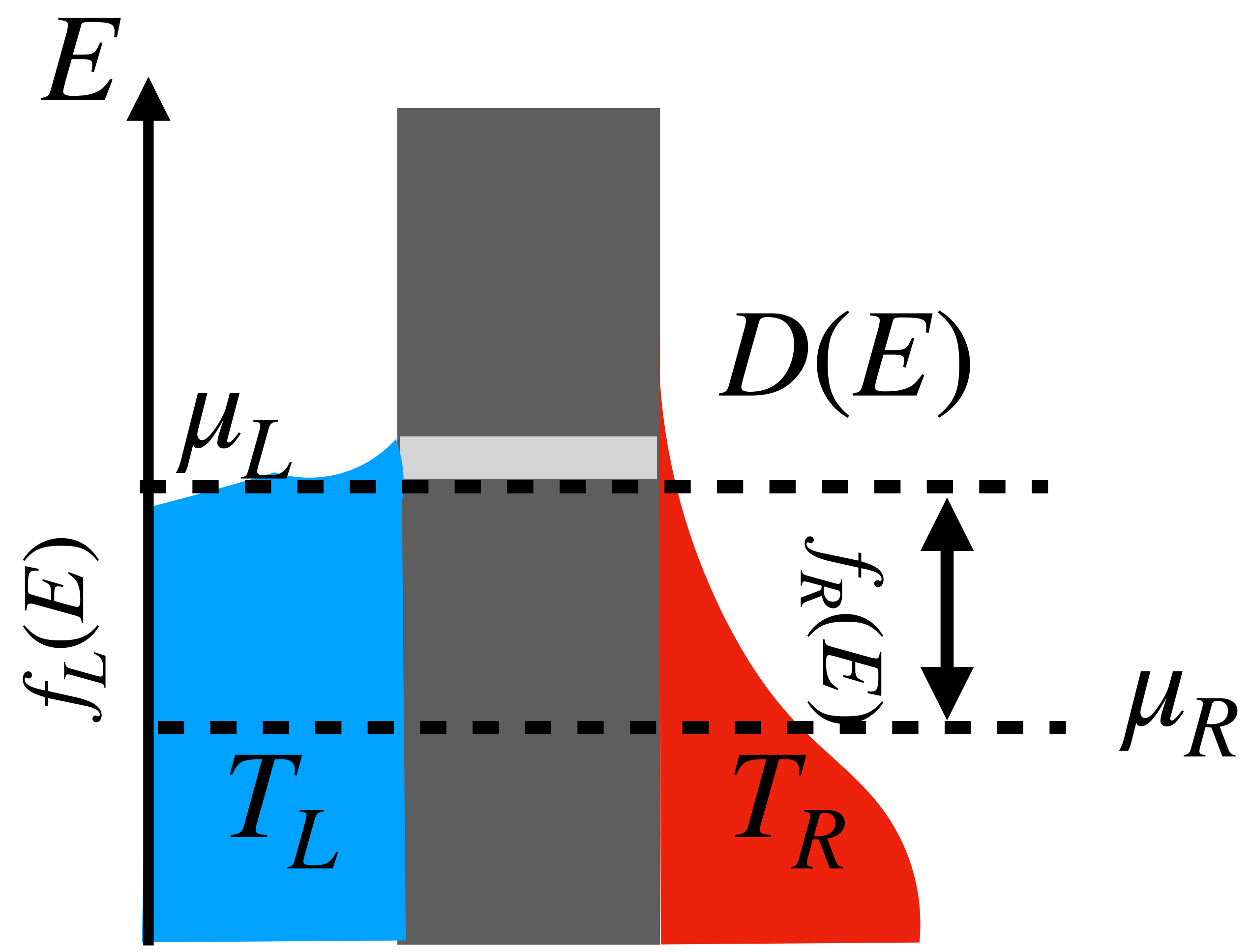

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- **Maximum COP** for $D(E) = \delta(f_L(E) - f_R(E))$ but zero cooling power

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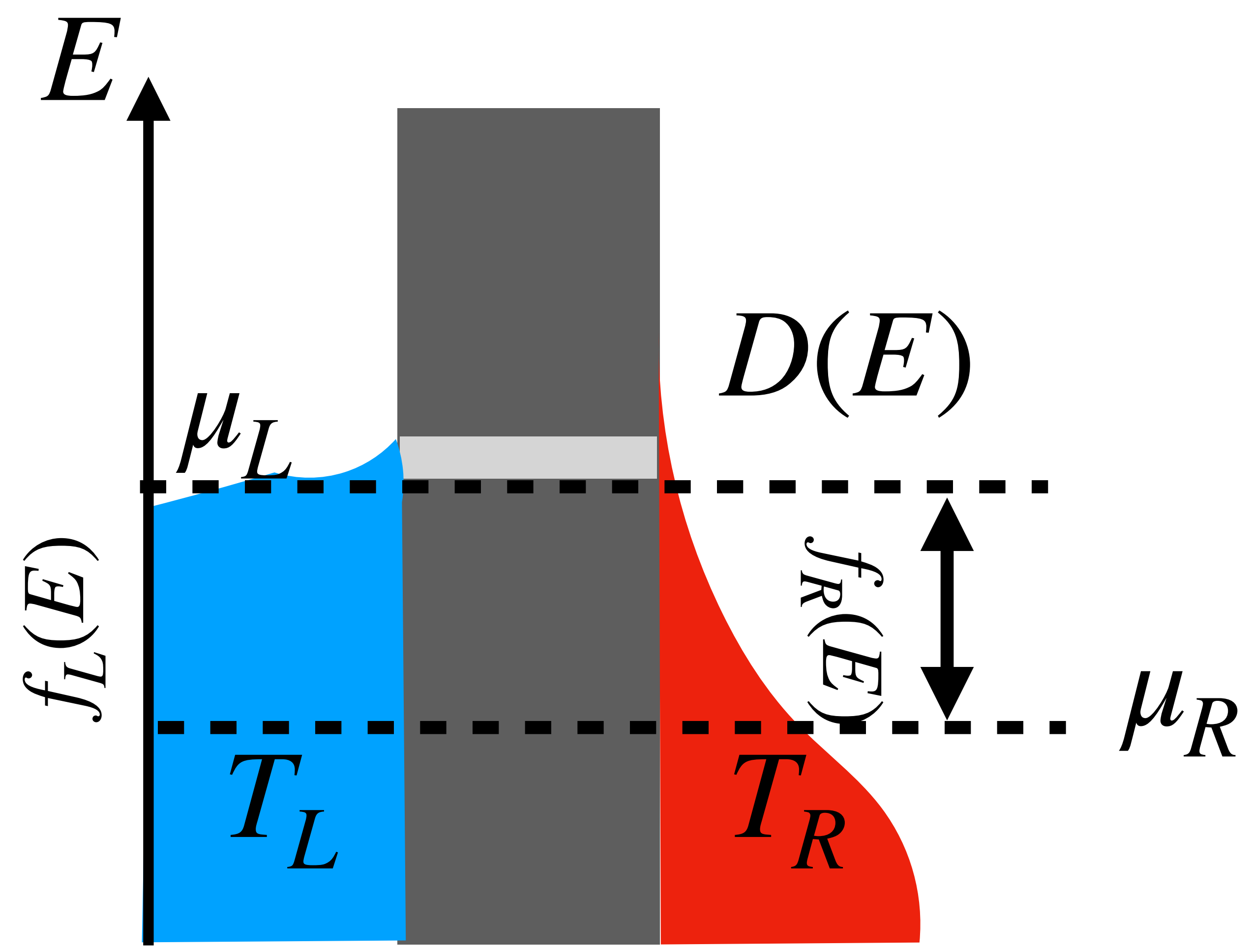

Thermoelectric with

- very low temperatures and low power input
- based on single-electron control
- originates from quantum effects

Hajiloo, F. et al. Phys. Rev. B 102, 155434 (2020)
Whitney, R. S. Phys. Rev. B 91, 115425 (2015)

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Task: Cooling with nonthermal resources

Collaborators

Elsa Danielsson

Janine Splettstoesser

Funded by
the European Union

European Research Council
Established by the European Commission

What is a nonthermal resources ?

