Quantum thermodynamics

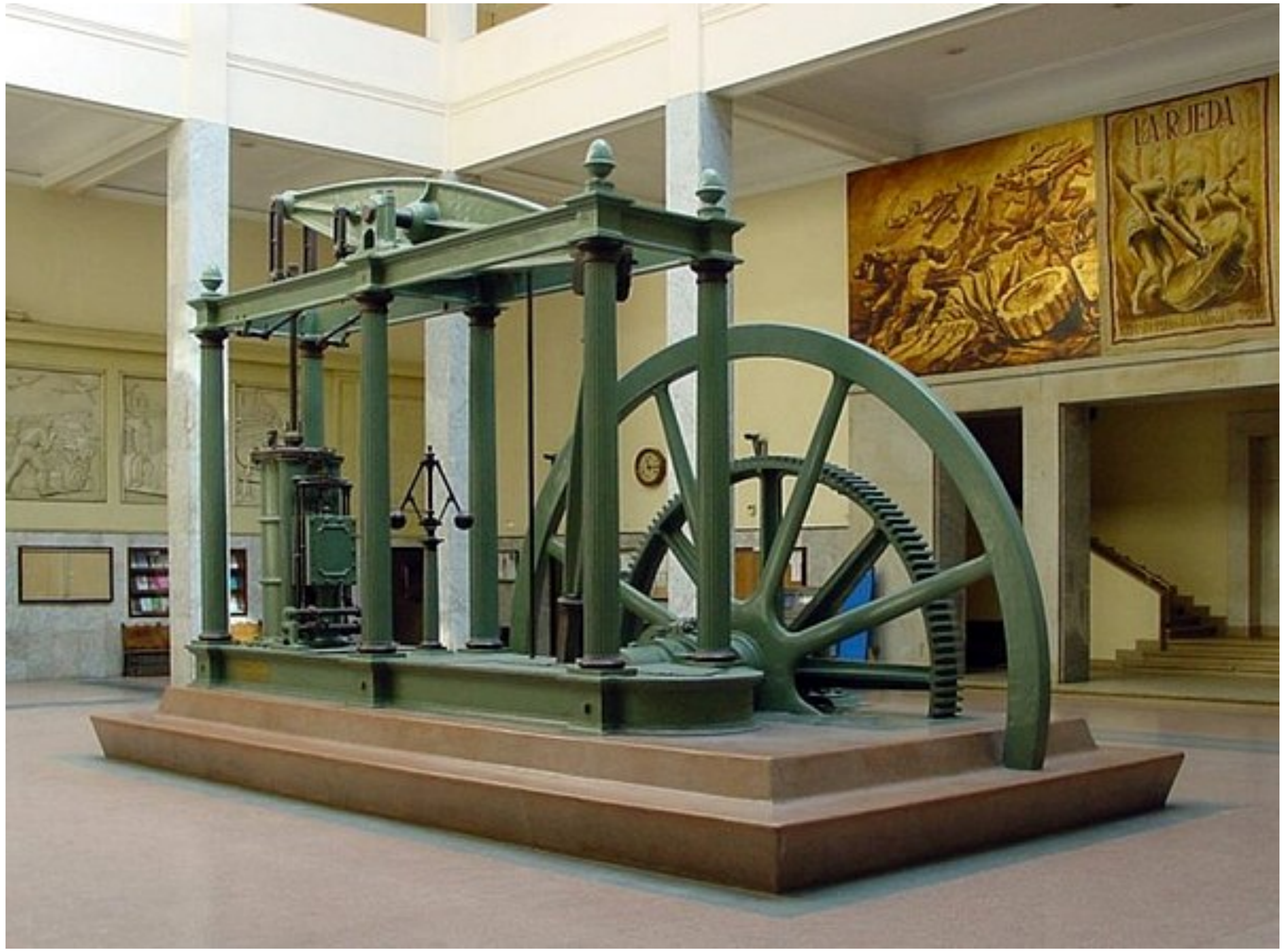
Lecture 1

Liliana Arrachea (2023)

Context and motivation

Themodynamics and Industrial Revolution

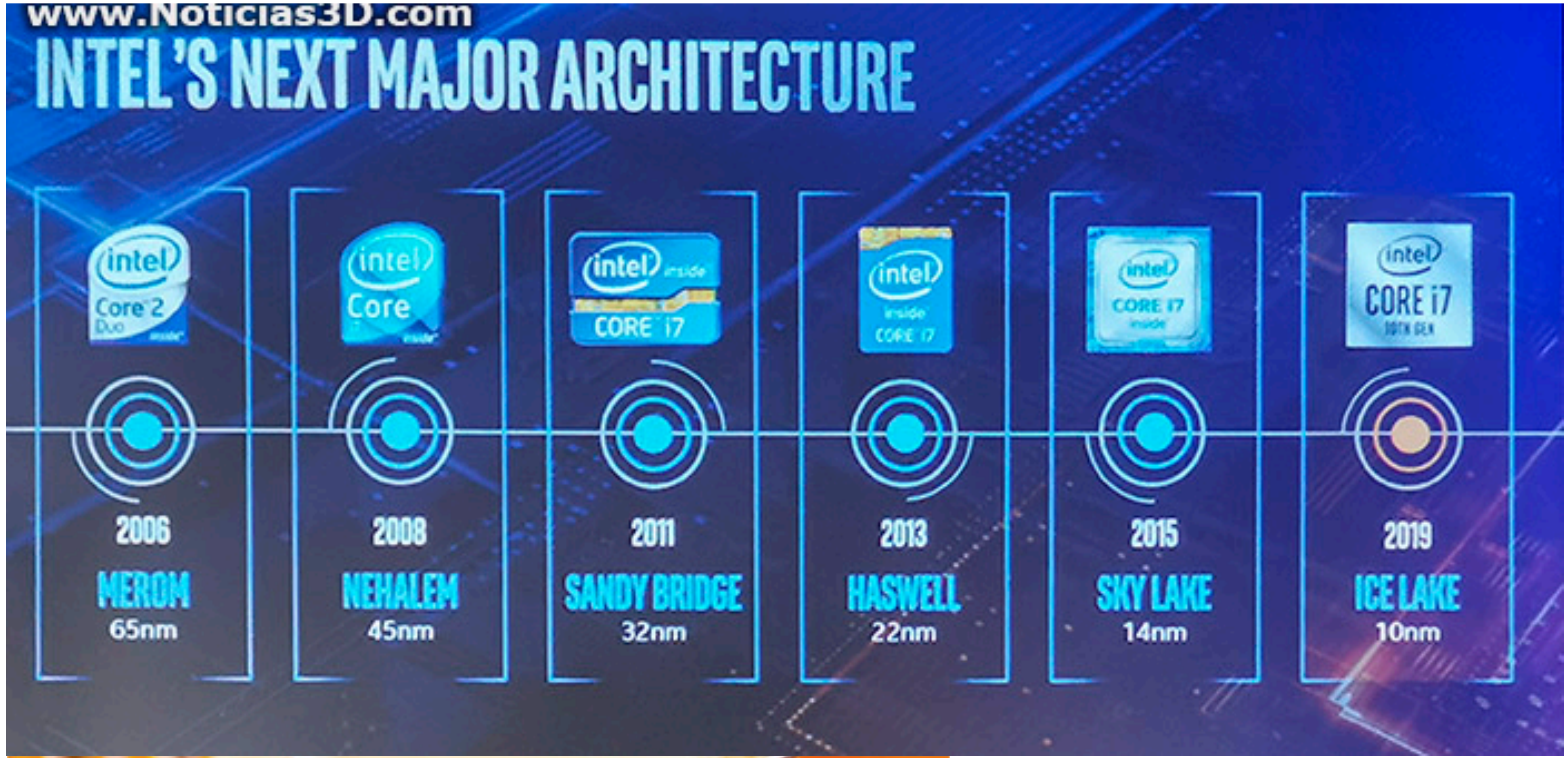
1750-1900



Watt steam engine

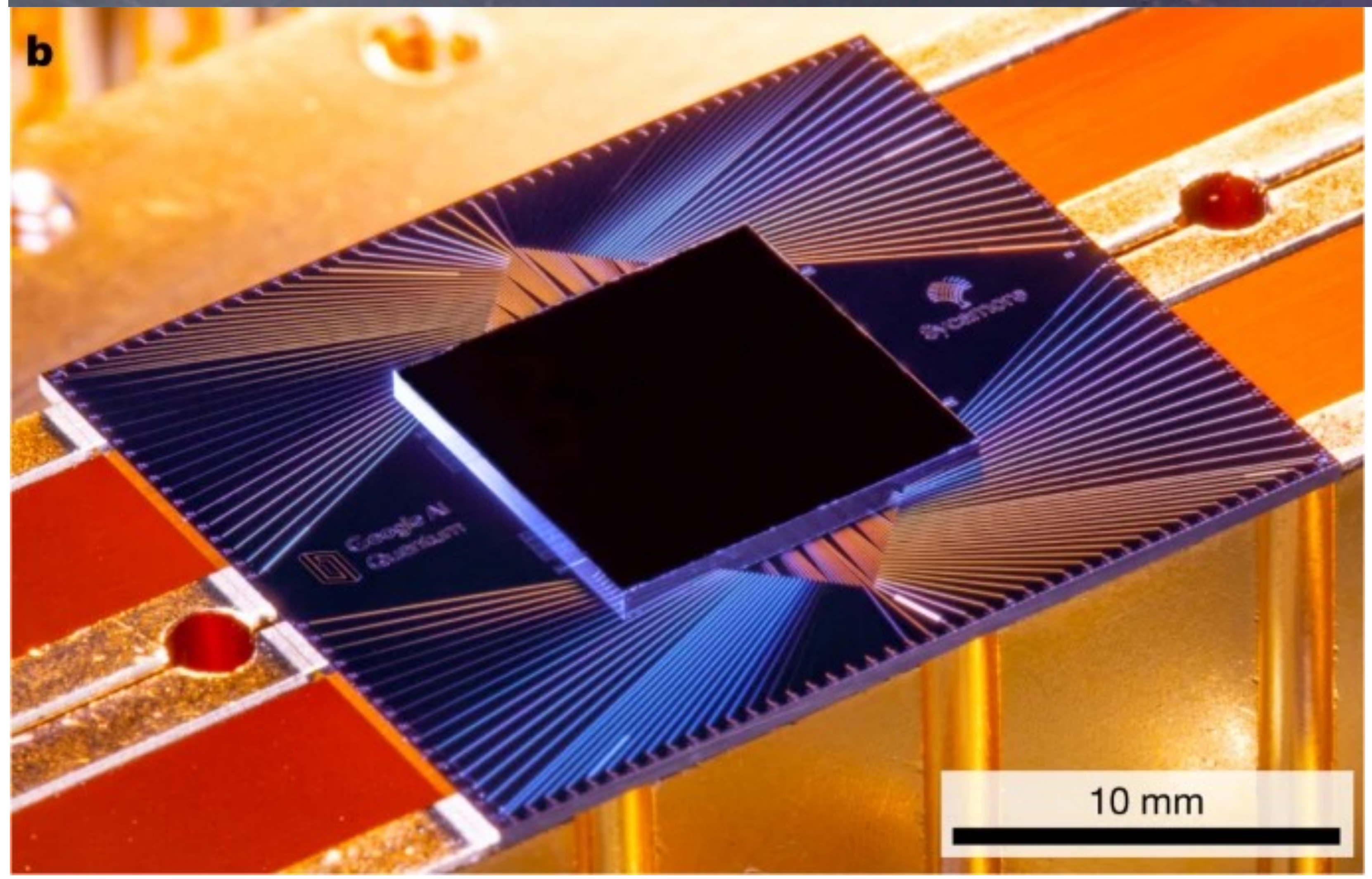
2nd quantum revolution

1947



Quantum supremacy using a programmable superconducting processor

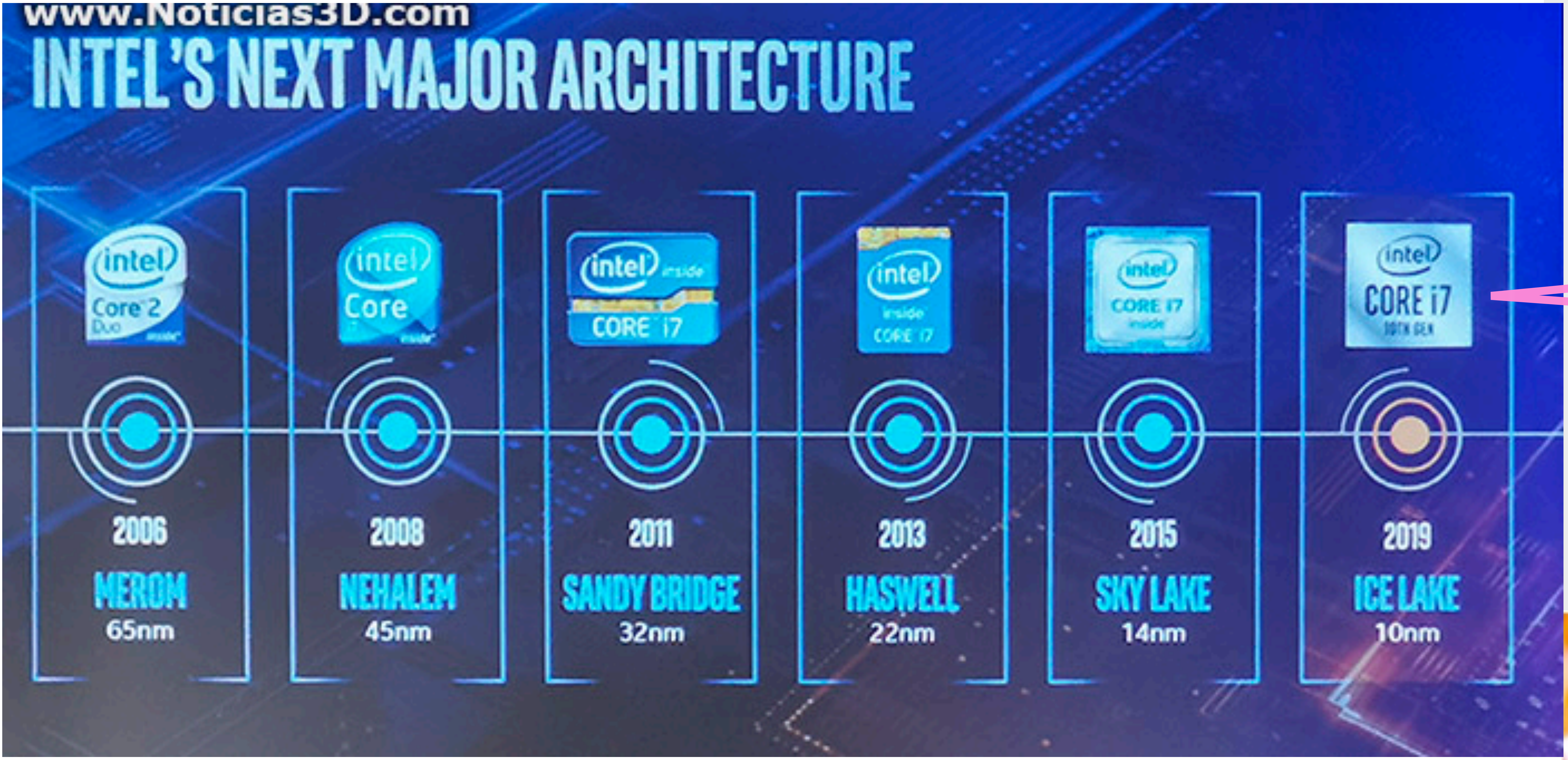
Nature | Vol 574 | 24 OCTOBER 2019 | **505**