Not characterized by a temperature or a chemical potential…

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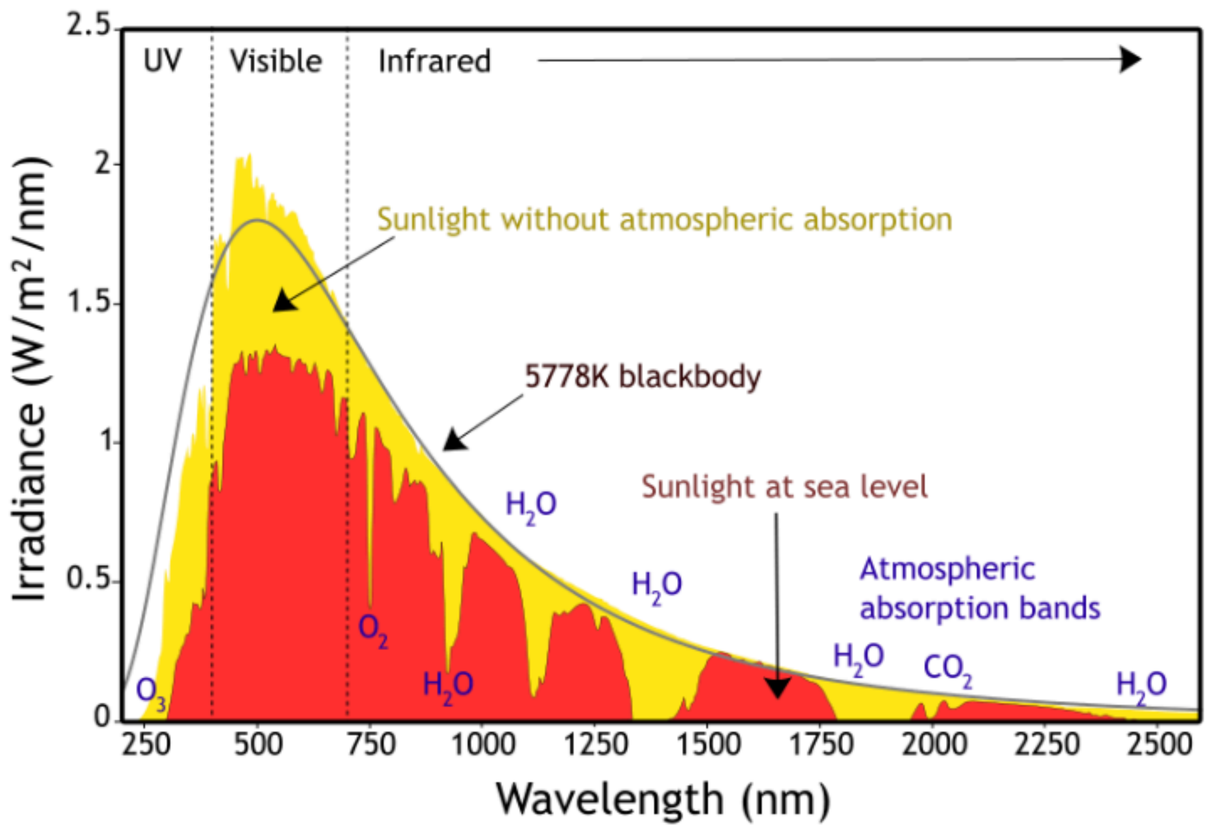
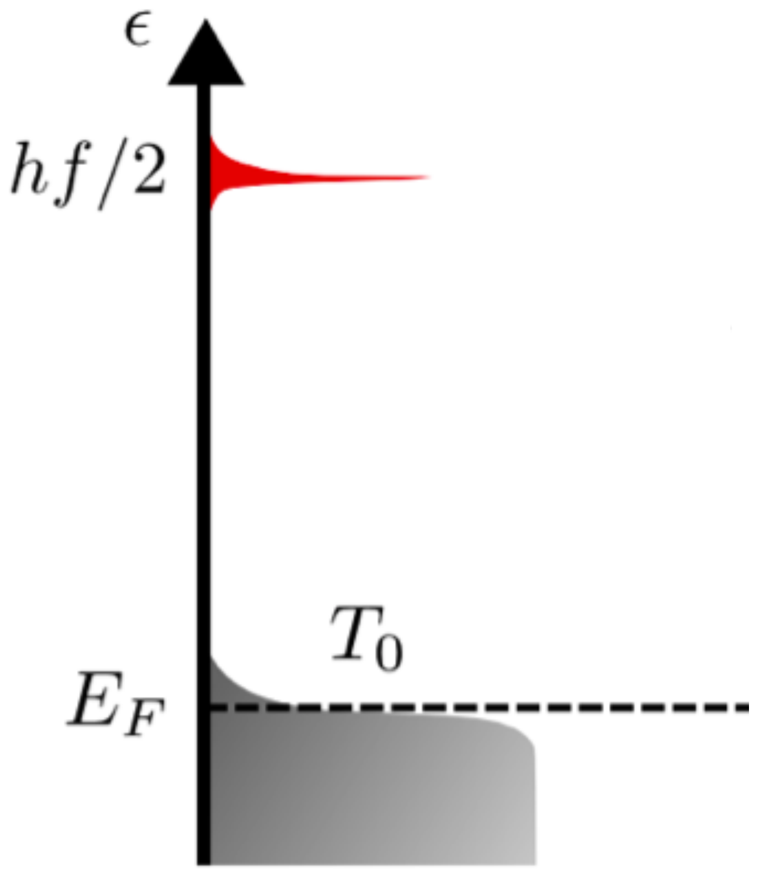
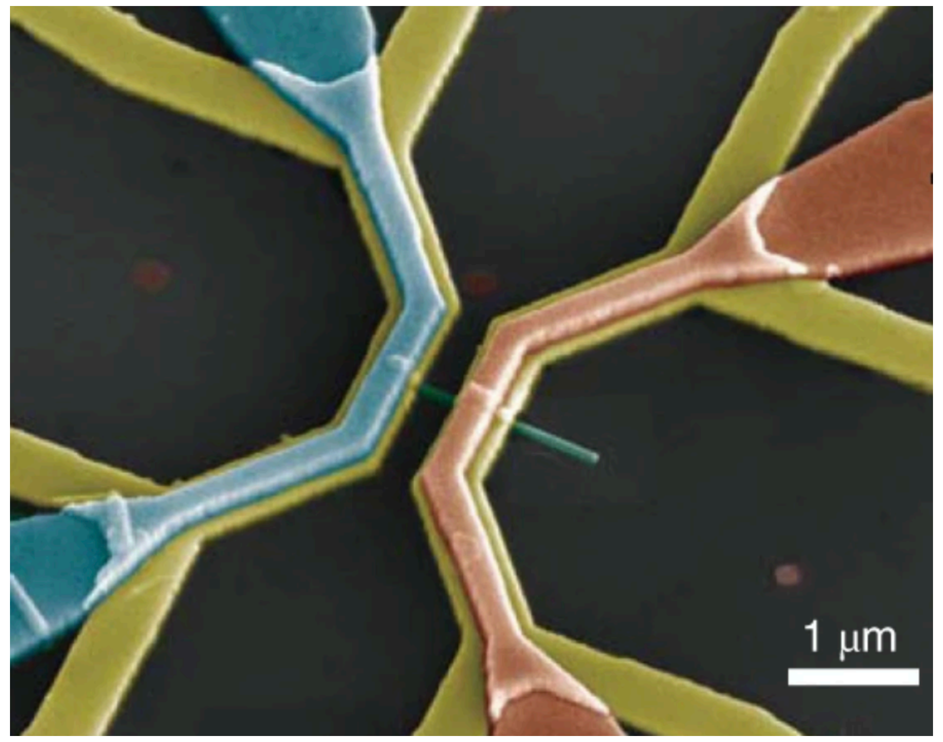
<u>Due to filtering or driving:</u>



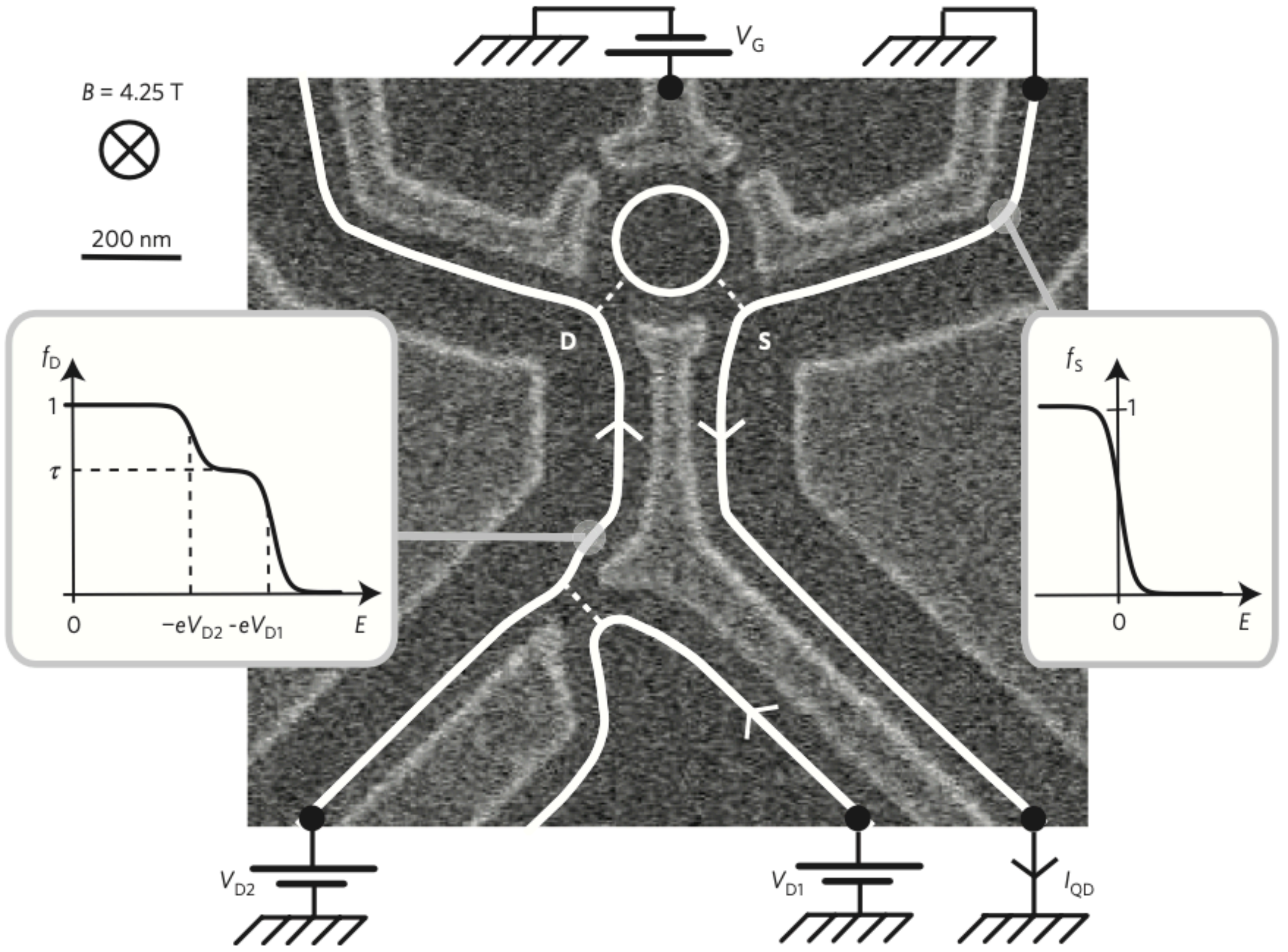


Song, J. C. W.; Levitov, L. S. J. Phys.: Condens. Matter 27, 164201 (2015)

<u>Due to competing environments:</u>

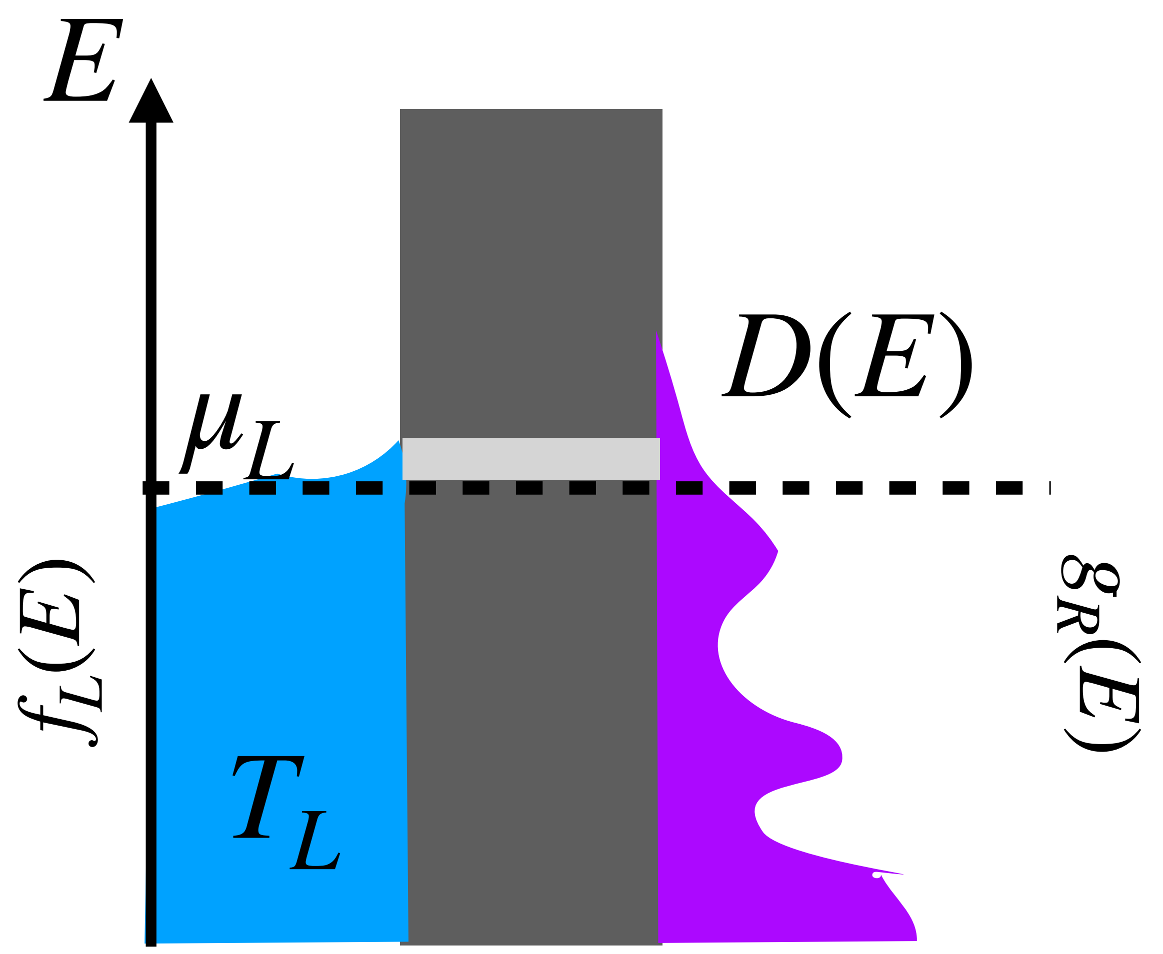


Josefsson, M. et al. Nat. Nanotechnol. 13, 920 (2018)



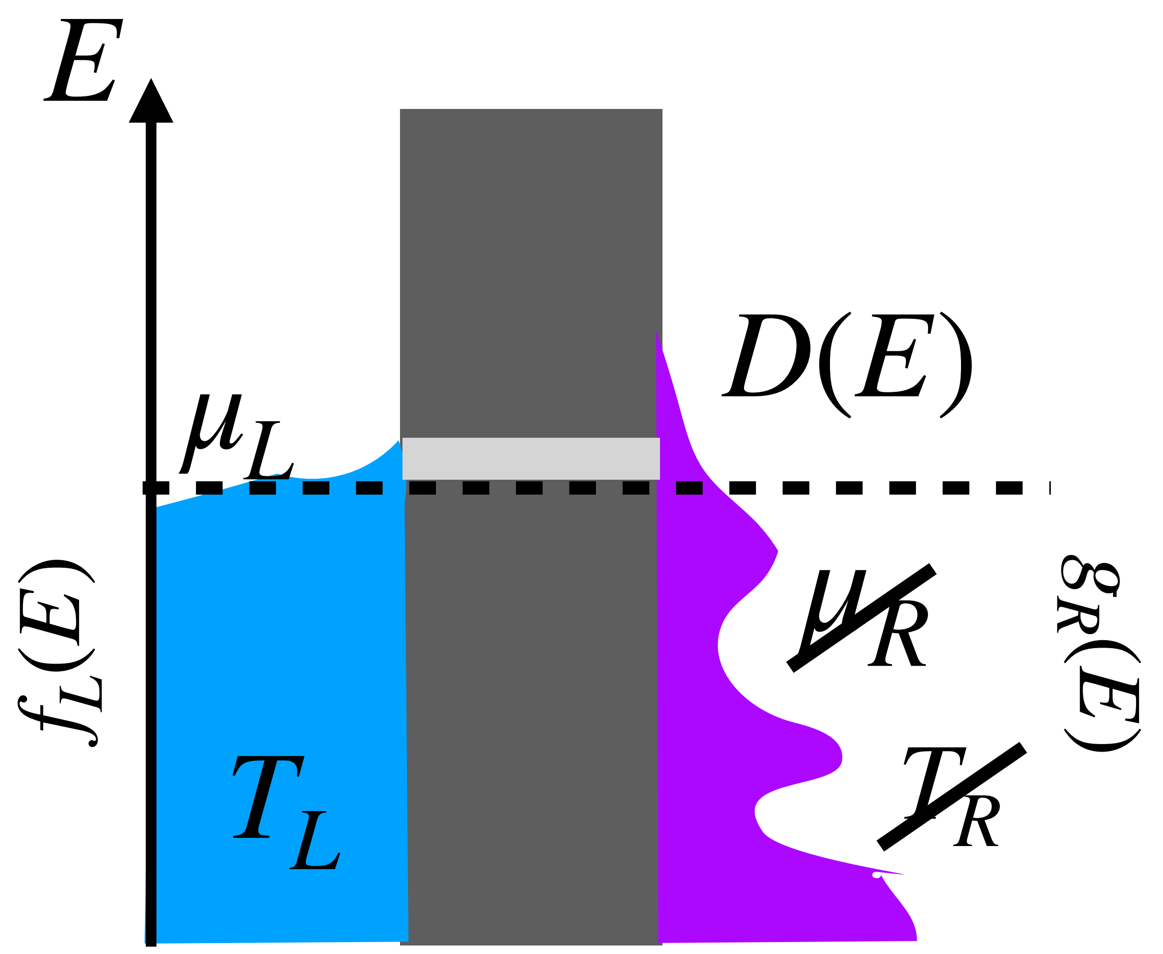
Altamiras, C.; Pierre, F. et al.. Nat. Phys. 6, 134 (2010)

Thermoelectric *cooling* with nonthermal resource



- **Task:** Cool left reservoir given nonthermal reservoir on the right side

Thermoelectric *cooling* with nonthermal resource



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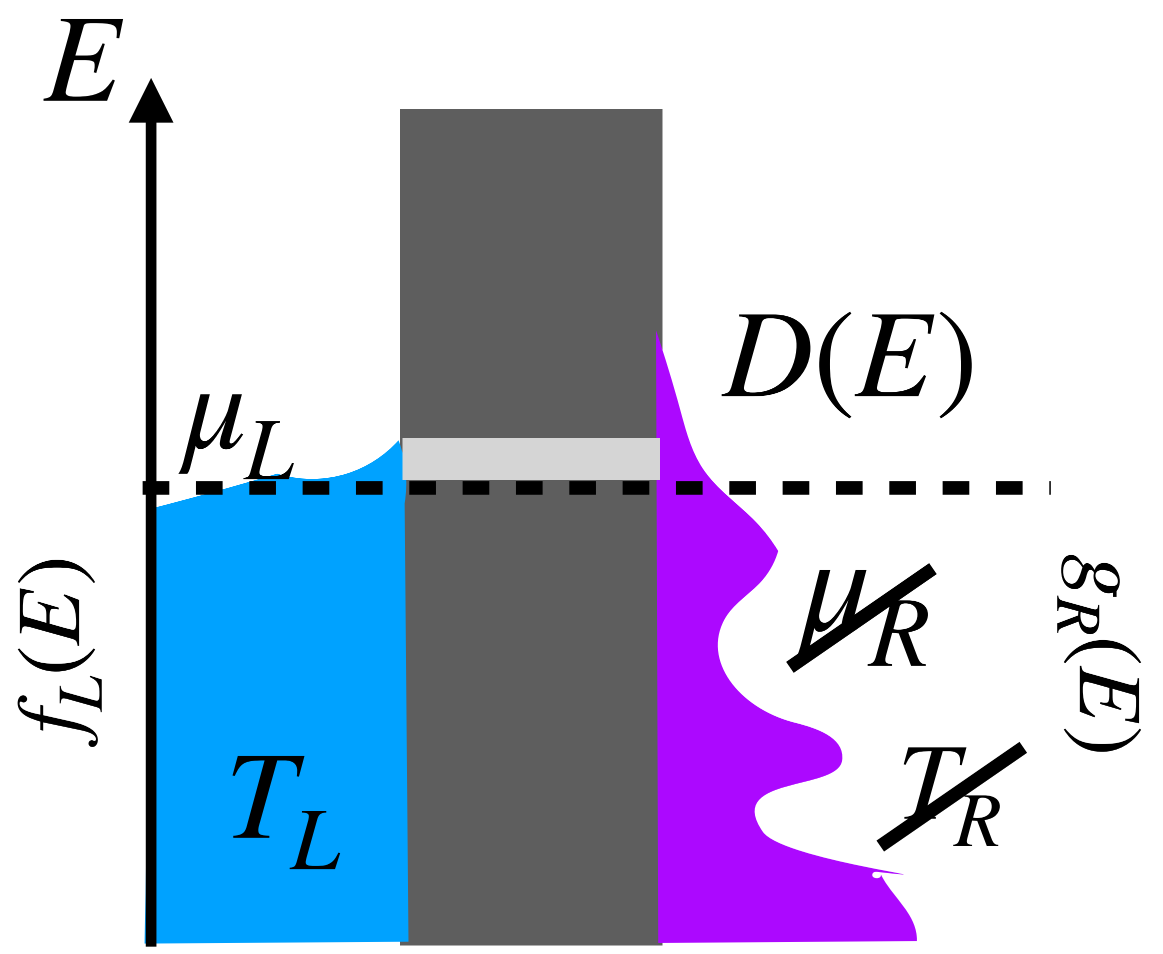

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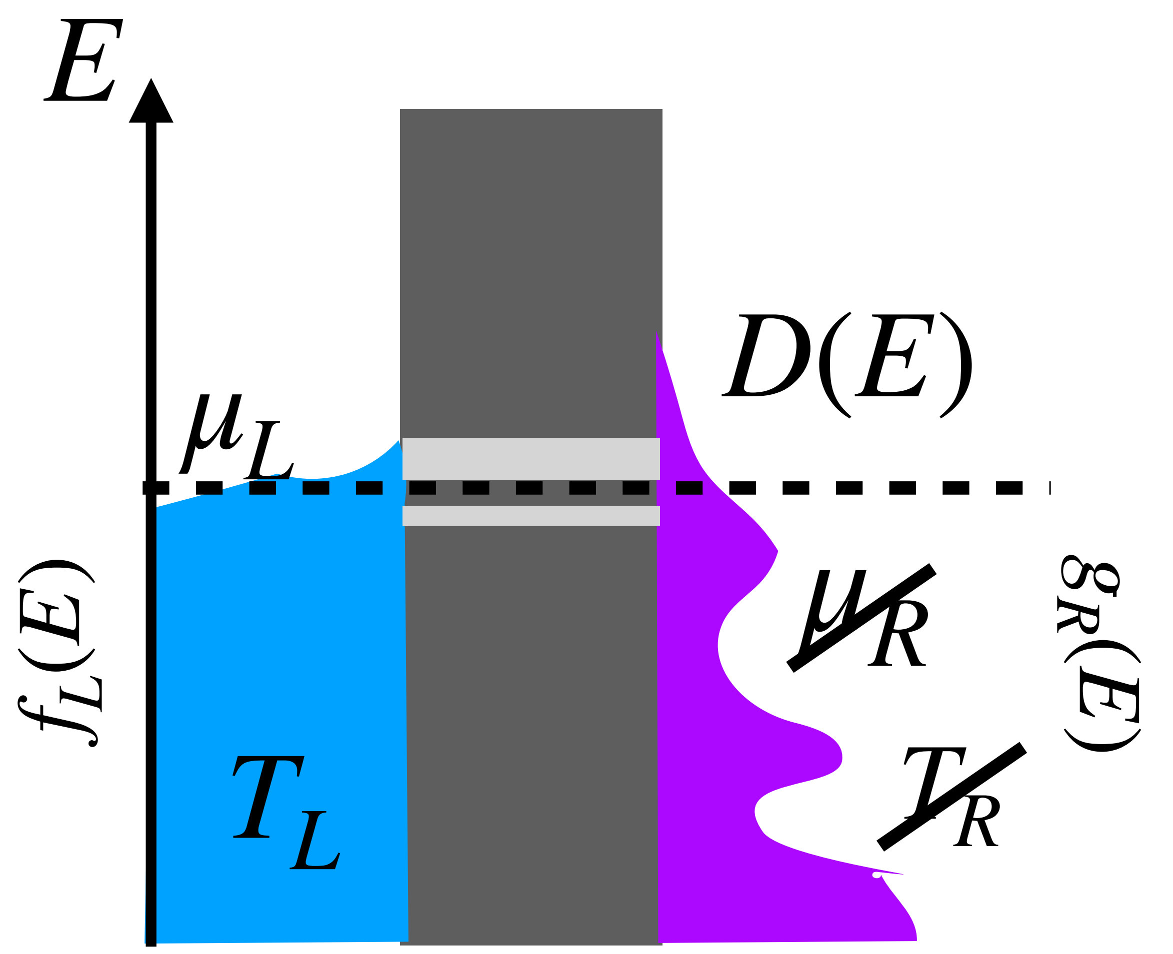