2006-2019

Google quantum AI

Logic states

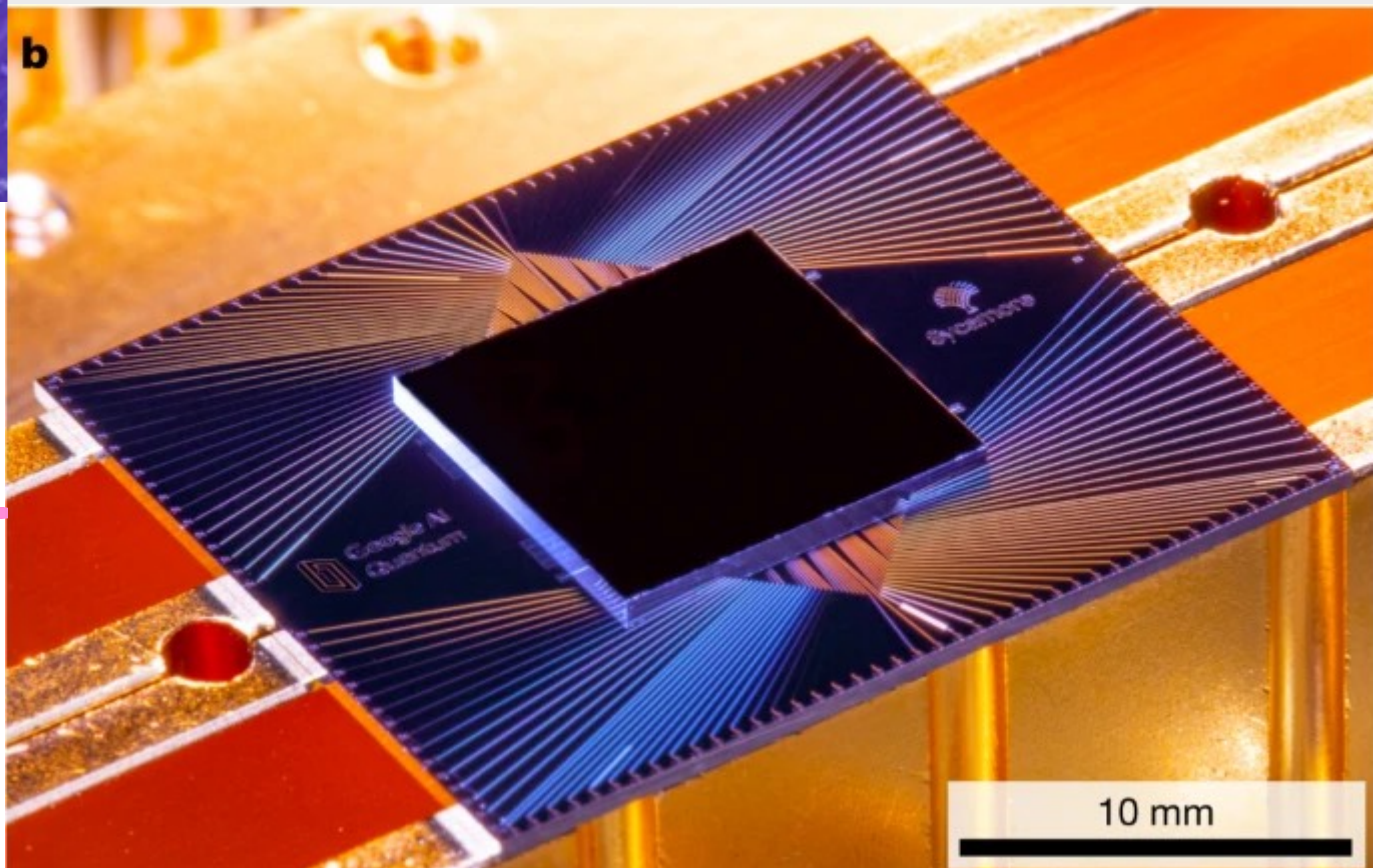


BITS

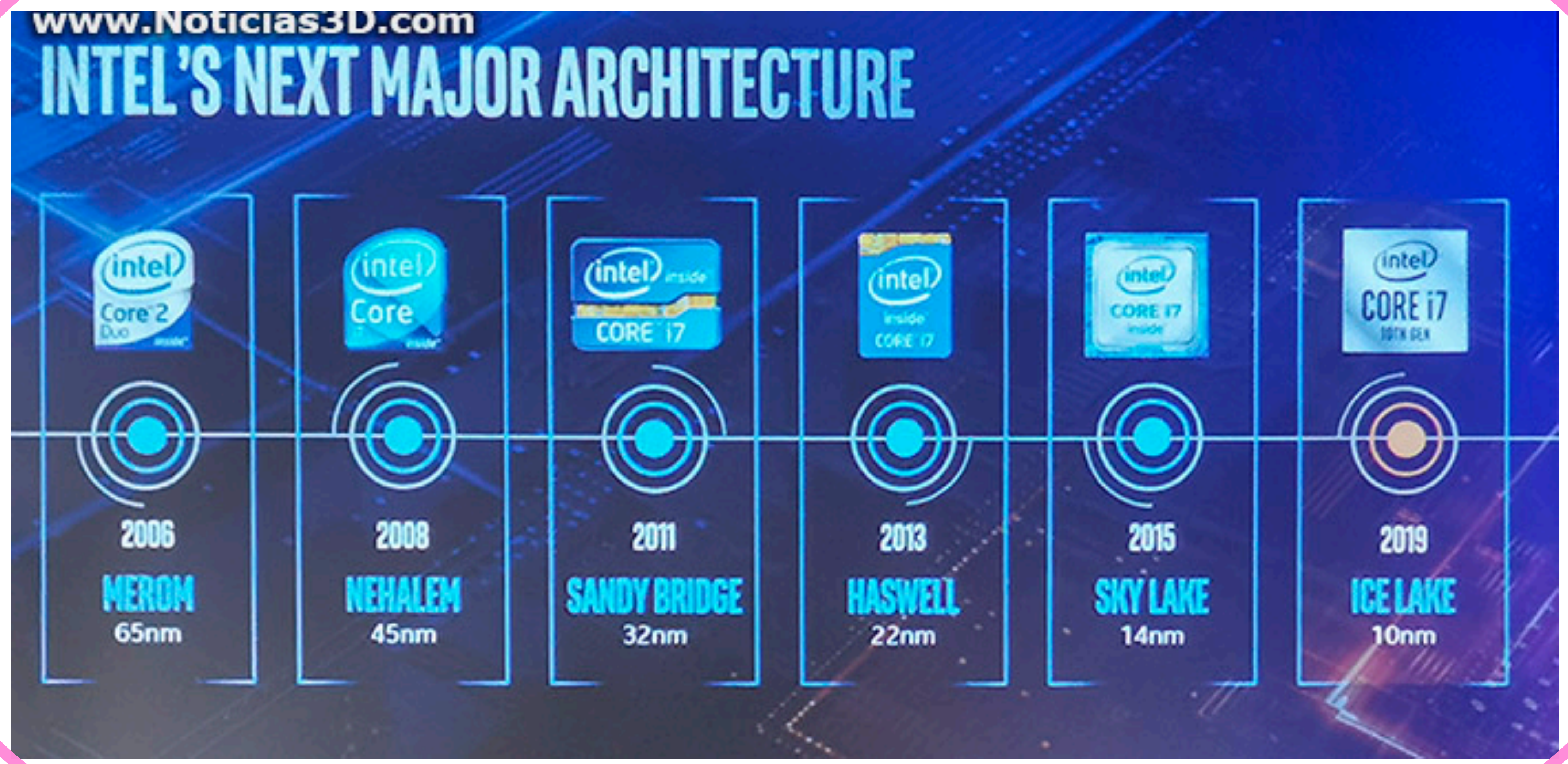
$0, \quad 1$

QUBITS

$\alpha_0 |0\rangle + \alpha_1 |1\rangle$



300K



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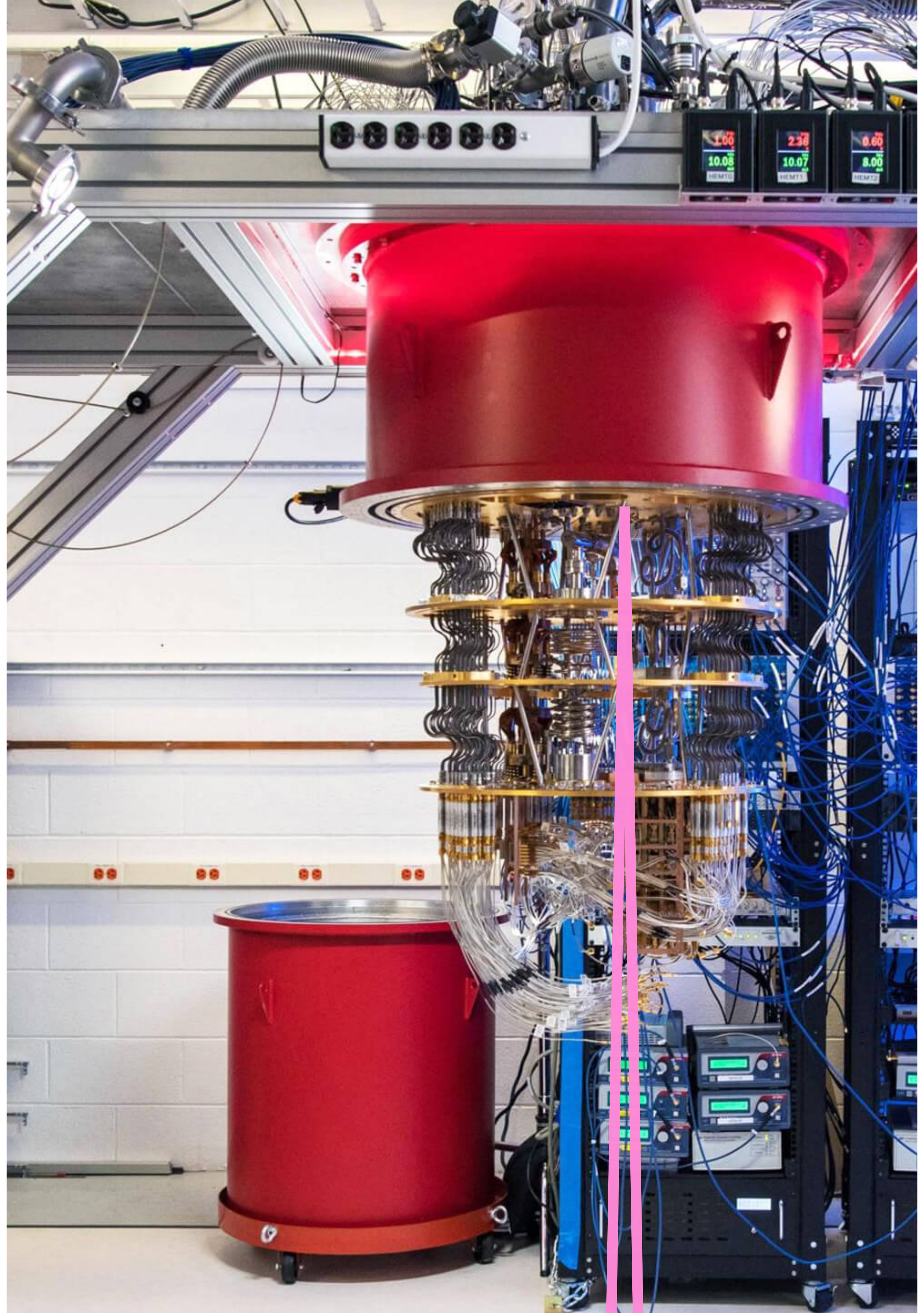
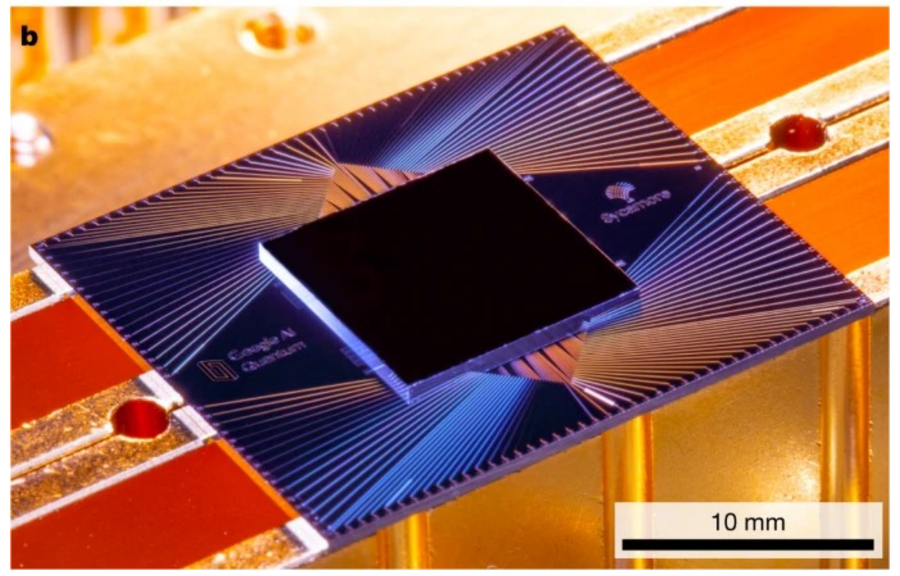
INTEL'S NEXT MAJOR ARCHITECTURE
2006
MEROM
65nm
2008
NEHALEM
45nm
2011
SANDY BRIDGE
32nm
2013
HASWELL
22nm
2015
SKY LAKE
14nm
2019
ICE LAKE
10nm