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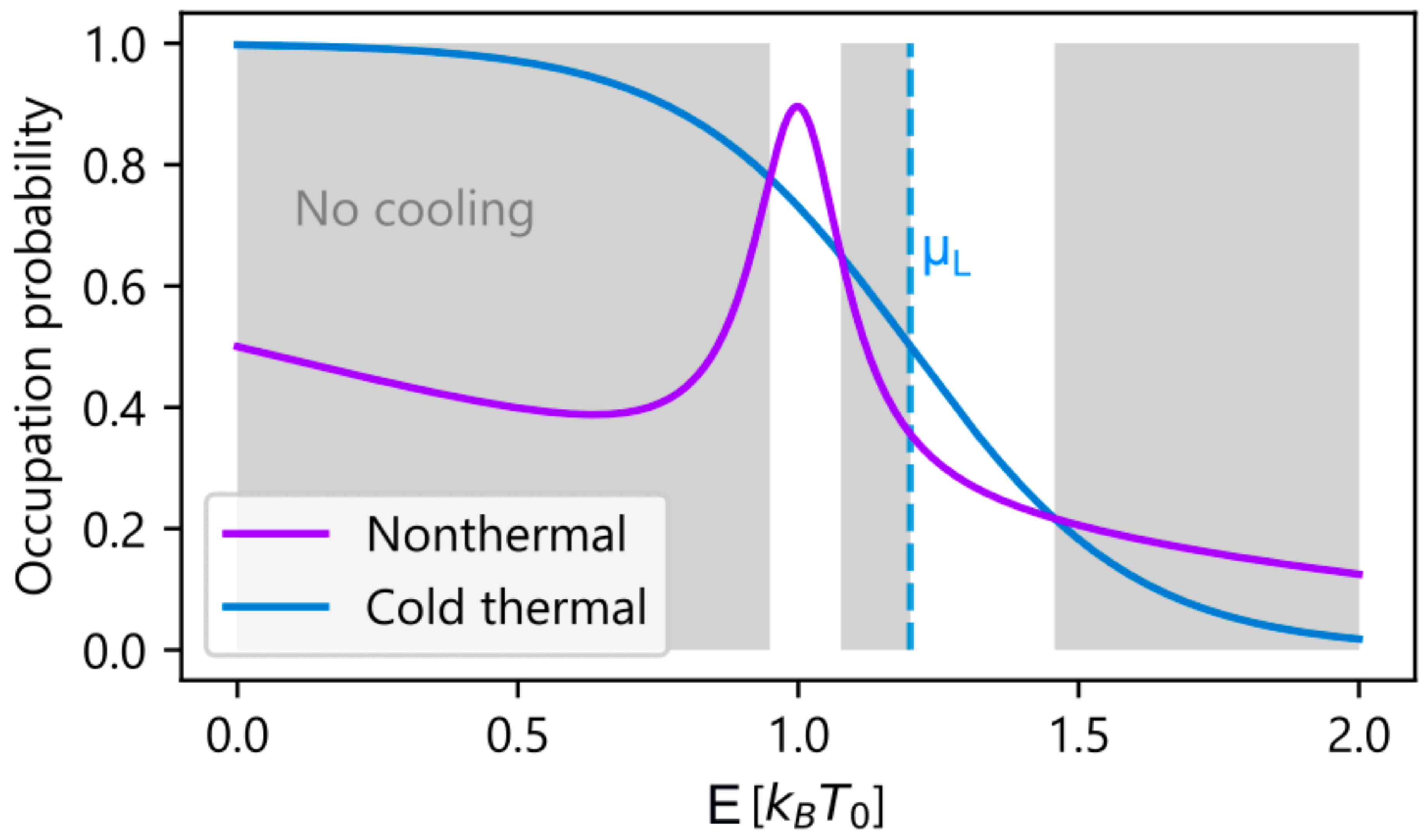
- Optimal **energy filter**: Boxcar transmission

$$D(E) = \Theta\big([E-\mu_L][f_L(E) - g_R(E)]\big)$$



Similar to thermal reservoir: Timpanaro, A. et al. Phys. Rev. B 111, 014301 (2025)
Whitney, R. S. Phys. Rev. B 91, 115425 (2015)

Performance for *cooling*

- **Power** and **heat current to right reservoir** are not well defined: How to **define the performance** of executing the task?

$$\eta := \frac{\text{Output}}{\text{Input}}$$

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$$J_{X_{i=L,R}} = \int \frac{dE}{h} D(E) X_i(E) [f_L(E) - g_R(E)]$$

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$$\eta := \frac{\text{Output}}{\text{Input}}$$

- Reinvestigate **general currents**

$$J_{X_{i=L,R}} = \int \frac{dE}{h} D(E) X_i(E) [f_L(E) - g_R(E)]$$

- Define "meaningful" **input** and **output currents**

$$X_L(E) = \ln\left[\frac{f_L(E)}{1 - f_L(E)}\right] \qquad X_R(E) = \ln\left[\frac{1 - g_R(E)}{g_R(E)}\right]$$

entropy

Carnot (1796-1832)

$$\longrightarrow J_{X_L} \equiv \frac{\dot{Q}_L}{T_L}$$

Acciai, M.; Tesser, L., Splettstoesser, J. et al. Phys. Rev. B 109, 075405 (2024)
Tesser, L., Kirchberg, H., Acciai, M., Splettstoesser, J., in preparation

Optimizing ratio of performance

- **Goal:** Best η at **output current** $J_{X_L} \equiv \dot{Q}_L / T_L$

$$\eta := \frac{\text{Output}}{\text{Input}} = \frac{J_{X_L}}{J_{X_R}}$$

Optimizing ratio of performance

- **Goal:** Best η at **output current** $J_{X_L} \equiv \dot{Q}_L / T_L$

$$\eta := \frac{\text{Output}}{\text{Input}} = \frac{J_{X_L}}{J_{X_R}}$$

- Find **best energy filter** at given J_{X_L} to maximize η

$$\frac{d}{dE}\left[\partial J_{X_R} - \lambda \partial J_{X_L}\right] < 0$$

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- **Energy filter**: updated **boxcars**

$$D(E) = \Theta\Big([X_R(E) - \lambda X_L(E)][g_R(E) - f_L(E)]\Big)$$

Optimizing ratio of performance

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- **Energy filter**: updated **boxcars**

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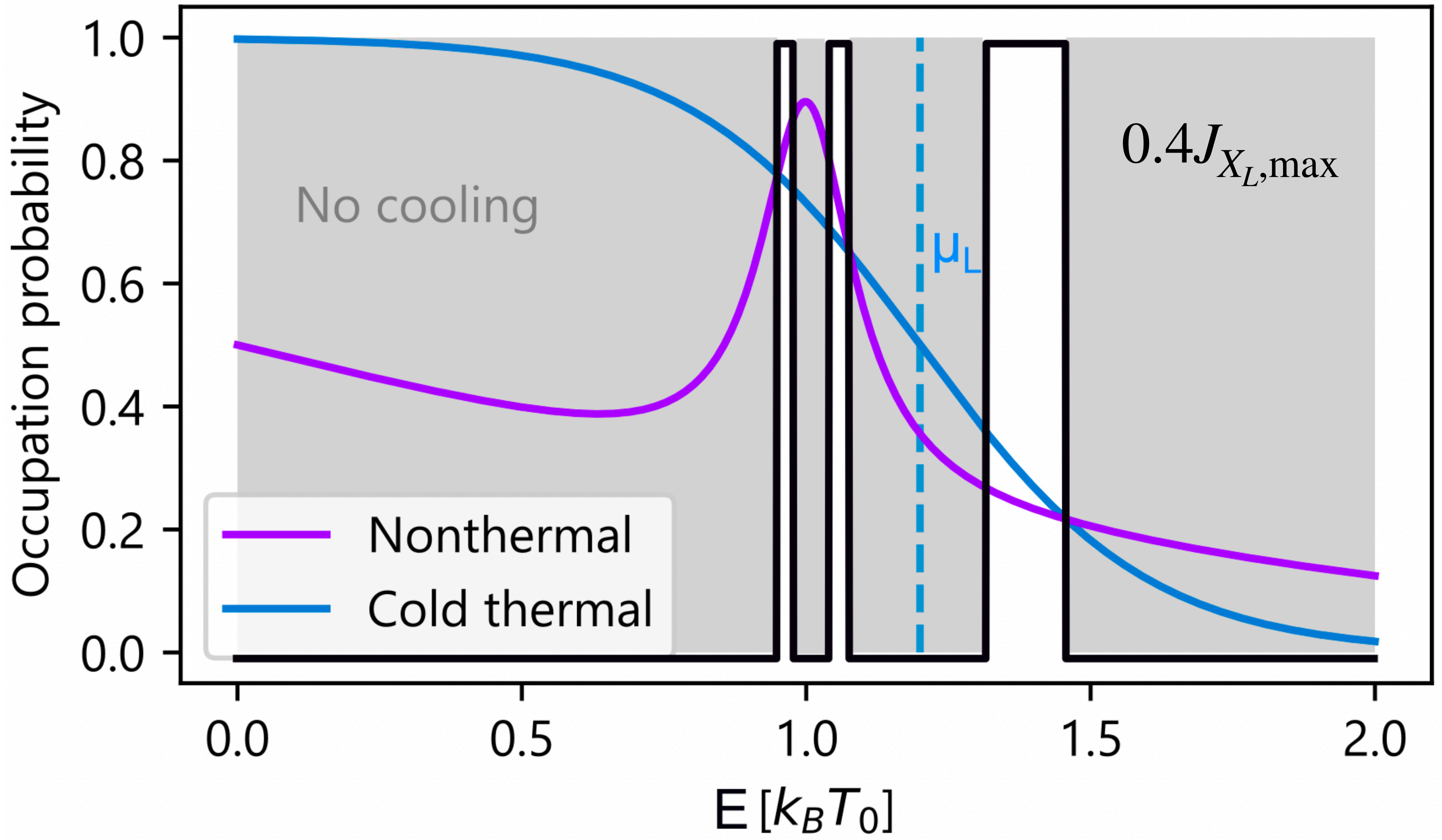
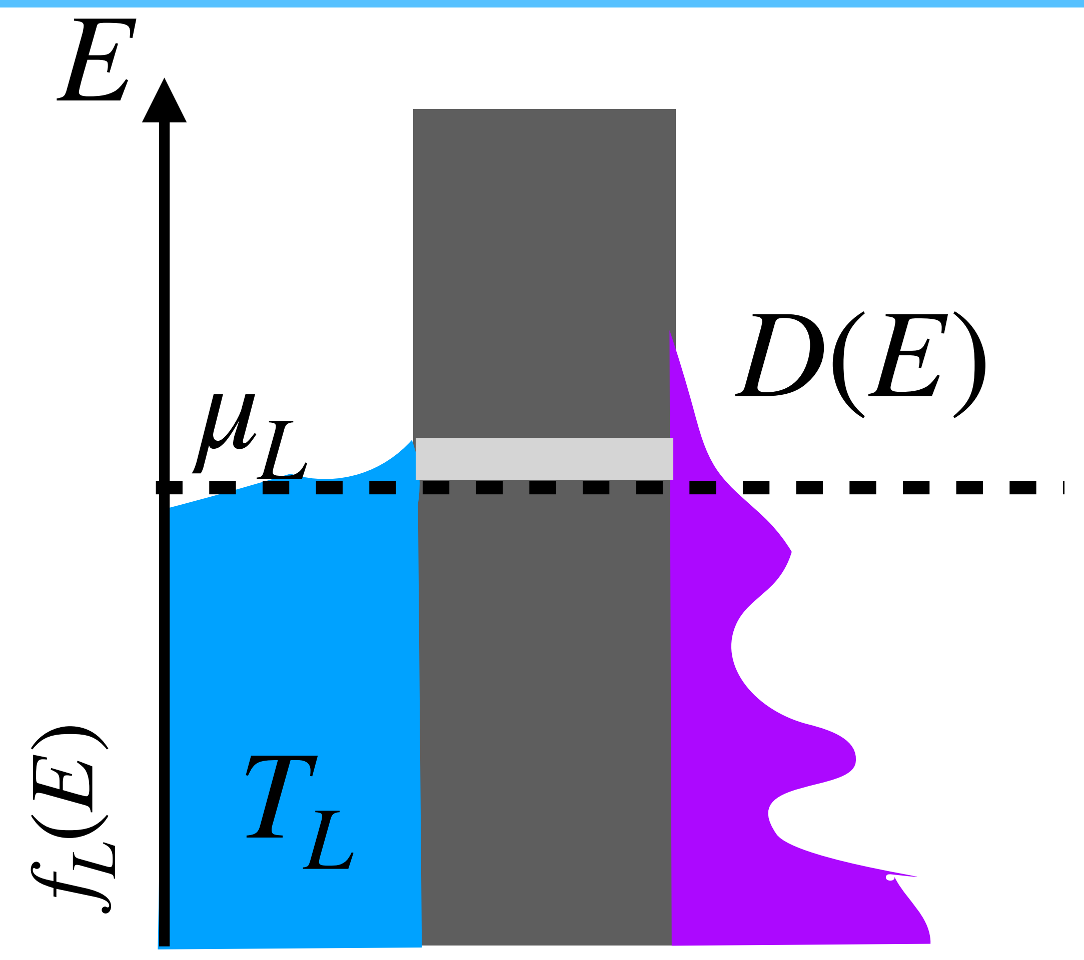
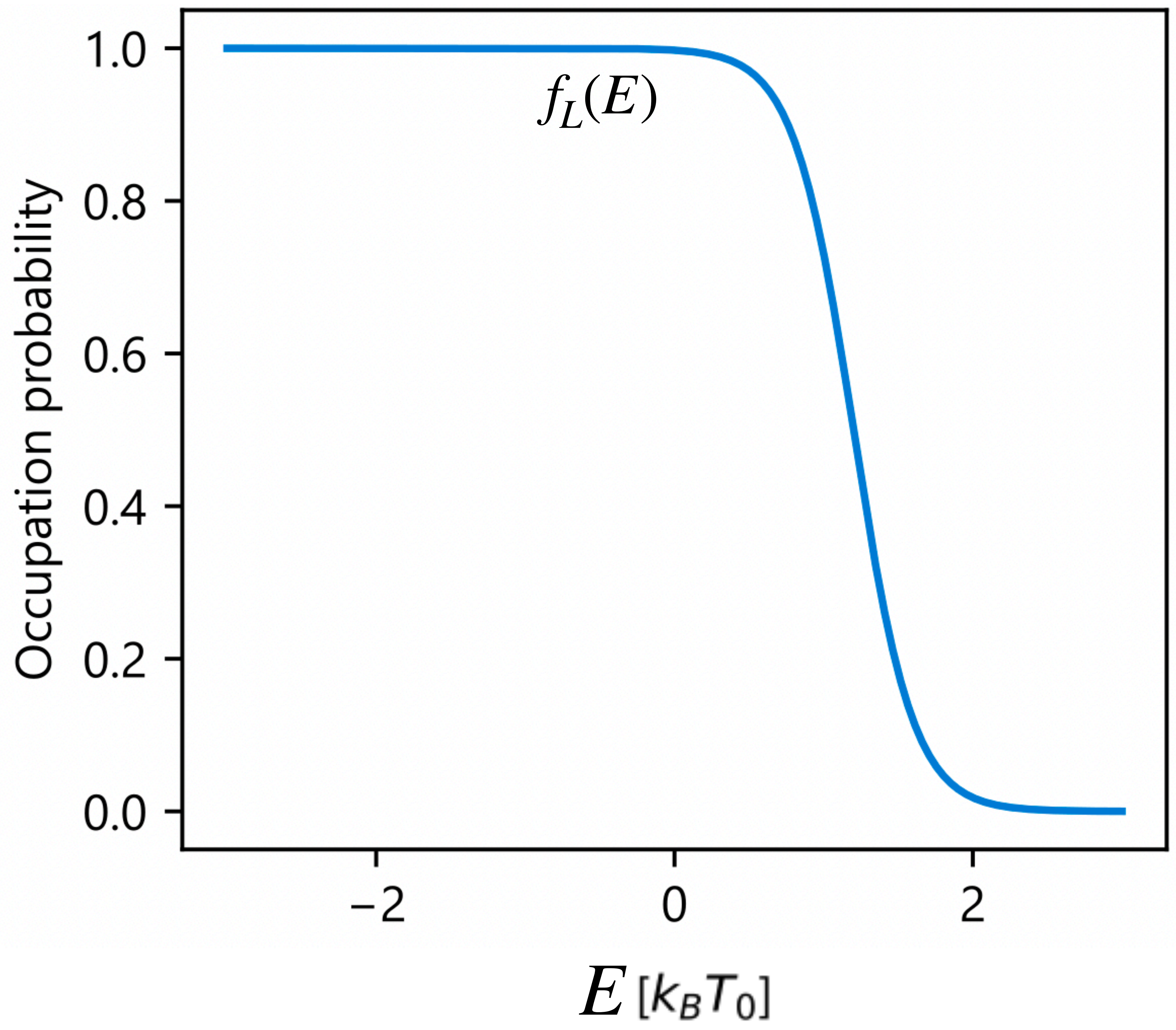
- **Particle flow near crossing** points near crossing points of distributions