20mK



b
10 mm

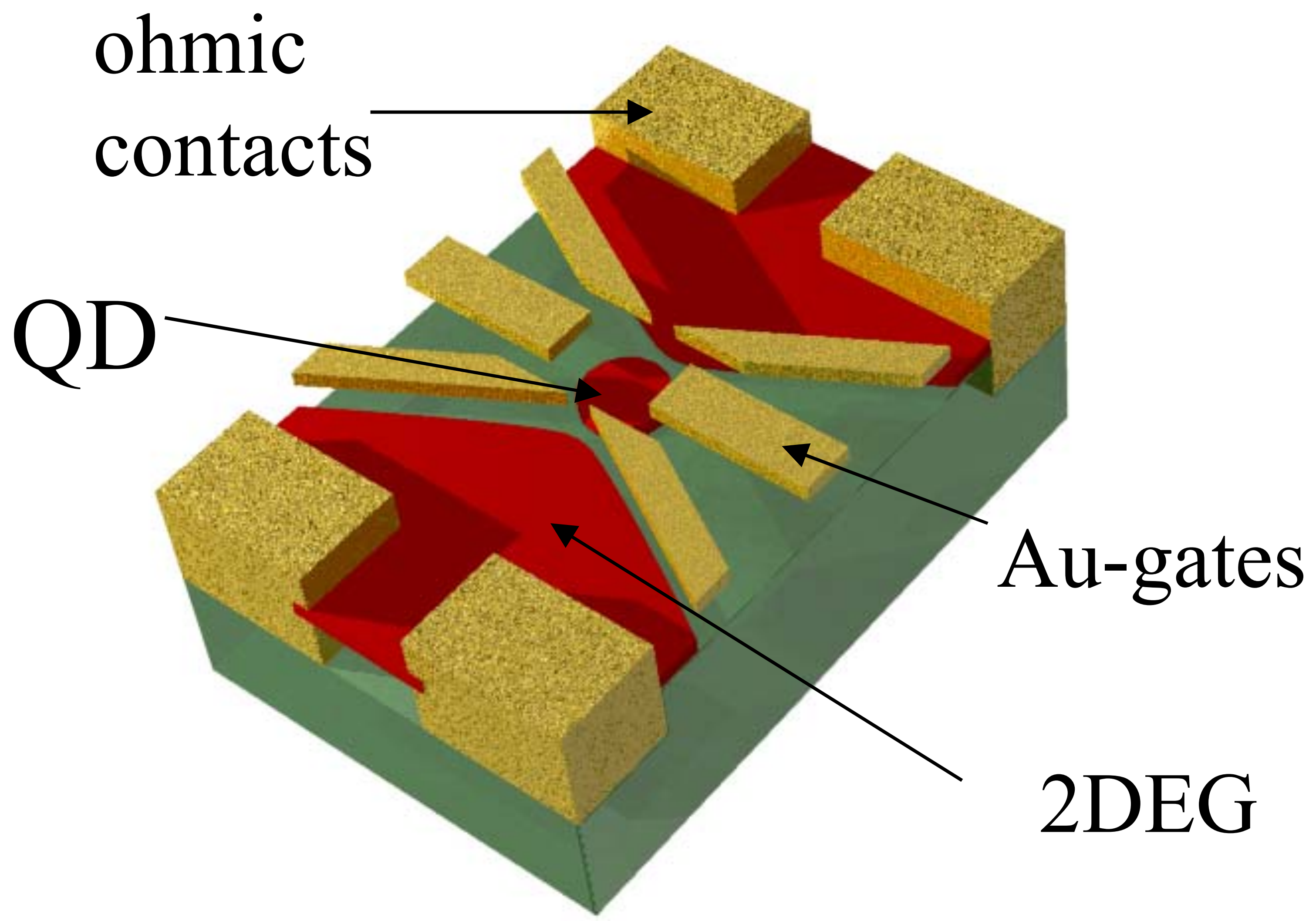
Experiments

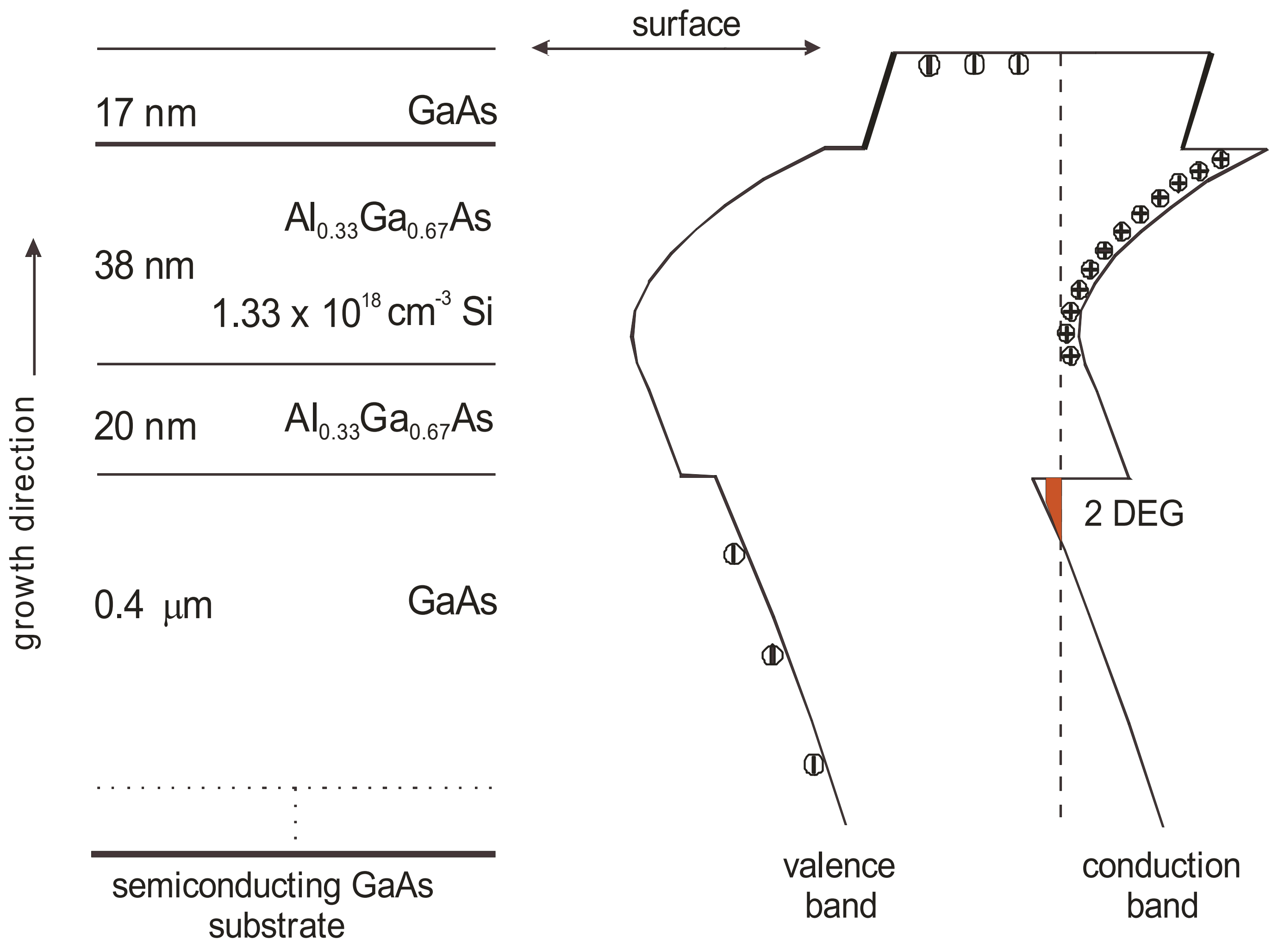
PRL 95, 176602 (2005) PHYSICAL REVIEW LETTERS week ending 21 OCTOBER 2005

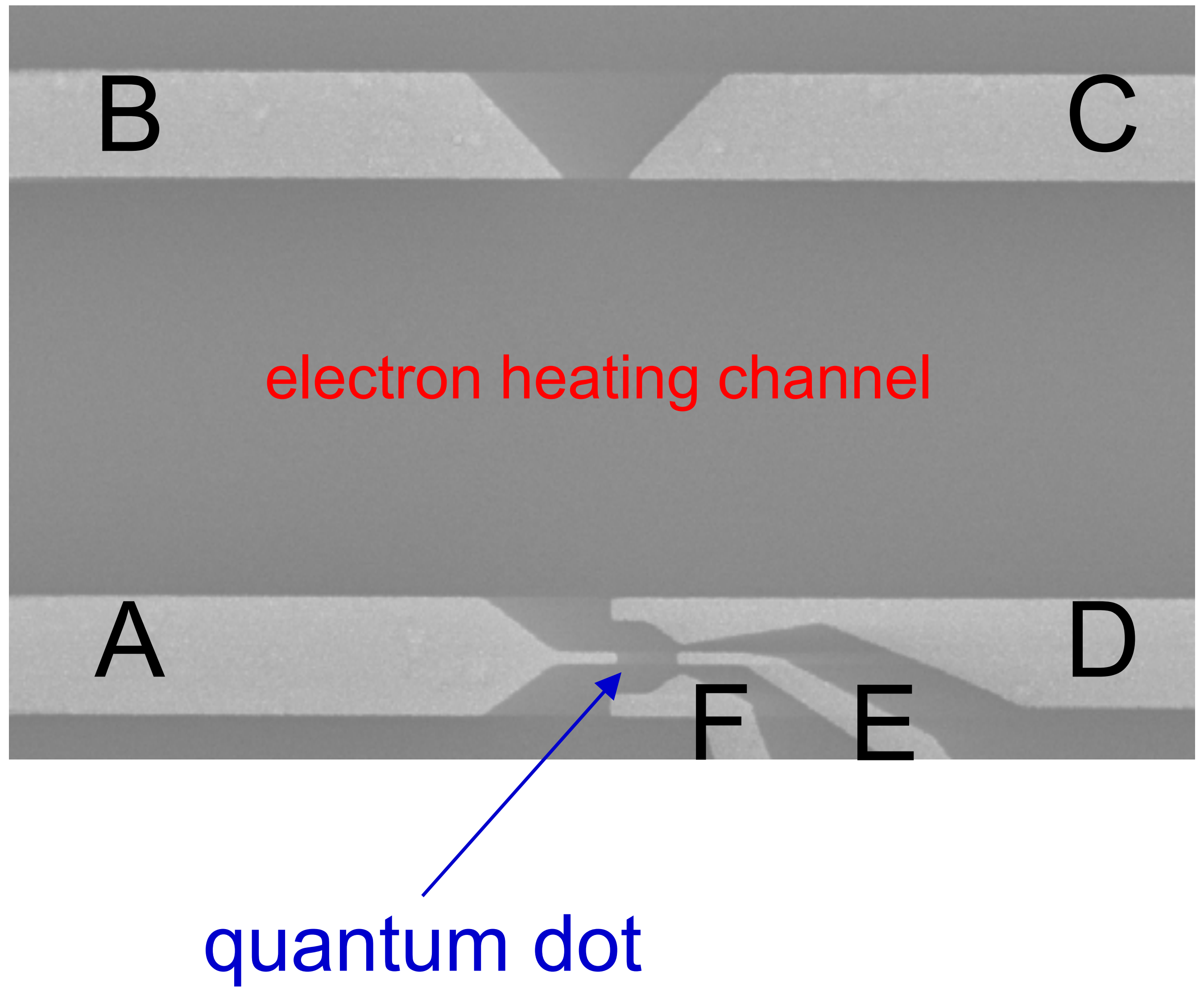
Thermopower of a Kondo Spin-Correlated Quantum Dot

R. Scheibner,[1] H. Buhmann,[1] D. Reuter,[3] M. N. Kiselev,[2] and L. W. Molenkamp[1]

- GaAs/AlGaAs - 2DEG
- $n = 2.3\ 10^{11}\ cm^{-2}$, $\mu = 10^{6}\ cm^2/Vs$
- Ti/Au-surface electrodes
- (opt. and e-beam lithography)
- Au/AuGe - ohmic contacts



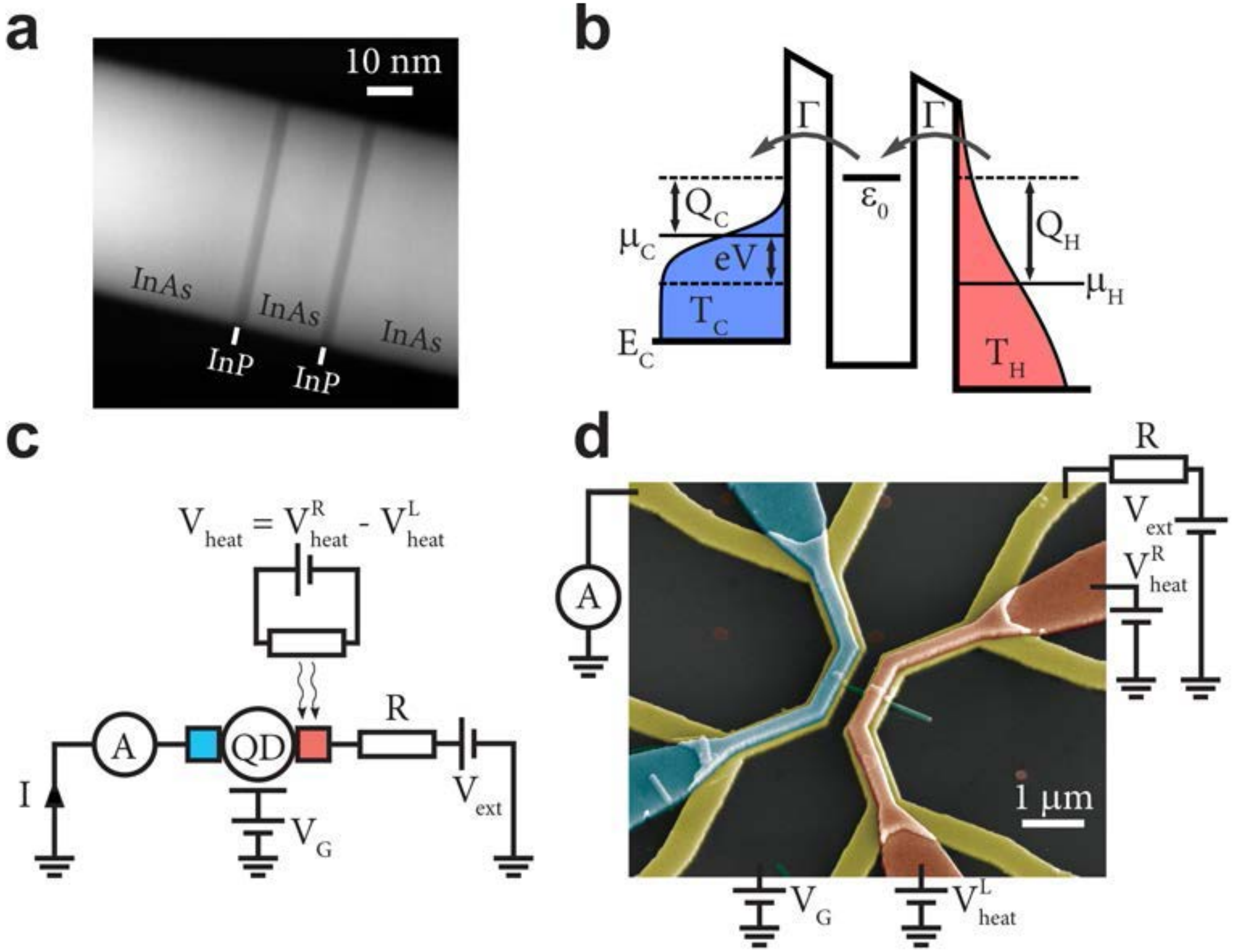




A quantum-dot heat engine operating close to the thermodynamic efficiency limits

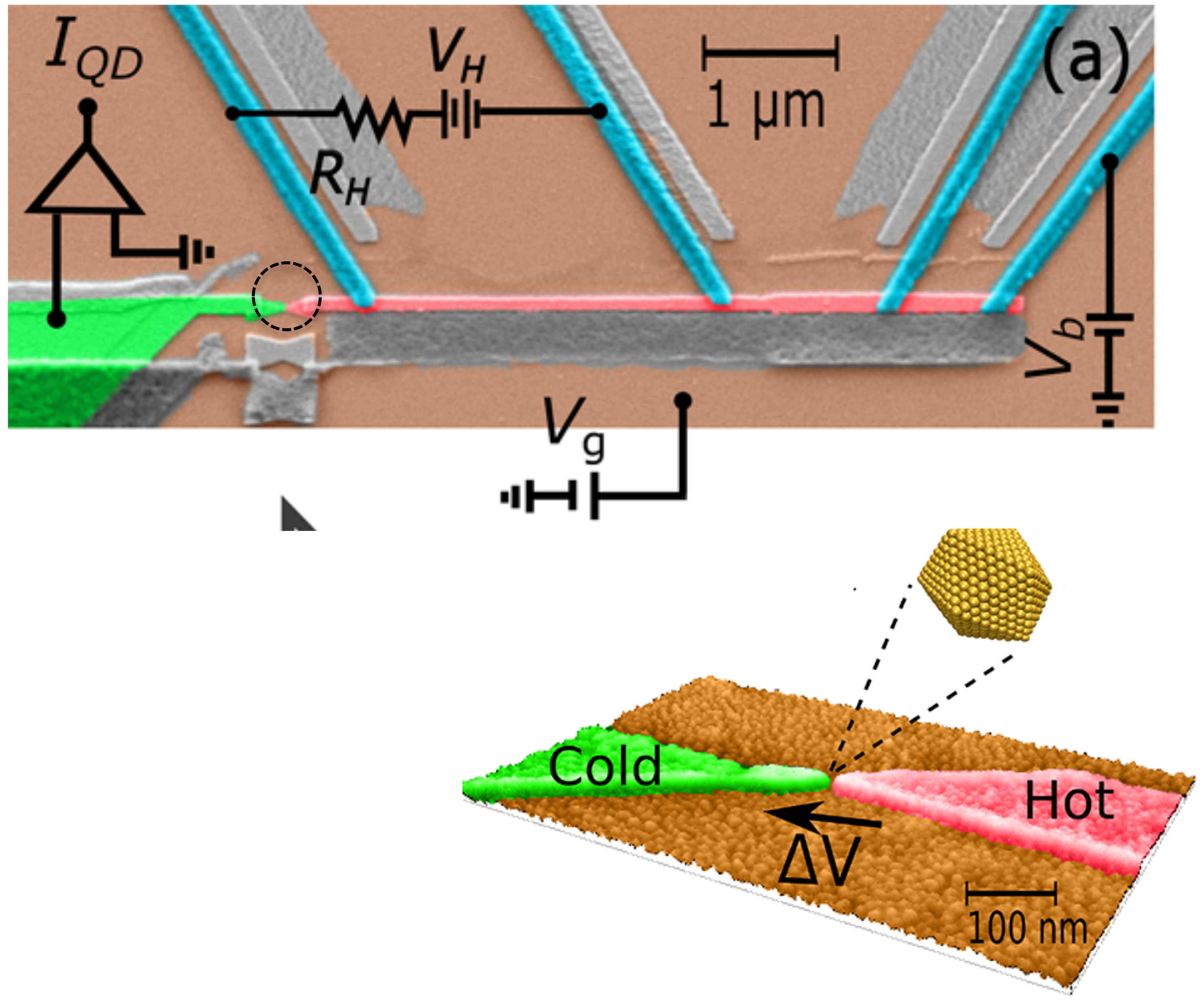
Martin Josefsson*, Artis Svilans*, Adam M. Burke, Eric A. Hoffmann, Sofia Fahlvik, Claes Thelander, Martin Leijnse and Heiner Linke

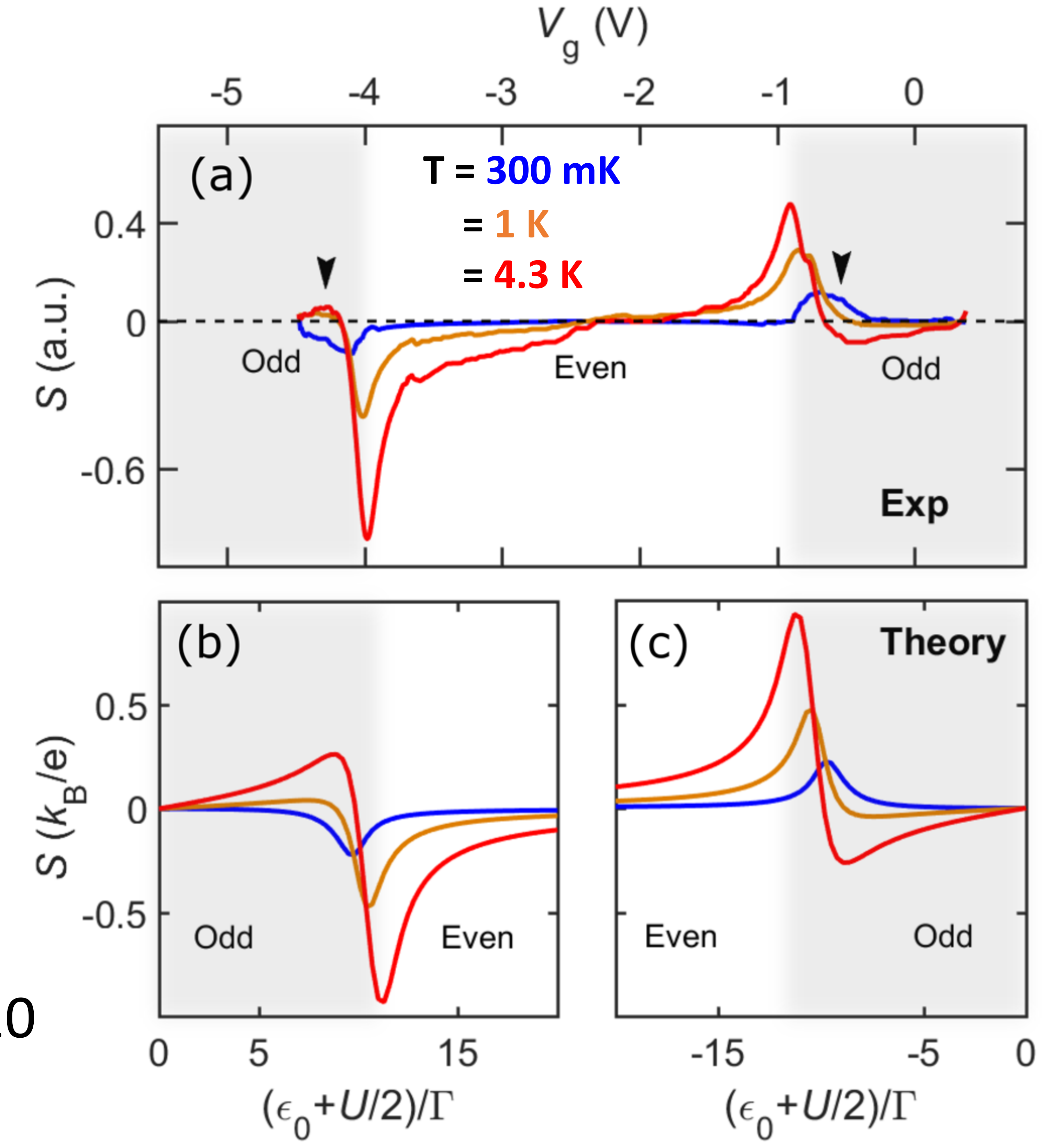
M. Josefsson, A. Svilans, et al. Nature Nanotechnology **13**, 920 (2018)



Direct Probe of the Seebeck Coefficient in a Kondo-Correlated Single-Quantum-Dot Transistor

Bivas Dutta,[†] Danial Majidi,[†] Alvaro García Corral,[†] Paolo A. Erdman,[‡] Serge Florens,[†] Theo A. Costi,[§] Hervé Courtois,[†] and Clemens B. Winkelmann*,[†]





- Spin-1/2 Kondo effect
- Single-level Anderson model, NRG, U/Γ=20

  Costi and Zlatic, PRB (2010)

B. Dutta, D. Majidi, A. Garcia Corral, P. Erdman, S. Florens, T. Costi, H. Courtois, CBW, Nano Lett. (2019)

see also Svilans et al., PRL (2018)

Quantum Limit of Heat Flow Across a Single Electronic Channel

S. Jezouin,[1*] F. D. Parmentier,[1*] A. Anthore,[1,2†] U. Gennser,[1] A. Cavanna,[1] Y. Jin,[1] F. Pierre[1†]

Quantum physics predicts that there is a fundamental maximum heat conductance across a single transport channel and that this thermal conductance quantum, G_Q, is universal, independent of the type of particles carrying the heat. Such universality, combined with the relationship between heat and information, signals a general limit on information transfer. We report on the quantitative measurement of the quantum-limited heat flow for Fermi particles across a single electronic channel, using noise thermometry. The demonstrated agreement with the predicted G_Q establishes experimentally this basic building block of quantum thermal transport. The achieved accuracy of below 10% opens access to many experiments involving the quantum manipulation of heat.

$$\kappa = \frac{\pi^2 k_B}{3h} T$$

Science 342, 601 (2013)

$$\nu = 1, 2$$

See also M. Banerjee, et al Nature 545 (2017)

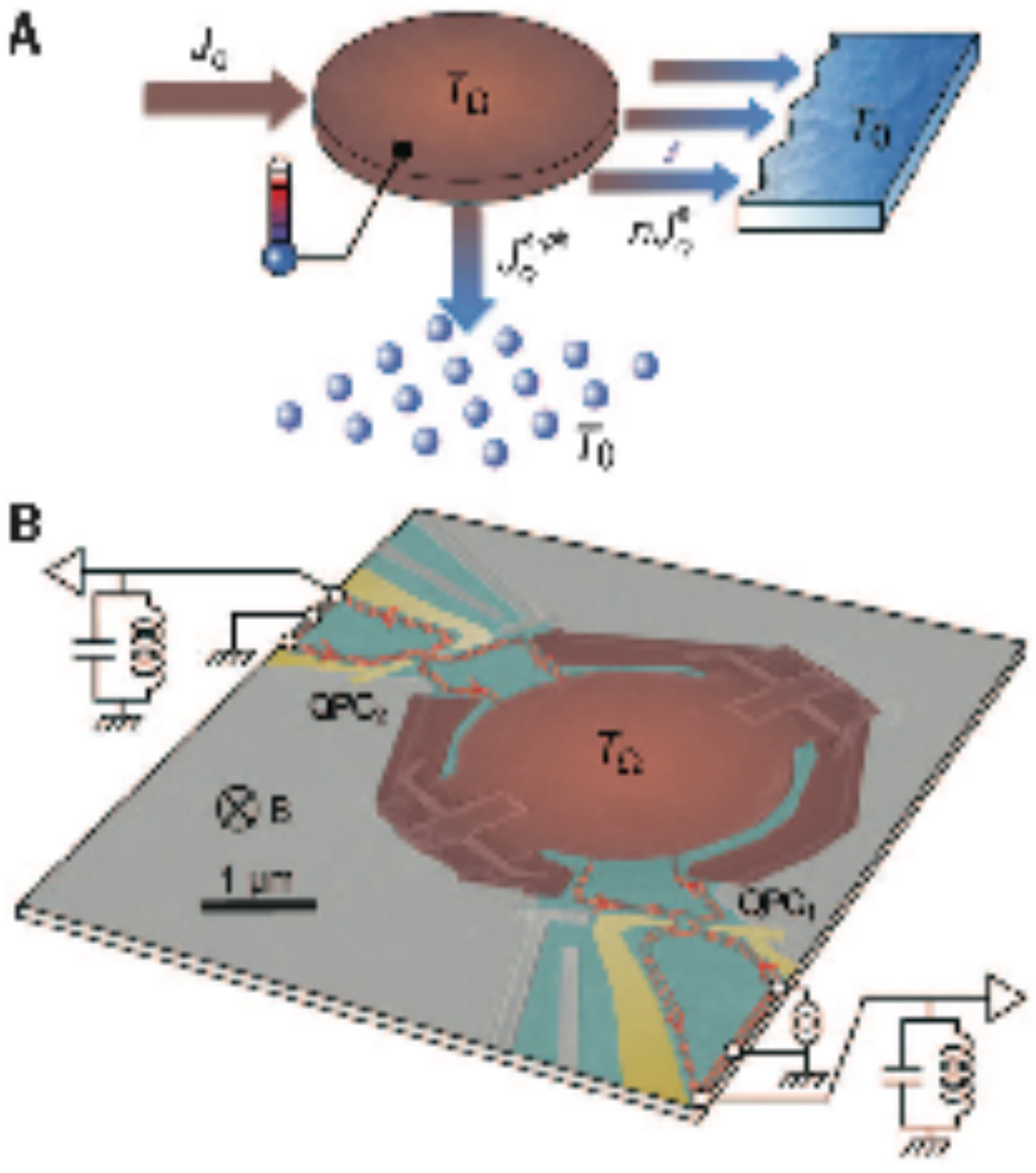
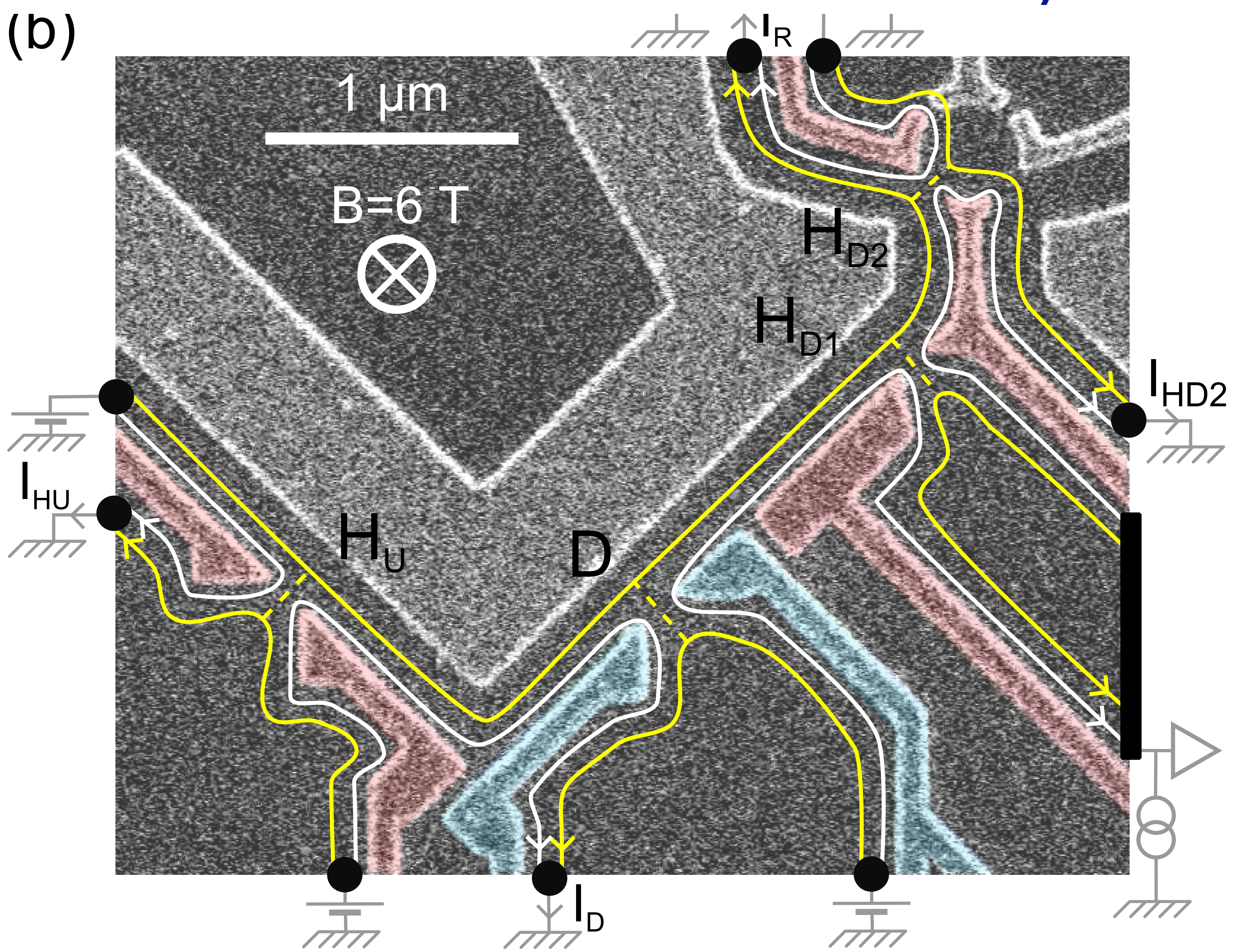


Fig. 1. Experimental principle and practical implementation. (**A**) Principle of the experiment: Electrons in a small metal plate (brown disk) are heated up to T_Ω by the injected Joule power J_Q. The large arrows symbolize injected power (J_Q) and outgoing heat flows (nJ_Q^e, $J_Q^{e\text{-}ph}$). (**B**) False-colors scanning electron micrograph of the measured sample. The Ga(Al)As 2D electron gas is highlighted in light blue, the QPC metal gates in yellow and the micrometer-sized metallic ohmic contact in brown. The light gray metal gates are polarized with a strong negative gate voltage and are not used in the experiment. The propagation direction of two co-propagating edge channels (shown out of $\nu = 3$ or $\nu = 4$) is indicated by red arrows. QPC$_1$ is here set to fully transmit a single channel ($n_1 = 1$) and QPC$_2$ two channels ($n_2 = 2$), corresponding to a total number of open electronic channels $n = n_1 + n_2 = 3$. The experimental apparatus is shown as a simplified diagram. It includes two $L-C$ tanks used to perform the noise thermometry measurements around 700 kHz. The Joule power J_Q is injected on the micrometer-sized metallic electrode from the DC polarization current partly transmitted through QPC$_1$.