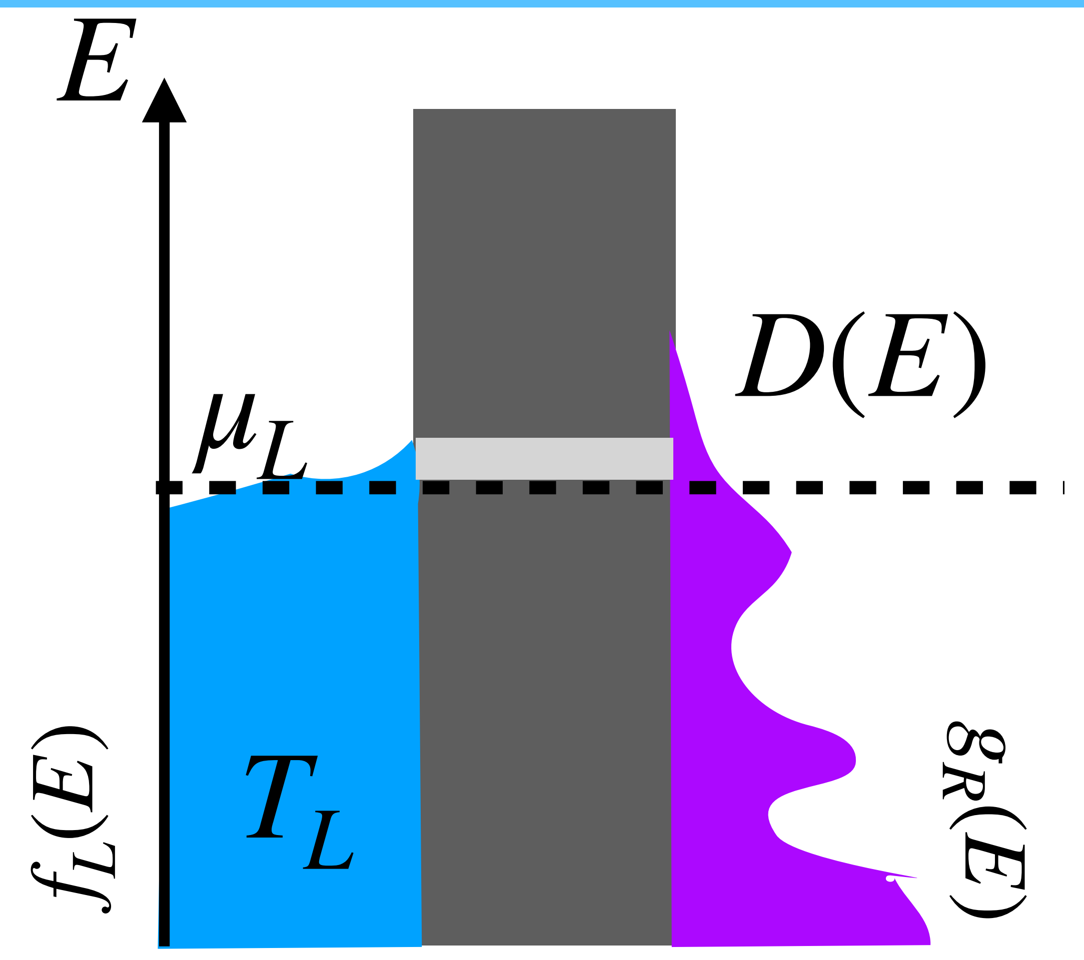
Reference probe



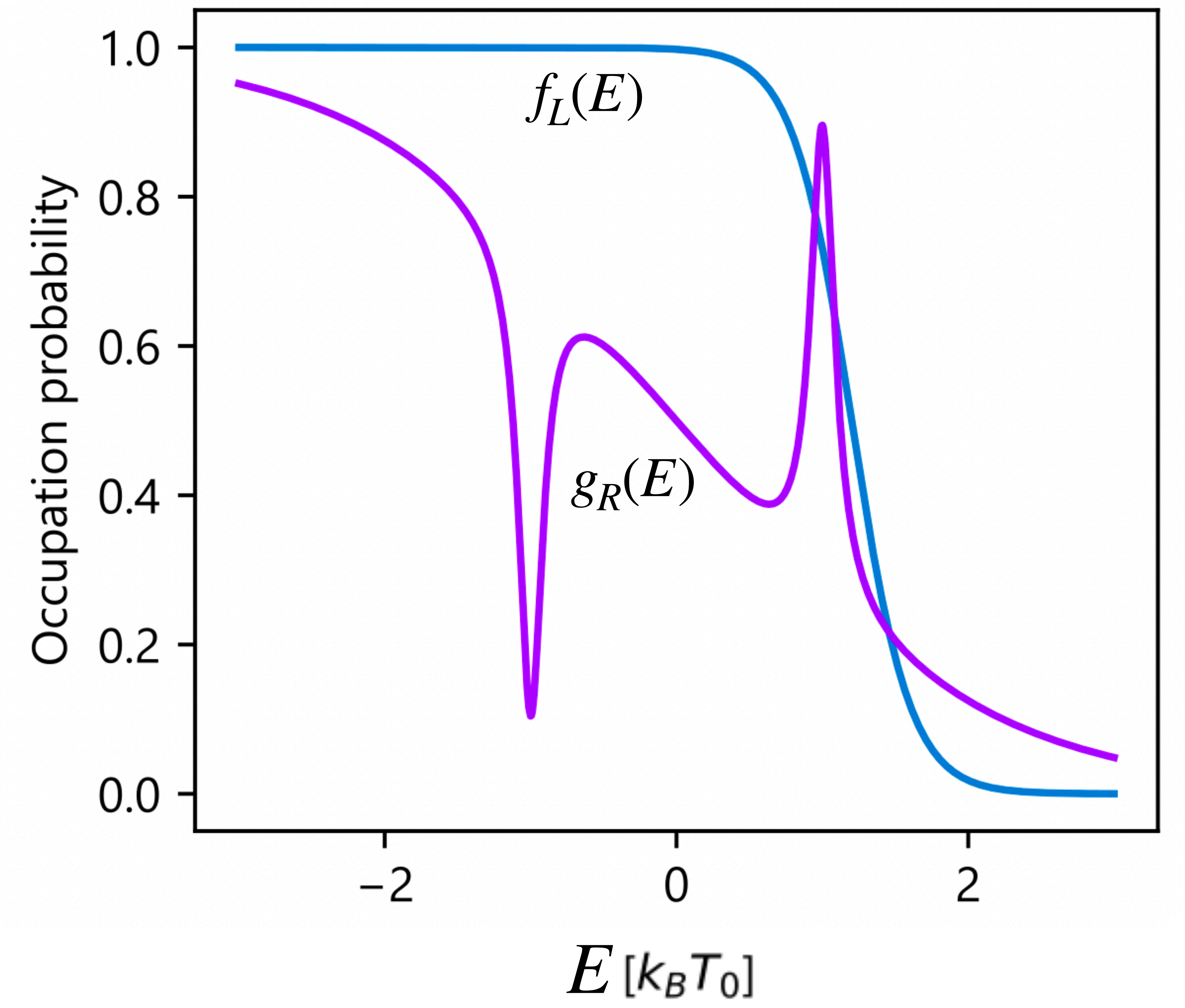
Goal: Maximize η at **output current** $J_{X_L} \equiv \dot{Q}_L / T_L$