Chargeless heat transport in the fractional quantum Hall regime

C. Altimiras,[1,*] H. le Sueur,[1,†] U. Gennser,[1] A. Anthore,[1] A. Cavanna,[1] D. Mailly,[1] and F. Pierre[1,‡]
[1] *CNRS / Univ Paris Diderot (Sorbonne Paris Cité), Laboratoire de Photonique et de Nanostructures (LPN), route de Nozay, 91460 Marcoussis, France*
(Dated: February 29, 2012)
Phys. Rev.Lett. 109, 026803 (2012)



$\nu = 2/3$

See also:
V.Venkatachalam, Nat.Phys. 8, 676 (2012)
H. Inoue, et al, Nat. Comm. (2014)

LETTER

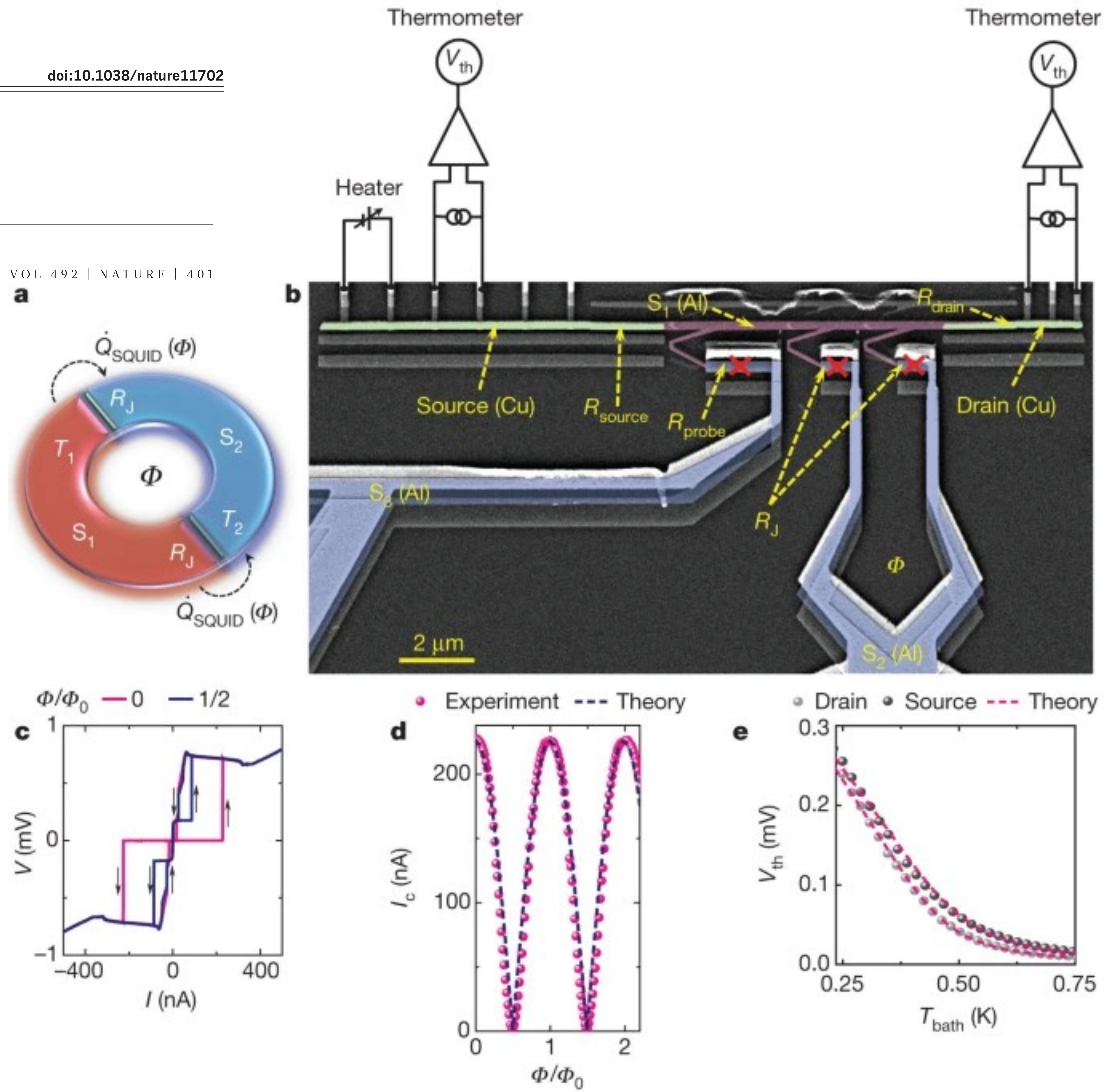
doi:10.1038/nature11702

The Josephson heat interferometer

Francesco Giazotto[1] & María José Martínez-Pérez[1]

[1]NEST, Istituto Nanoscienze—CNR and Scuola Normale Superiore, Piazza San Silvestro 12, I-56127 Pisa, Italy.

20/27 DECEMBER 2012 | VOL 492 | NATURE | 401



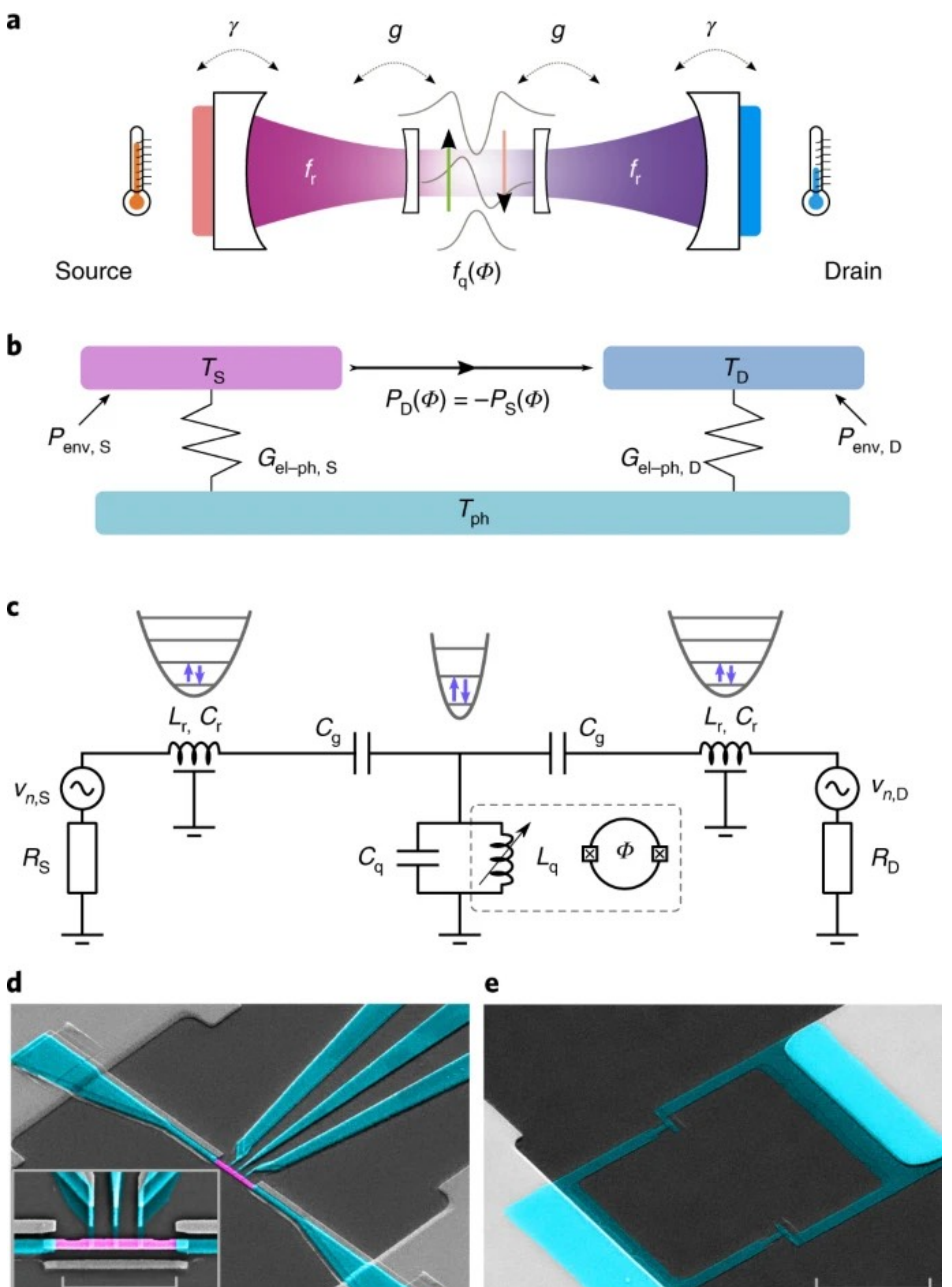
nature physics

LETTERS

https://doi.org/10.1038/s41567-018-0199-4

Tunable photonic heat transport in a quantum heat valve

Alberto Ronzani[1]*, Bayan Karimi[1], Jorden Senior[1], Yu-Cheng Chang[1,2,3], Joonas T. Peltonen[1], ChiiDong Chen[1,3] and Jukka P. Pekola[1]



PHYSICAL REVIEW LETTERS 126, 080603 (2021)

Editors' Suggestion Featured in Physics

Thermodynamics of Gambling Demons

Gonzalo Manzano,[1,2,*] Diego Subero,[3] Olivier Maillet,[3] Rosario Fazio,[1,4] Jukka P. Pekola,[3] and Édgar Roldán[1,†]

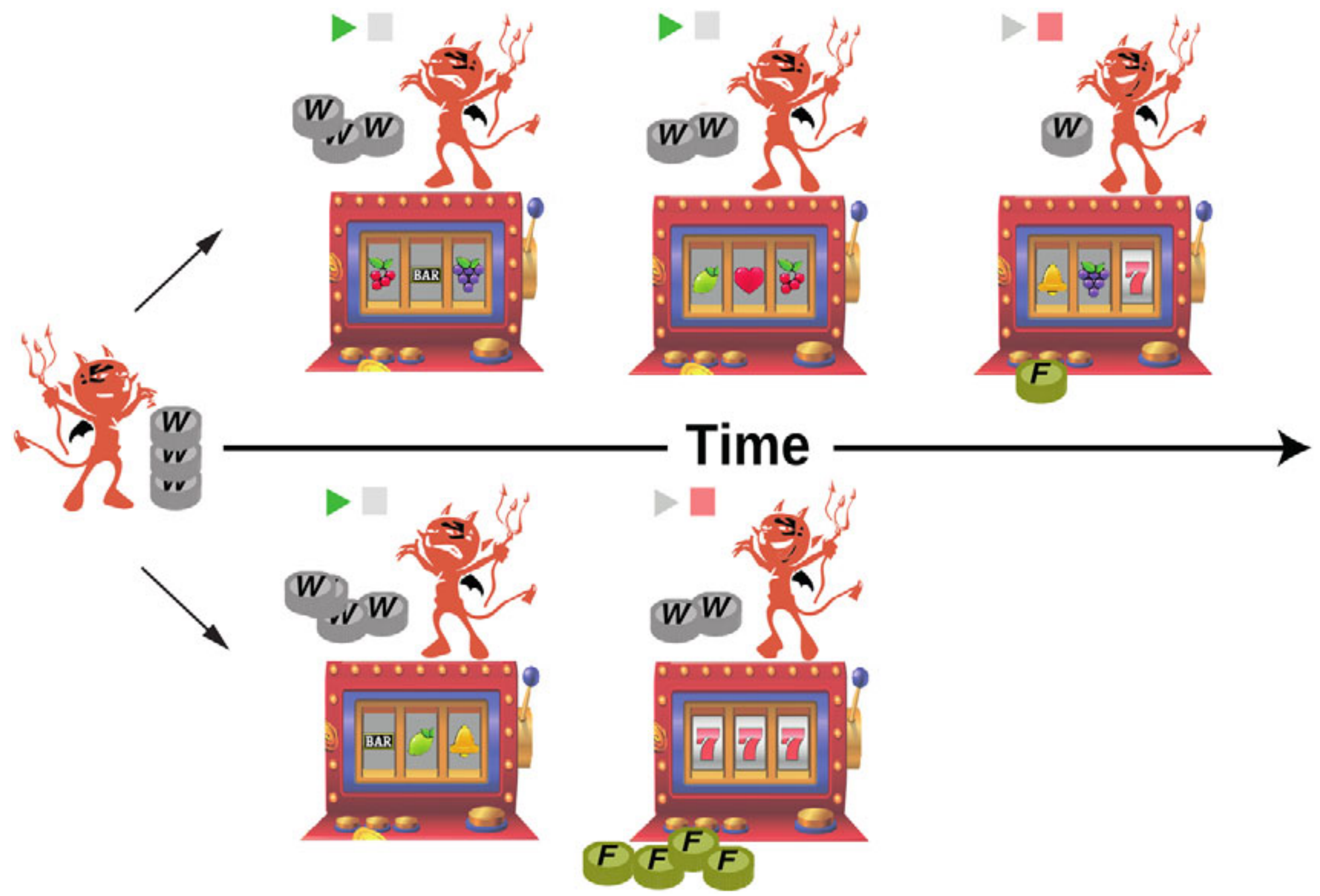
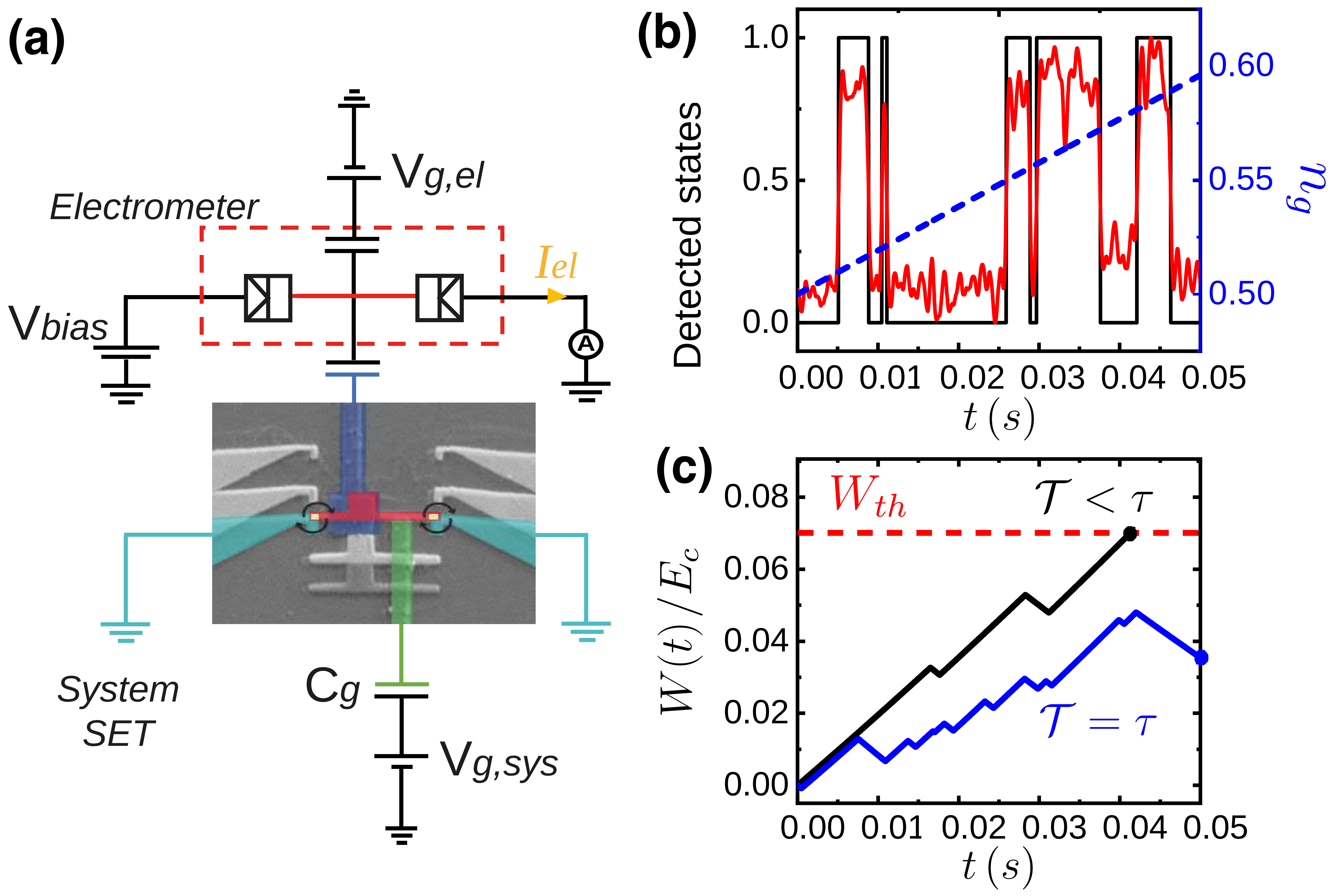


FIG. 1. Illustration of a gambling demon. The demon spends work (W, silver coins) on a physical system (slot machine) hoping to collect free energy (F, gold coins) by executing a gambling strategy. In each time step, the demon does work on the system (introduces a coin in the machine) and decides whether to continue ("play" sign) or to quit gambling and collect the prize ("stop" sign) at a stochastic time $\mathcal{T}$ following a prescribed strategy. In the illustration, the demon plays the slot machine until a fixed time $\mathcal{T} = 3$ (top row) unless the outcome of the game is beneficial at a previous time, e.g., $\mathcal{T} = 2$ (bottom row). Under specific gambling schemes, the demon can extract on average more free energy than the work spent over many iterations, a scenario that is forbidden by the standard second-law inequality.



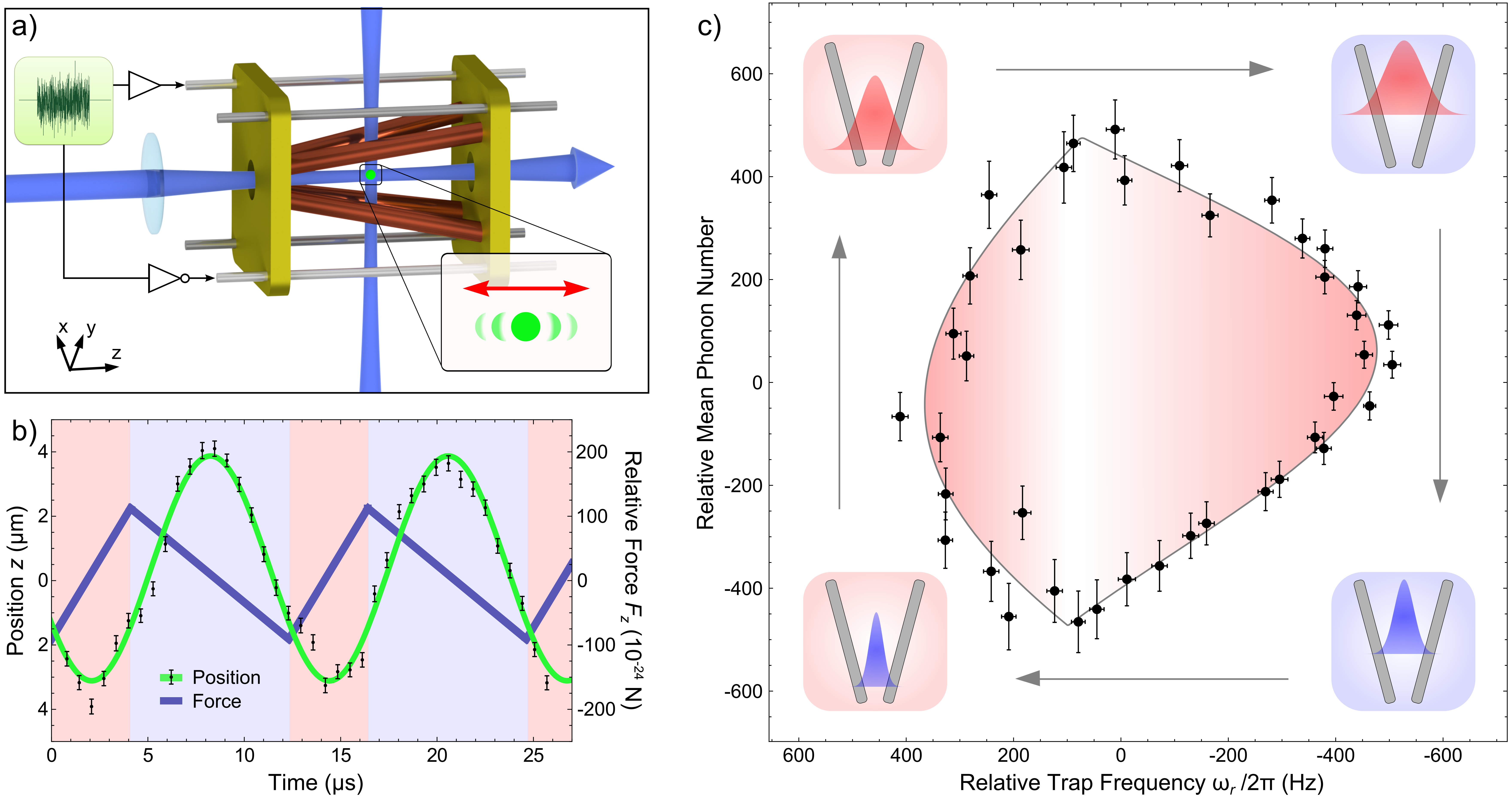
Science 352, 325 (2016)

A single-atom heat engine

Johannes Roßnagel,[1,*] Samuel Thomas Dawkins,[1] Karl Nicolas Tolazzi,[1]
Obinna Abah,[2] Eric Lutz,[2] Ferdinand Schmidt-Kaler,[1] and Kilian Singer[1,3]

[1] *Quantum, Institut für Physik, Universität Mainz, D-55128 Mainz, Germany*
[2] *Department of Physics, Friedrich-Alexander Universität Erlangen-Nürnberg, D-91058 Erlangen, Germany*
[3] *Experimentalphysik I, Universität Kassel, Heinrich-Plett-Str. 40, D-34132 Kassel, Germany*

(Dated: October 14, 2015)



A Thermoelectric Heat Engine with Ultracold Atoms

Jean-Philippe Brantut,[1] Charles Grenier,[2] Jakob Meineke,[1]* David Stadler,[1] Sebastian Krinner,[1] Corinna Kollath,[3] Tilman Esslinger,[1]† Antoine Georges[2,4,5]

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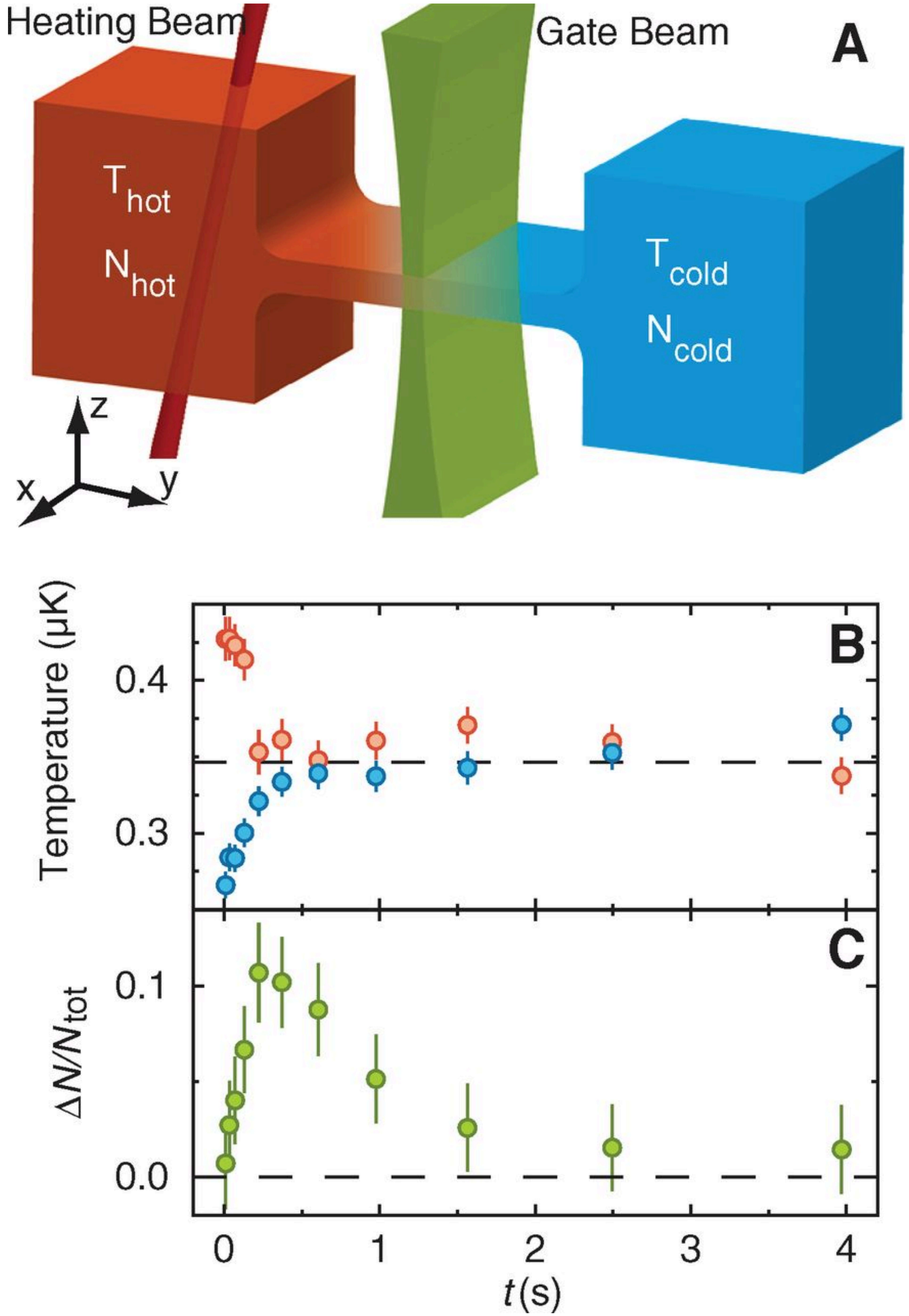


Conditions:

Nanoscale + Low temperatures

Open questions

- Are quantum devices energetically efficient?
- How is energy transported and dissipated?
- Mechanisms of energy exchange and heat-work conversion?
- Fluctuations?

Statistical mechanics

Cold atoms and ions

Quantum information

Quantum optics

Condensed matter

Plan of lectures: focus on heat-work conversion

- Lecture 1: Steady-state heat-work conversion. Quantum transport and thermoelectricity.
- Lecture 2: Heat, work. Finite-time processes, entropy generation and dissipation.
- Lecture 3: Cycles. Quasistatic and finite-time heat-work conversion.

The laws of thermodynamics

Zeroth law

If two systems are in thermal equilibrium with a third system, then they are in thermal equilibrium with each other.