Reference probe



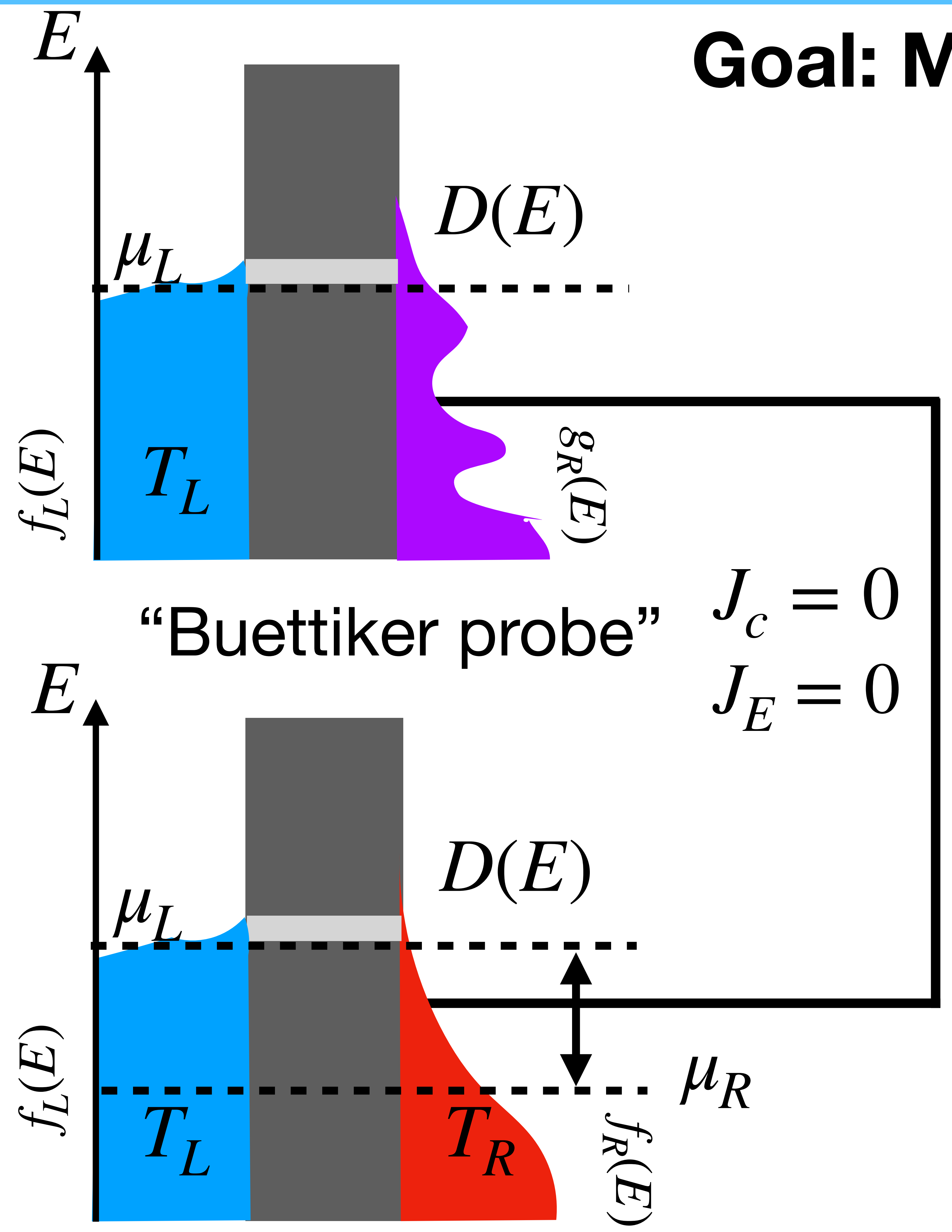
Goal: Maximize η at **output current** $J_{X_L} \equiv \dot{Q}_L/T_L$



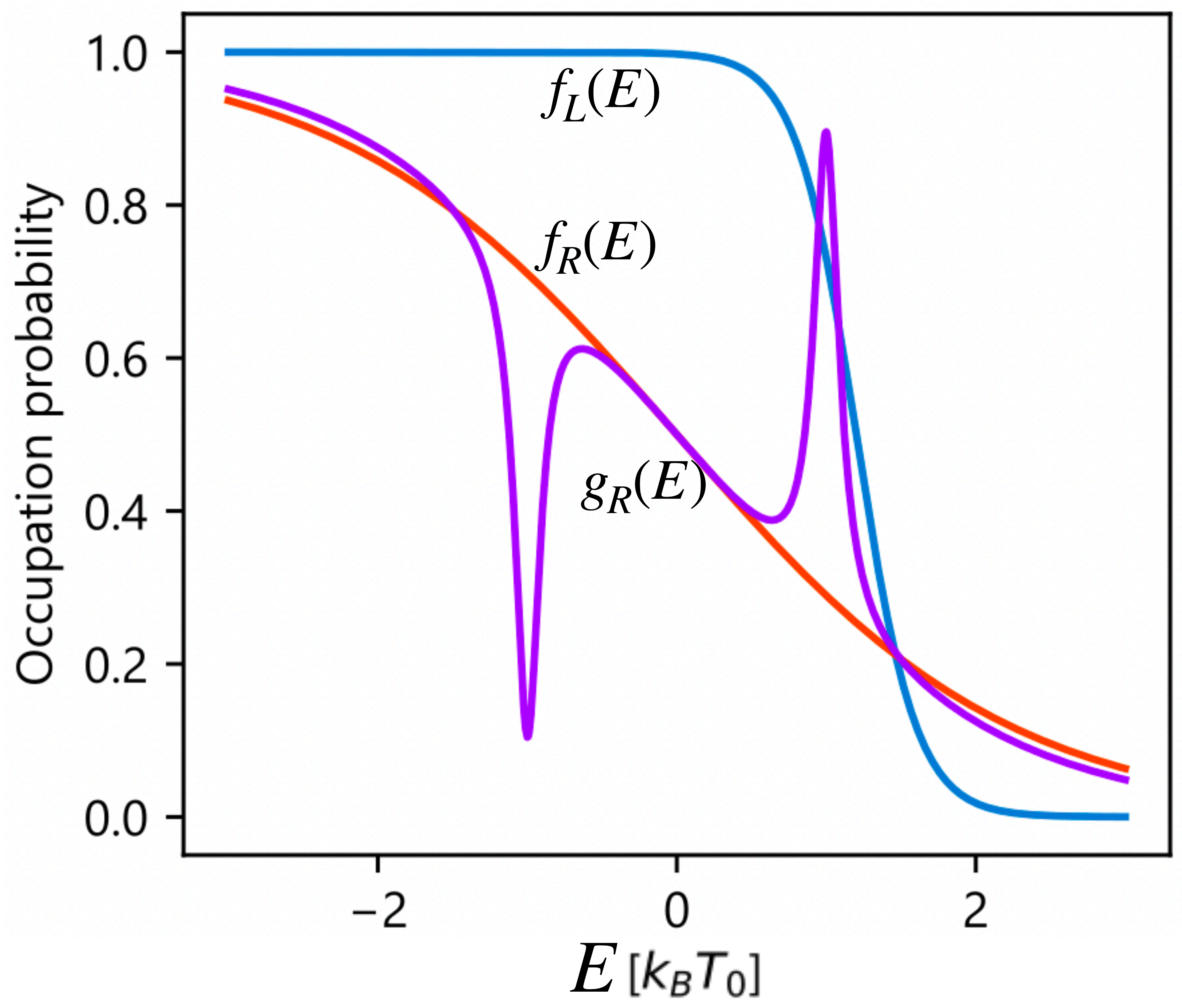
What is a good way to **compare** η at given **output current** to?

Reference probe

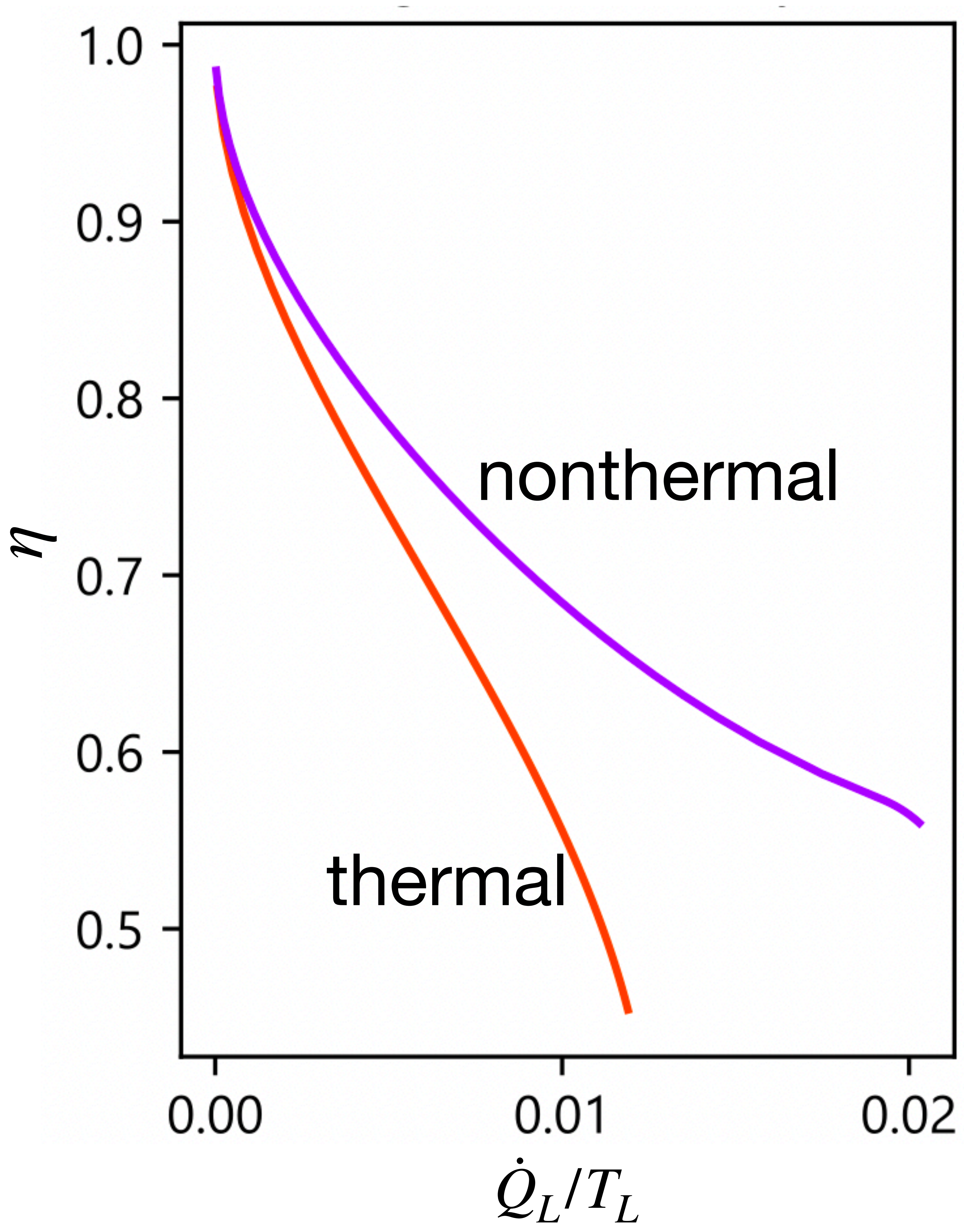
Goal: Maximize η at **output current** $J_{X_L} \equiv \dot{Q}_L / T_L$