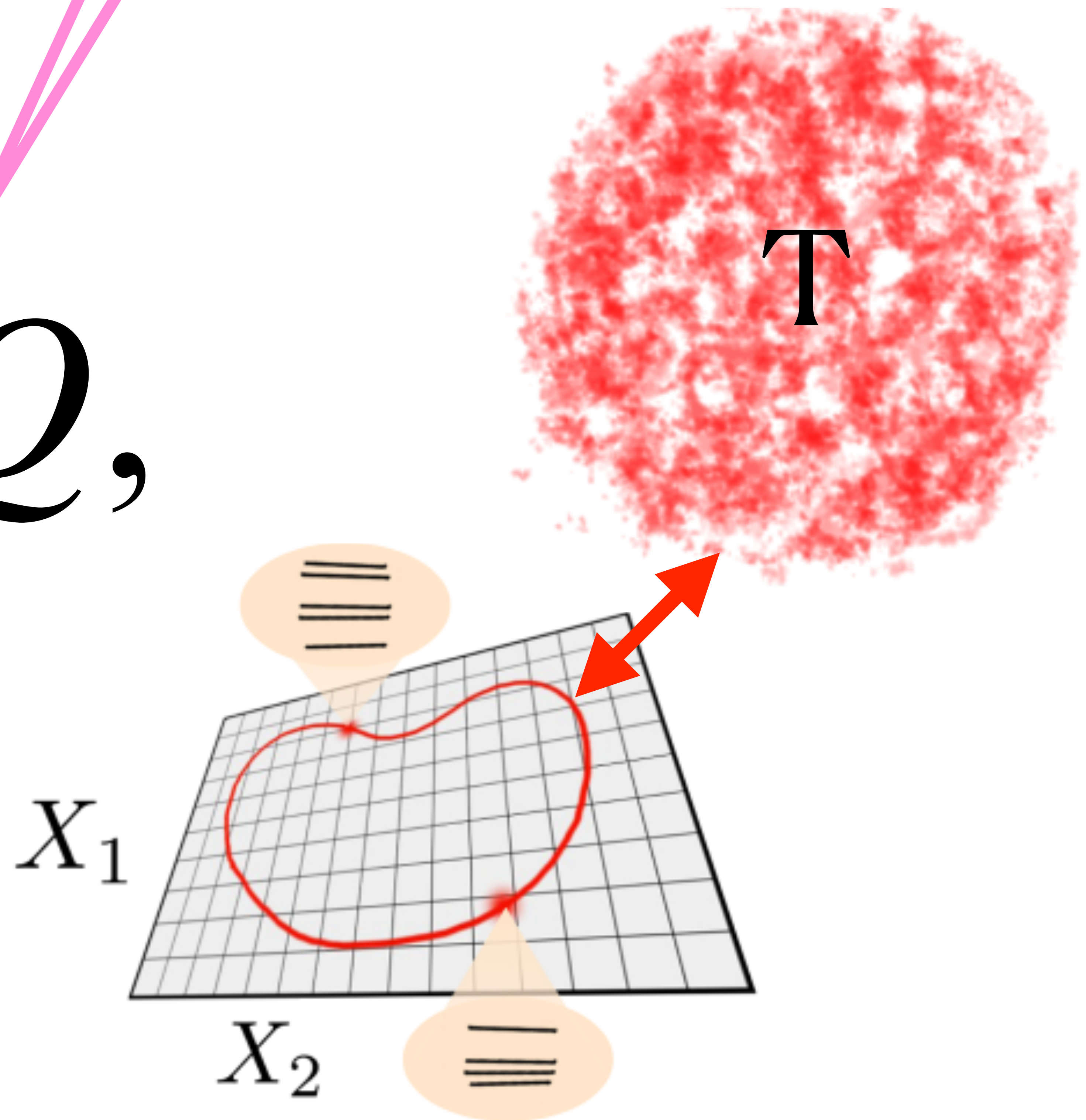
First law

Change in the internal energy

Work: controlled energetic change

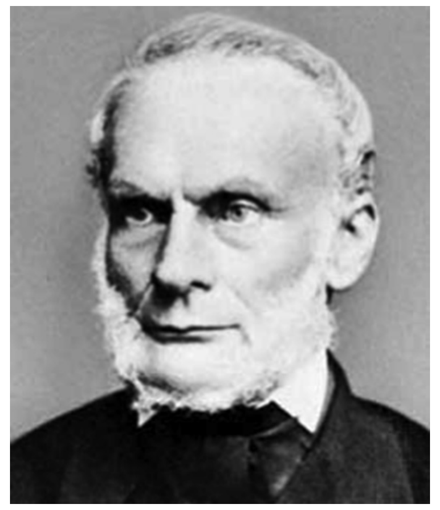
Heat: energy exchange with a thermal bath

$$dE = đW + đQ,$$



Control parameters

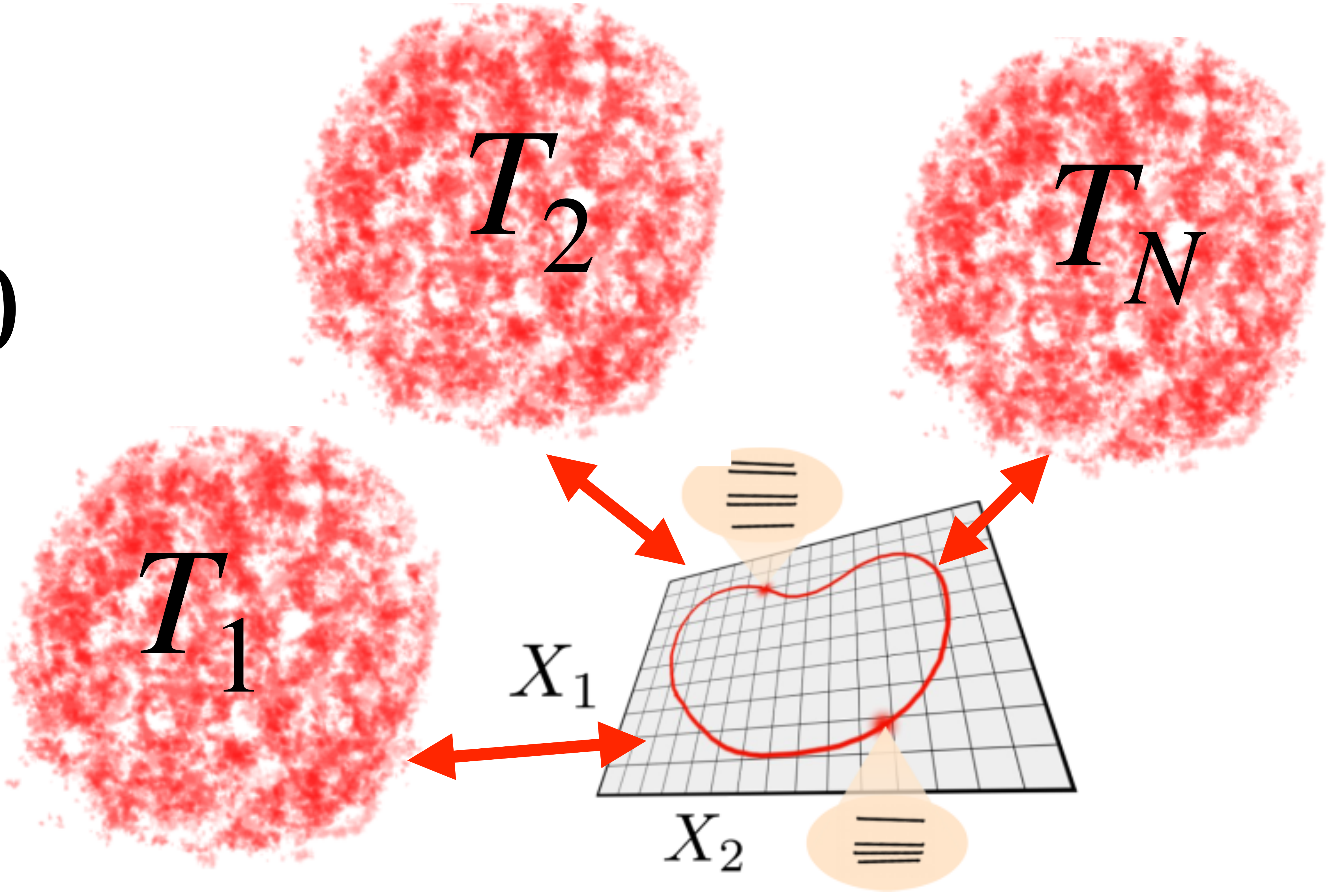
Rudolf J E Clausius:



Second law

In a process between two thermodynamic states A and B

$$\Delta S_{A \to B} = \sum_{j=1}^{N} \int_A^B \frac{\delta Q_1}{T_j} \geq 0$$



Third law

$$\lim_{T \to 0} \Delta S \to 0$$

Lars Onsager:

Fourth law

Lets assume a system with well defined:

- Particle density $n(\vec{r}, t)$
- Energy density $e(\vec{r}, t)$
- Local temperature $T(\vec{r}, t)$ and chemical potential $\mu(\vec{r}, t)$

The variation of the local entropy density, defined as a function of extensive variables E_k:

$$\dot{s} = \sum_k \frac{\partial s}{\partial E_k} \frac{dE_k}{dt}$$

Fluxes j_k

Affinities X_k

In general, the fluxes are complicated functions of the affinities:

$$j_k(X_1, \ldots, X_N), \quad k = 1, \ldots, N$$

Linear (leading) order:

$$j_k = \sum_j L_{k,j} X_j, \quad k = 1, \ldots, N$$

Onsager coefficients: $$L_{kj} = \frac{\partial J_k}{\partial X_j}\Big|_{X_j=0}, \quad k = 1, \ldots, N$$

Response functions evaluated in equilibrium!

Substituting in the change of the entropy density:

$$\dot{s} = \sum_k X_k \, j_k = \sum_{k,j} L_{k,j} X_k X_j$$

Bilinear in the affinities

Onsager theorem

4th Law

As a consequence of microscopic reversibility:

$$L_{kj}(B) = \pm L_{jk}(-B)$$

Magnetic field

Depends on the parity of the operators entering the response function under time-reversal symmetry

Thermoelectricity: Steady-state heat-work conversion

Effective conversion of a temperature difference into an electrical voltage and viceversa

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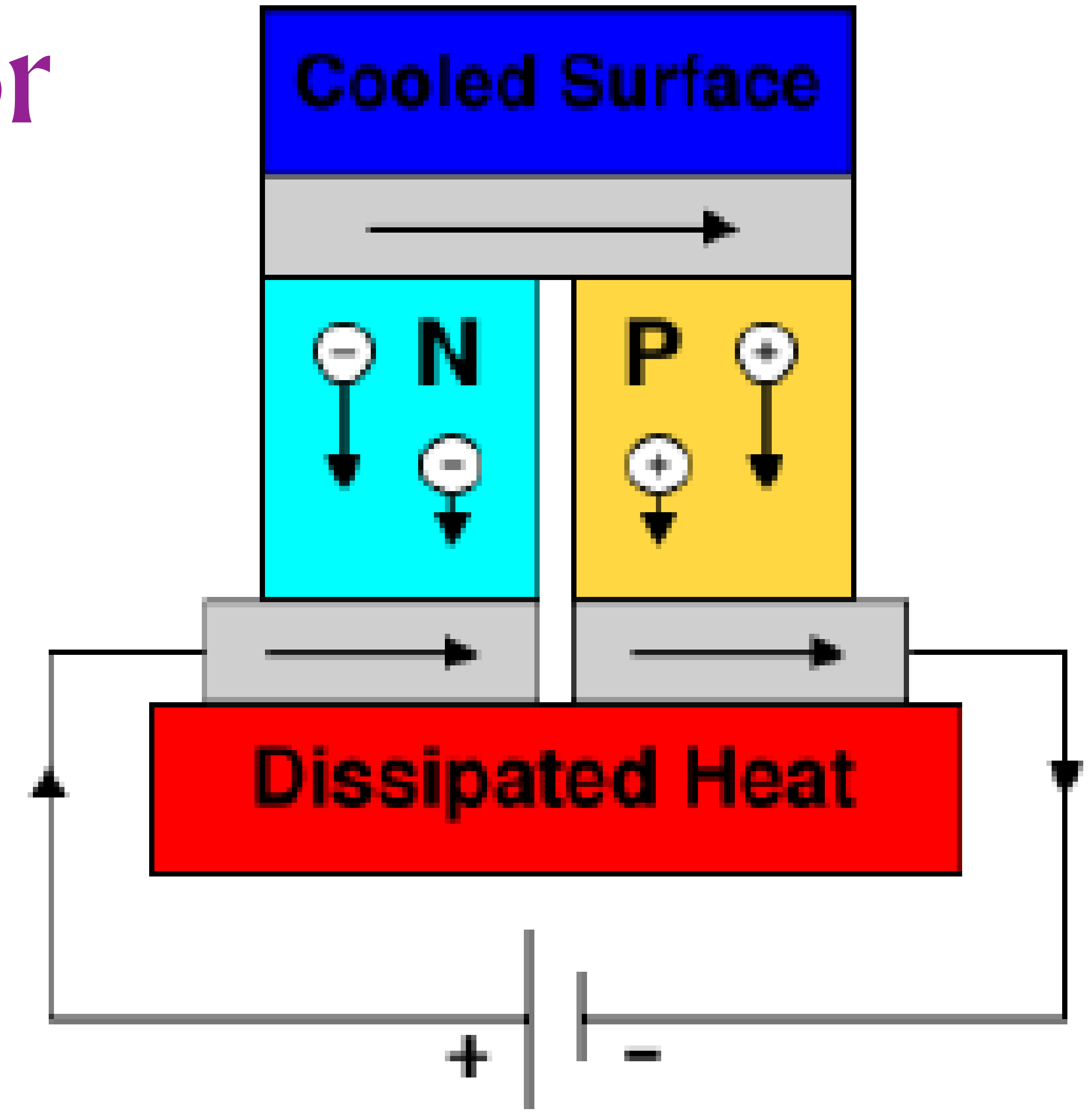
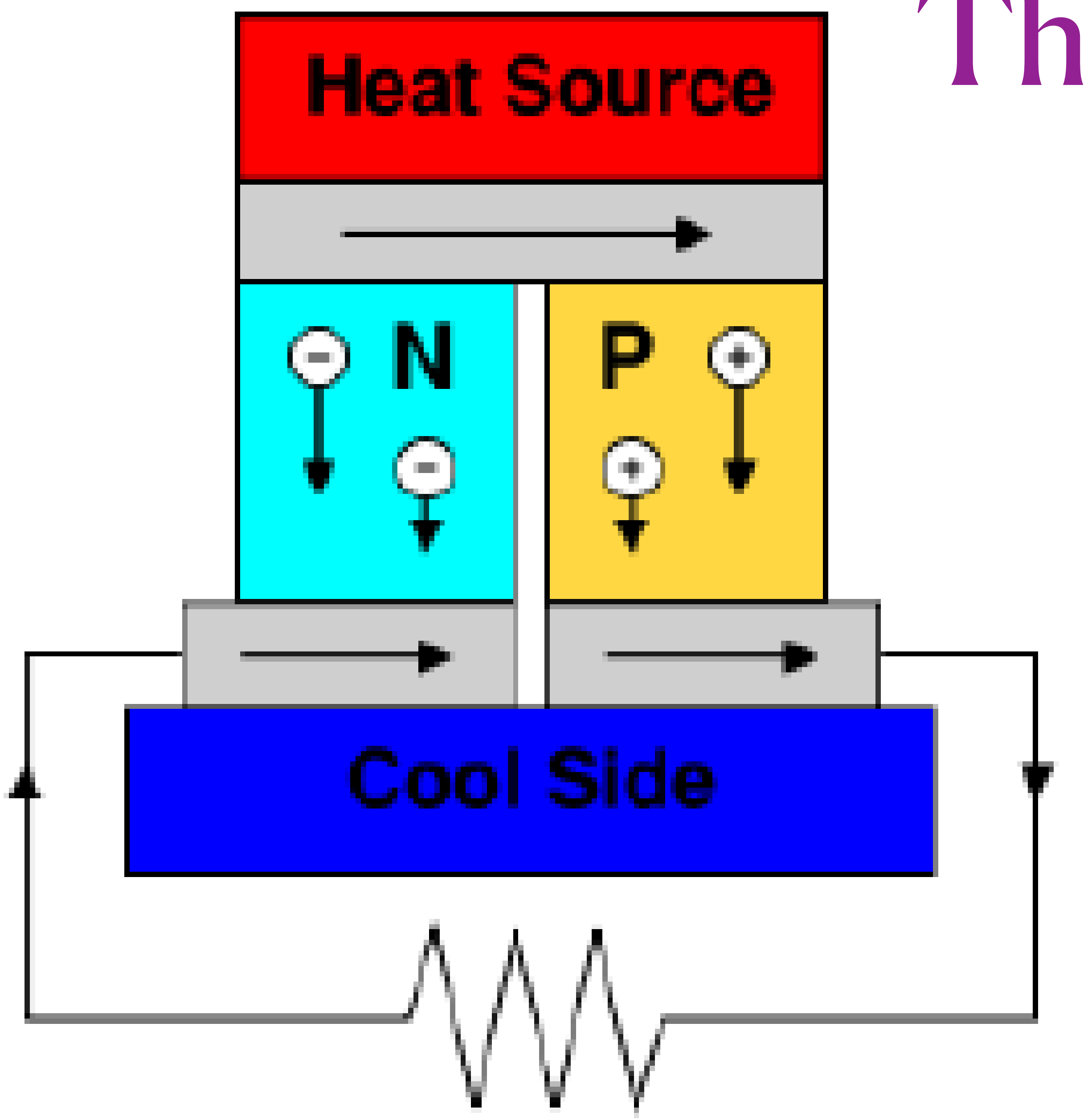
Refrigerator