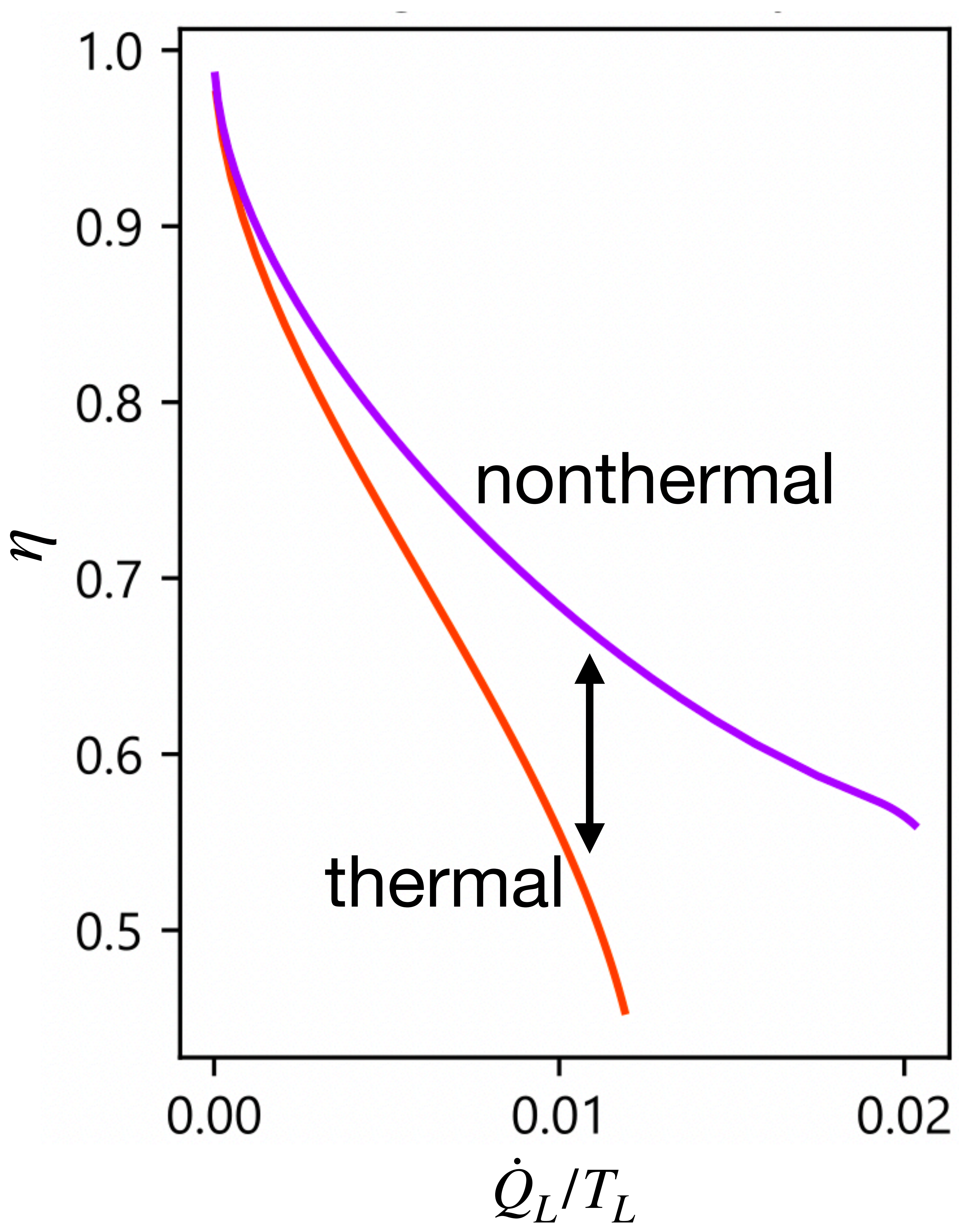
Buettiker, M. IBM J. Res. Dev. 32, 63 (1988)
Buettiker, M. Phys. Rev. B 40, 3409 (1989)



Cooling performance

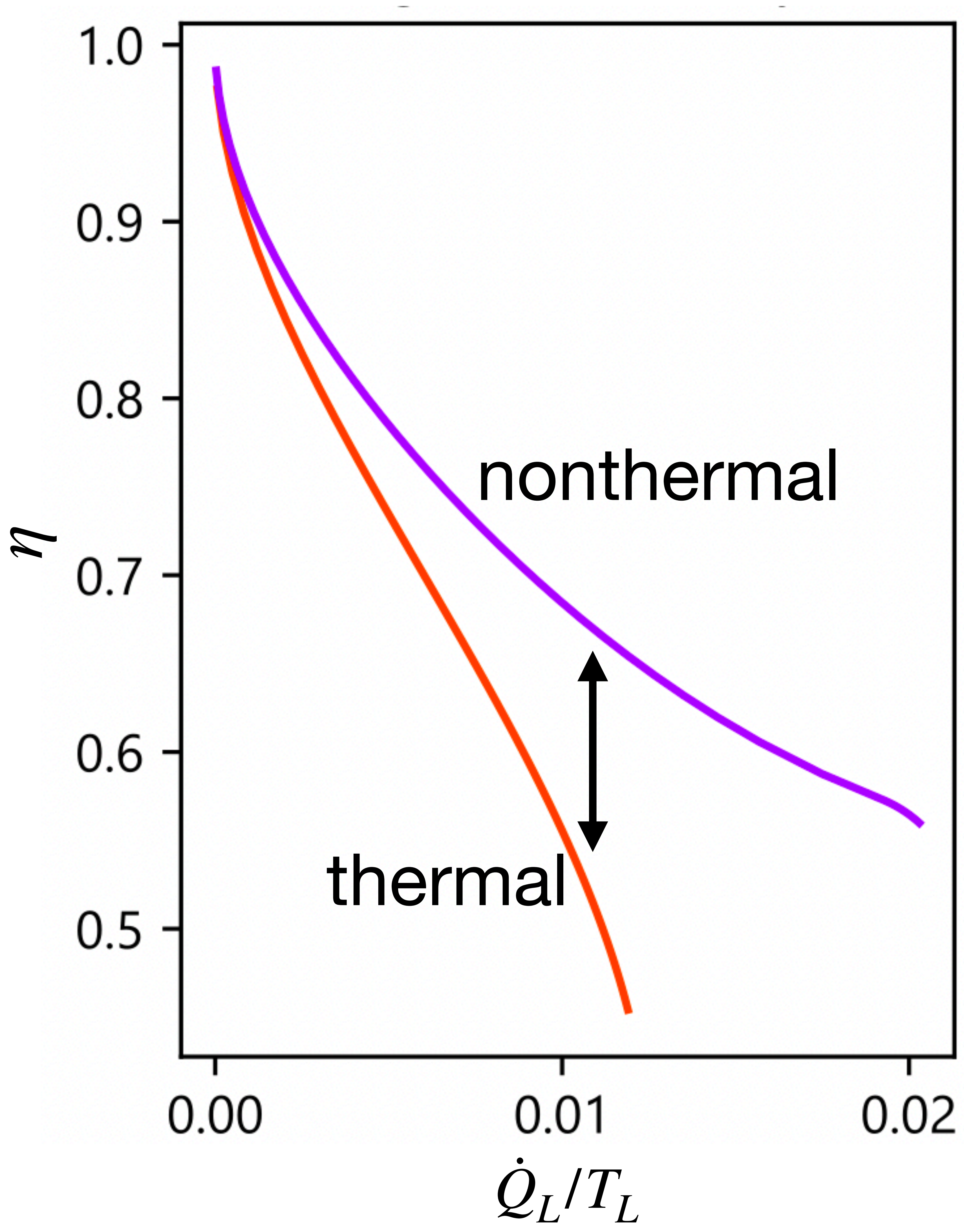


Cooling performance



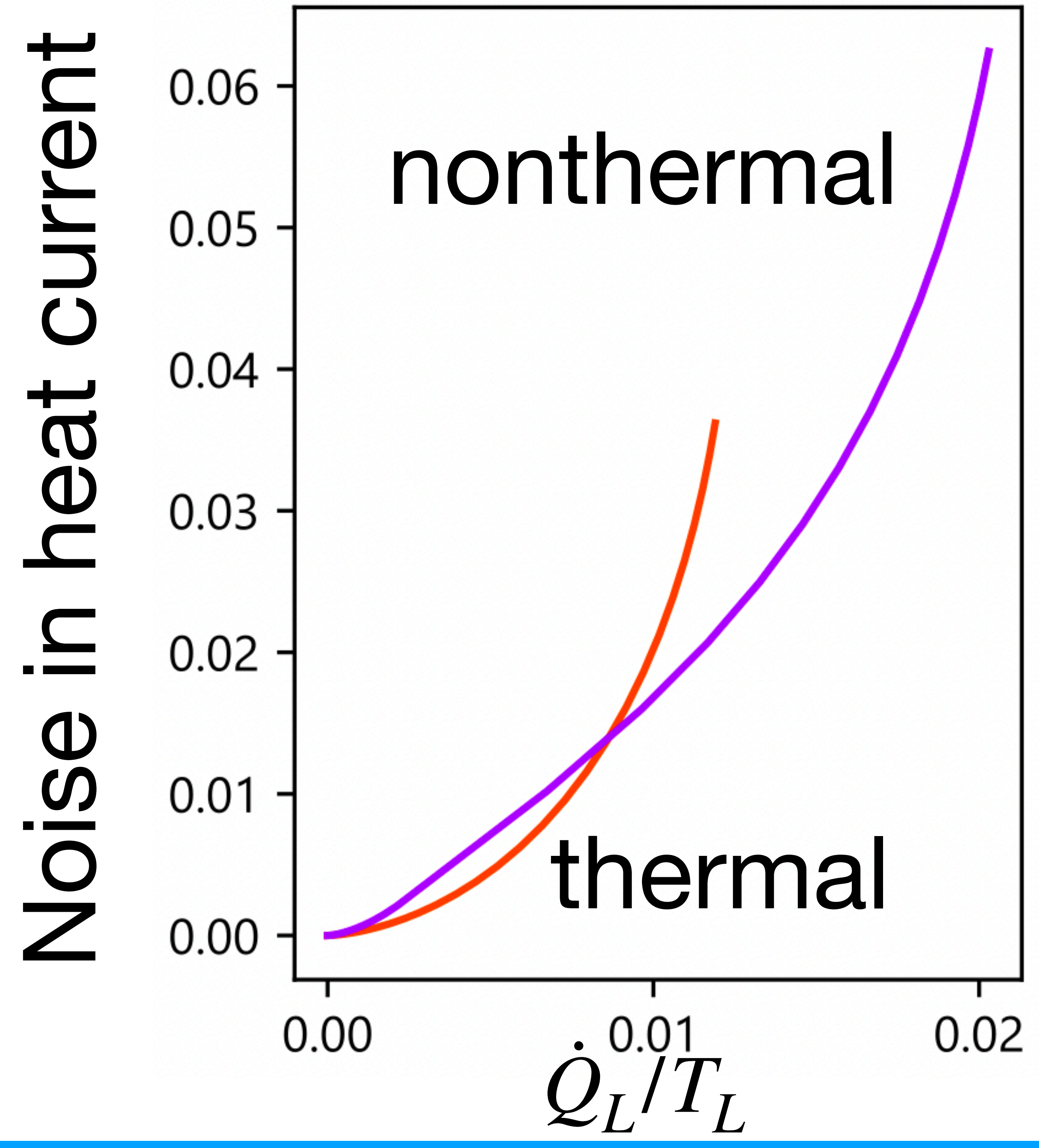
- **Better cooling performance** with nonthermal resource in comparison to thermal probe

Cooling performance



- **Better cooling performance** with nonthermal resource in comparison to thermal probe

- **Versatile procedure** - e.g. **Goal**: **minimize noise** given **output current**



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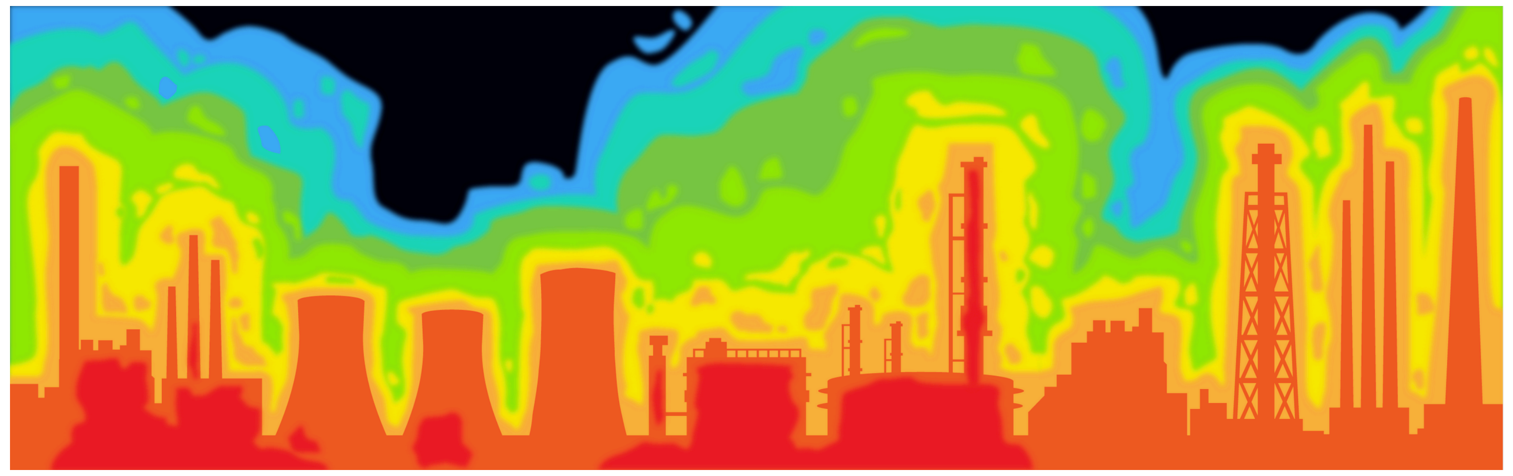
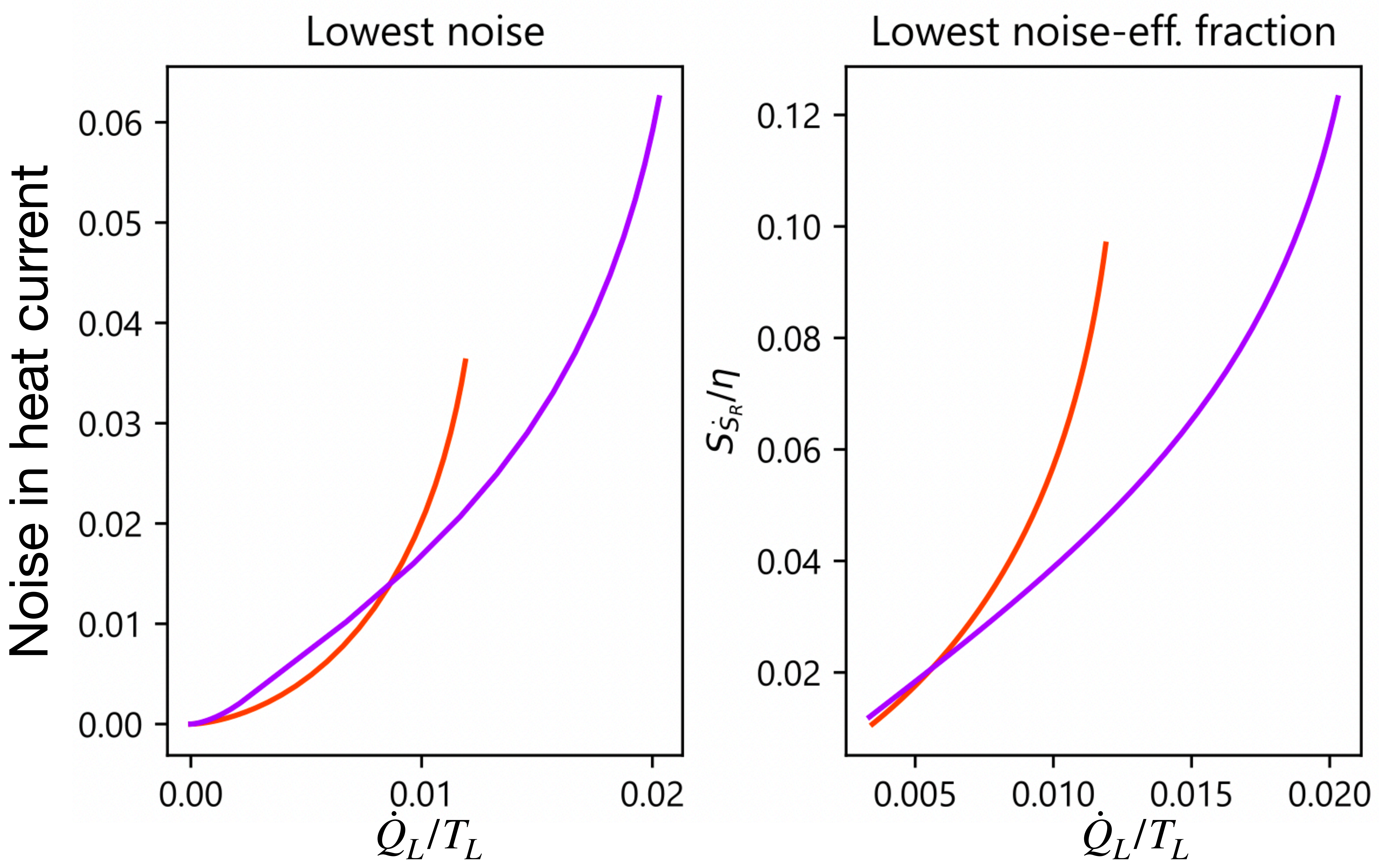
Open questions

- Can one find **generalized performance quantifiers?**
- Is it possible to **design tasks** for **specific nonthermal resource?**
- **Can one characterize & classify nonthermal resources** to perform specific tasks?
- Is there another way to **quantify “resourcefulness”** of nonthermal resources? $\rightarrow$e.g. ergotropy?
- What is the effect of including **dissipation** and damping OR **interacting** electrons?



#QEI
the quantum energy initiative
https://quantum-energy-initiative.org/

Backup — low noise & high performance



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Optimizing ratio of performance detailed

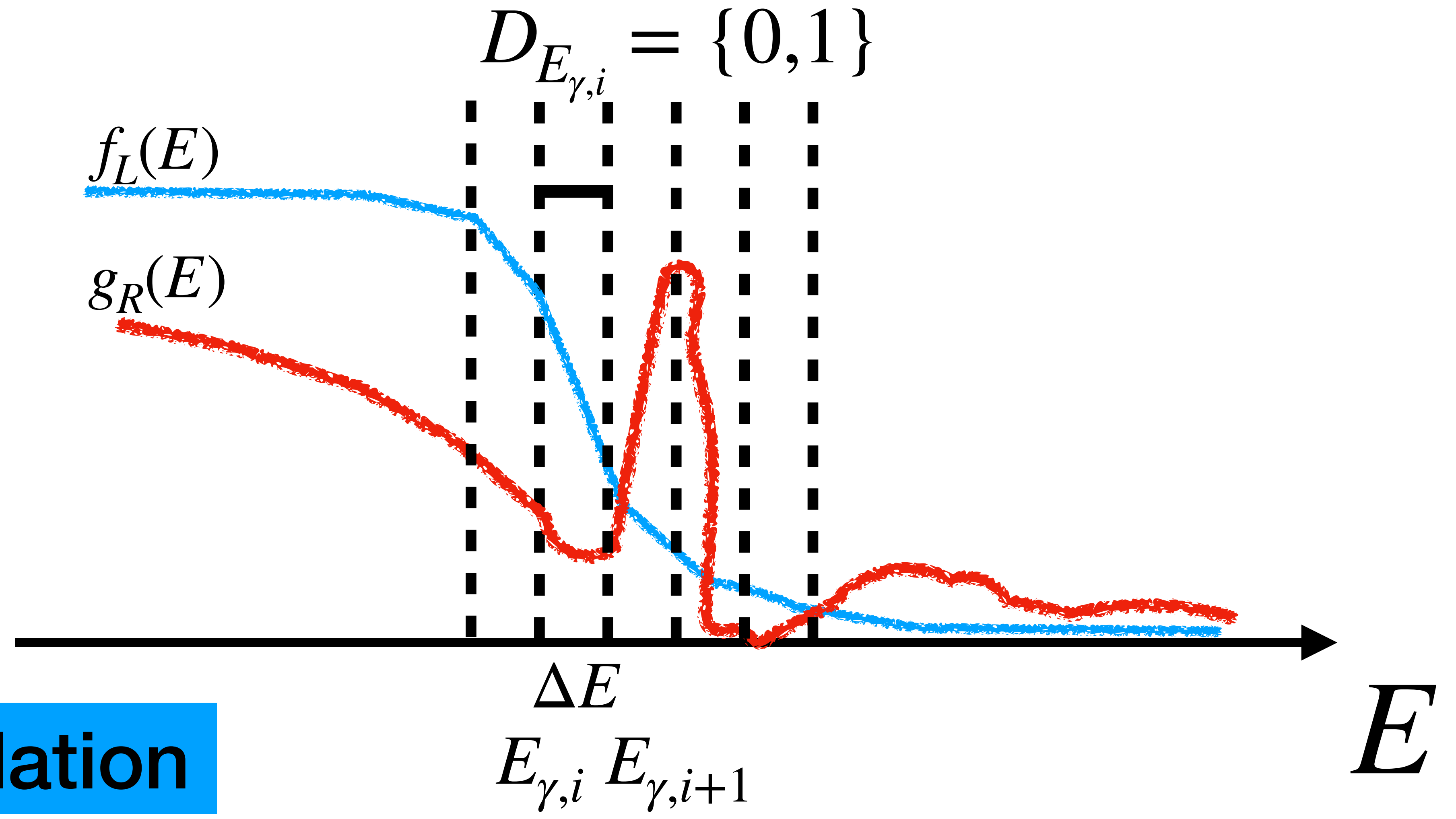
- Set a fixed output current J_{X_L} and exploit scattering theory (non-interacting particles)

$$\eta := \frac{J_{X_L}}{J_{X_R}} = \frac{\sum_{E_\gamma} \frac{\Delta E}{h} D_{E_\gamma} X_L(E_\gamma)[f_L(E_\gamma) - g_R(E_\gamma)]}{\sum_{E_\gamma} \frac{\Delta E}{h} D_{E_\gamma} X_R(E_\gamma)[f_L(E_\gamma) - g_R(E_\gamma)]} = \frac{\sum_{E_\gamma} j_{X_L,E_\gamma}(D_{E_\gamma})}{\sum_{E_\gamma} j_{X_R,E_\gamma}(D_{E_\gamma})}$$

- Variational calculus

$$\lim_{\Delta E \to 0} \quad J_{X_R} = \lambda J_{X_L} + \sum_{E_\gamma} [j_{X_R}(D_{E_\gamma}) - \lambda j_{X_L}(D_{E_\gamma})]$$

Minimize: $$\frac{dJ_{X_R}}{dD_{E_{\gamma,i}}} = \Delta E (X_{R,E_{\gamma,i}} - \lambda X_{L,E_{\gamma,i}})(f_{L,E_{\gamma,i}} - g_{R,E_{\gamma,i}}) < 0$$



Sum over all slices to fulfill the constraint! —> Numerical simulation

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