Electrical current to extract heat

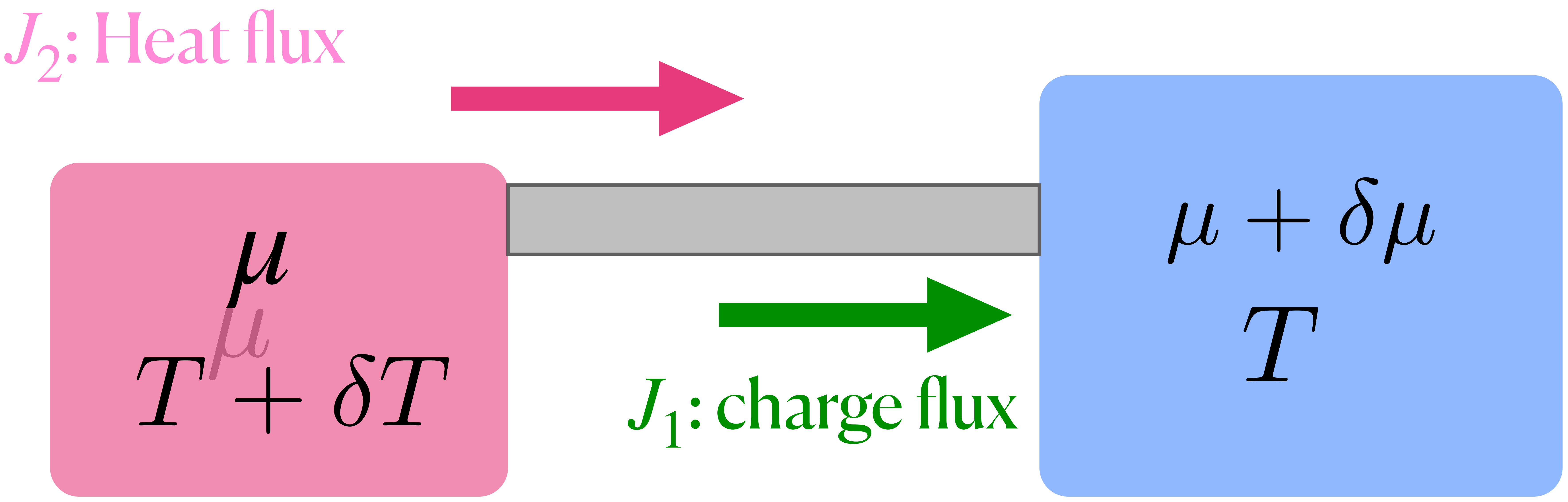
Thermal machine



Heat to generate an electrical current

Quantum conductor. 2-terminal setup

$\delta\mu = eV$, V : Voltage difference



$$H = H_L + H_{cL} + H_S + H_{cR} + H_R$$

Energy and heat fluxes

$$J_\alpha^E = \frac{d\langle H_\alpha \rangle}{dt}$$

Energy flux into the reservoir α

$$J_\alpha^p = \frac{d\langle N_\alpha \rangle}{dt}$$

Particle flux into α

$$J_\alpha^Q = J_\alpha^E - \mu_\alpha J_\alpha^p$$

Heat flux into α

$$J_\alpha^E = -\frac{i}{\hbar}\langle [H_\alpha, H] \rangle$$

Flujo de energía hacia el baño α

$$J_\alpha^p = -\frac{i}{\hbar}\langle [N_\alpha, H] \rangle$$

Flujo de partículas hacia el baño α

H :Hamiltoniano completo. Sistema H_S + reservorios $H_L,\ H_R$ + contactos $H_{cL},\ H_{cR}$

Linear response.

Affinities: $X_1 = \frac{\delta\mu}{T}, \quad X_2 = \frac{\delta T}{T^2}$

$$J_1 \equiv e J^p_R, \qquad J_2 \equiv J^Q_R$$

Electrical conductance

Seebeck

$$J_1 = L_{11} X_1 + L_{12} X_2$$

Heat-work conversion

$$J_2 = L_{21} X_1 + L_{22} X_2$$

Peltier

Thermal conductance

Transport coefficients

$$G = \frac{L_{11}}{T}$$

Electrical conductance

Without Thermoelectricity

$$\kappa = \frac{1}{T^2} \frac{det\hat{L}}{L_{11}} \rightarrow \frac{1}{T^2} L_{22}$$

Thermal conductance

$$TS = \Pi = \frac{L_{12}}{L_{11}}$$

Thermoelectric coefficients:

Seebeck and Peltier

Thermodynamic laws

Onsager relations (4th law) =>micro reversibility

$$L_{11}(B) = L_{11}(-B), \qquad L_{12}(B) = L_{21}(-B)$$

Rate of entropy production:

$$\dot{S} = \frac{\dot{Q}_L}{T_L} + \frac{\dot{Q}_R}{T_R},$$

2nd law

$$\dot{S} = \mathbf{X}^{\mathrm{t}} \cdot \mathbf{L} \cdot \mathbf{X},$$

$$L_{11}, \quad L_{22} > 0$$

$$L_{11}L_{22} - L_{12}L_{21} > 0$$

Operational modes

dc- Heat engine: electrical power/heat flux

$$\eta = \frac{eTJ_1X_1}{J_2} \leq \eta_C, \qquad \eta_C = \frac{\delta T}{T}$$

dc- Heat pump: heat flux/electrical power

$$\eta = \frac{-J_2}{eTJ_1X_1} \leq \eta_C, \qquad \eta_C = \frac{T}{\delta T}$$

Maximum efficiency for a given diff of temperature :

$$\eta = \eta_C \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+1} \qquad ZT = \frac{L_{12}L_{21}}{det\mathbf{L}}$$

Figure of merit

Fundamental aspects of steady-state conversion of heat to work at the nanoscale

Giuliano Benenti[a,b], Giulio Casati[a,c], Keiji Saito[d], Robert S. Whitney[e]

[a] *Center for Nonlinear and Complex Systems, Dipartimento di Scienza e Alta Tecnologia, Università degli Studi dell'Insubria, Via Valleggio 11, 22100 Como, Italy*
[b] *Istituto Nazionale di Fisica Nucleare, Sezione di Milano, via Celoria 16, 20133 Milano, Italy*
[c] *International Institute of Physics, Federal University of Rio Grande do Norte, Natal, Brazil*
[d] *Department of Physics, Keio University 3-14-1 Hiyoshi, Kohoku-ku, Yokohama 223-8522, Japan*
[e] *Laboratoire de Physique et Modélisation des Milieux Condensés (UMR 5493), Université Grenoble Alpes and CNRS, Maison des Magistères, 25 Avenue des Martyrs, BP 166, 38042 Grenoble, France*

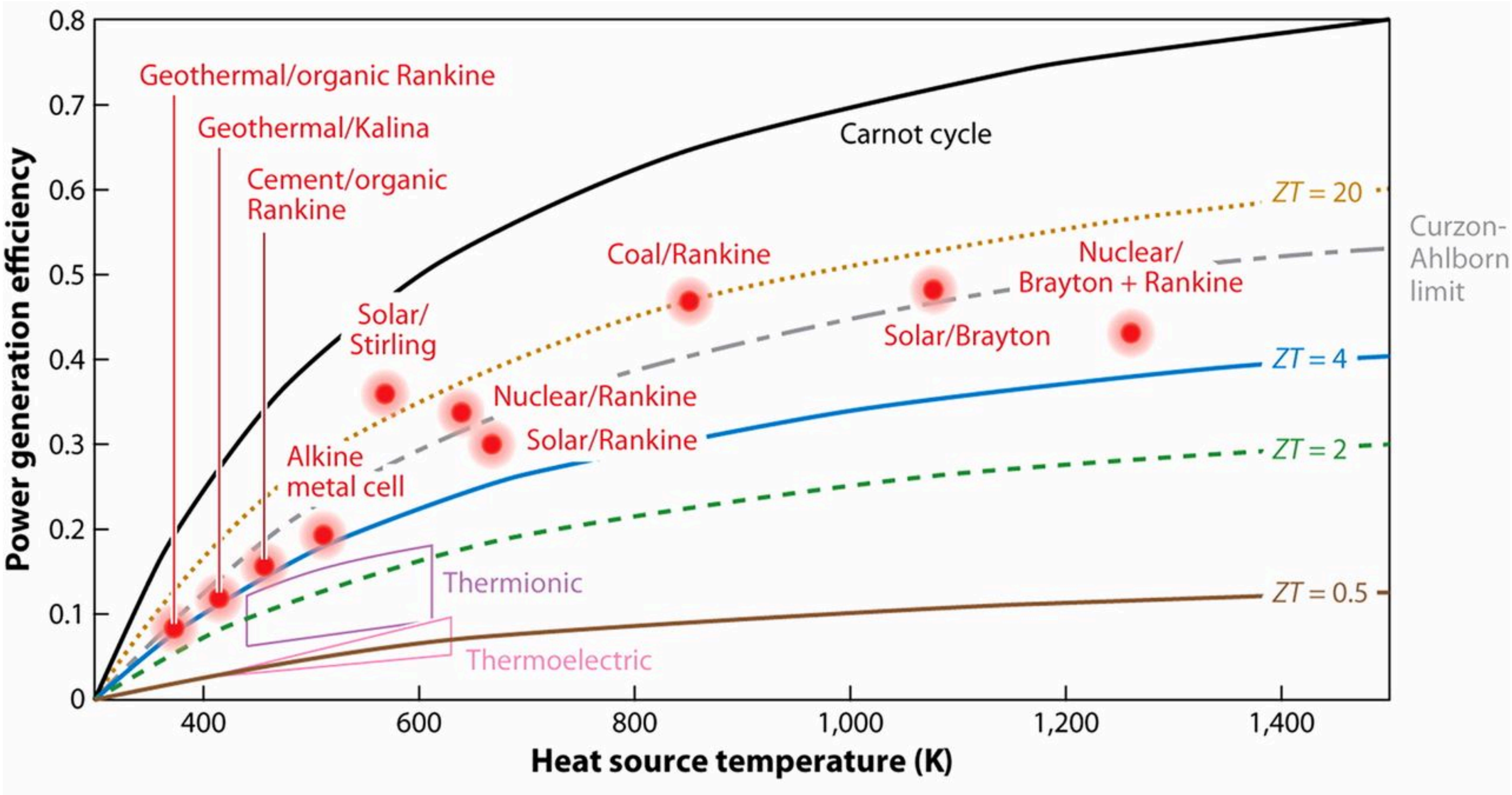
Physics Reports 694,1 (2017)

Desired efficiency	Necessary ZT
Carnot efficiency	∞
$9/10\times$ Carnot efficiency	360
$3/4\times$ Carnot efficiency	48
$1/2\times$ Carnot efficiency	8
$1/3\times$ Carnot efficiency	3
$1/6\times$ Carnot efficiency	$24/25 \sim 1$
$1/10\times$ Carnot efficiency	$40/81 \sim 0.5$
$1/100\times$ Carnot efficiency	$400/9801 \sim 0.04$

Table 1: Examples of the dimensionless figure of merit ZT necessary for a desired heat-engine efficiency, see Eq. (27). This connection between the maximum efficiency and ZT is convenient, as it is easier to calculate ZT from basic transport measurements than to measure the maximum efficiency directly. Current bulk semiconductor thermoelectric have $ZT \sim 1$, while a $ZT \sim 3$ would be necessary for most industrial or household applications. However the connection between maximum efficiency and ZT only exists in the linear-response regime, as ZT has no meaning outside the linear-response regime.

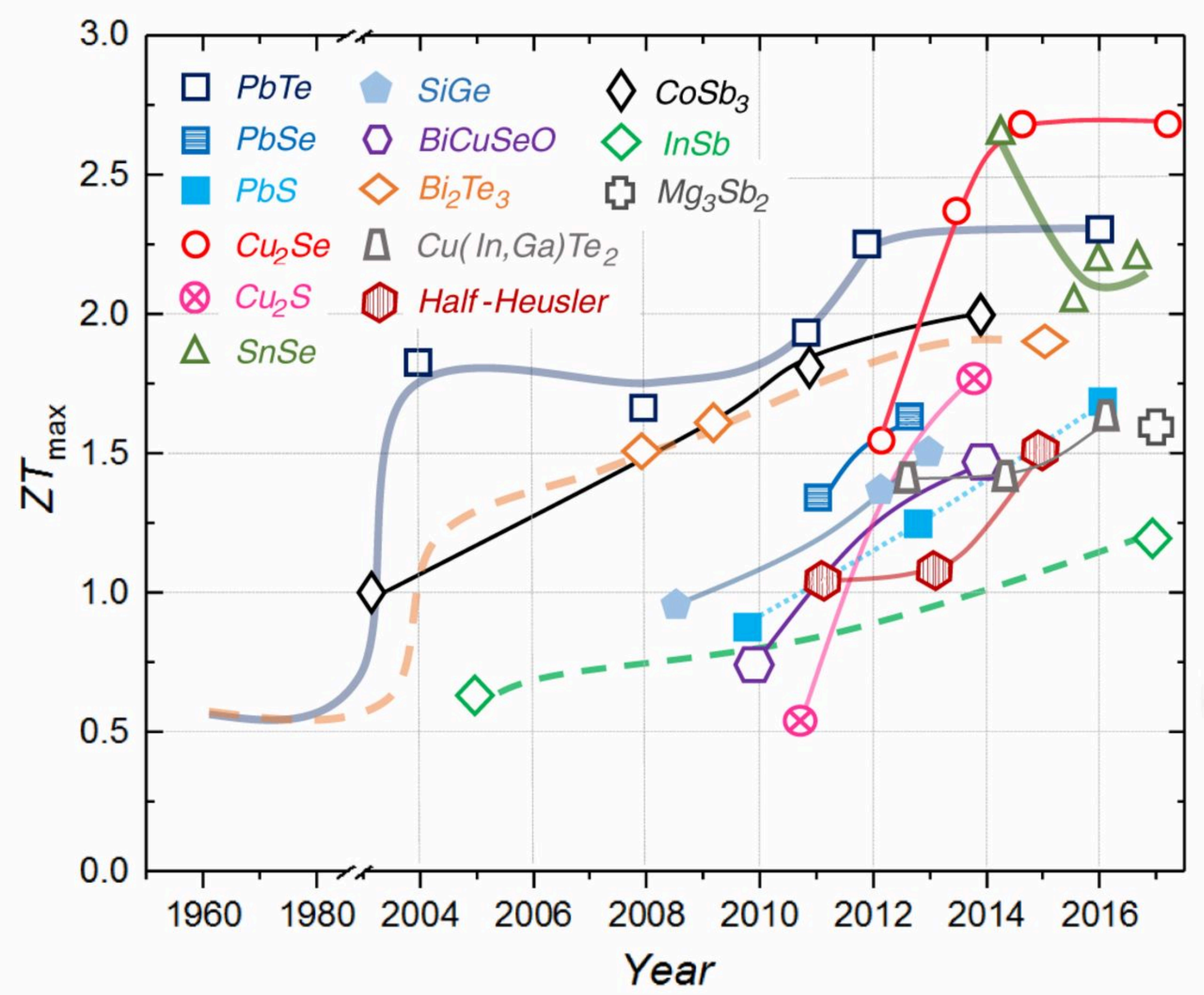
Thermoelectricity in the global context

J. He, T. M. Tritt, Science 357, 6358, 2017



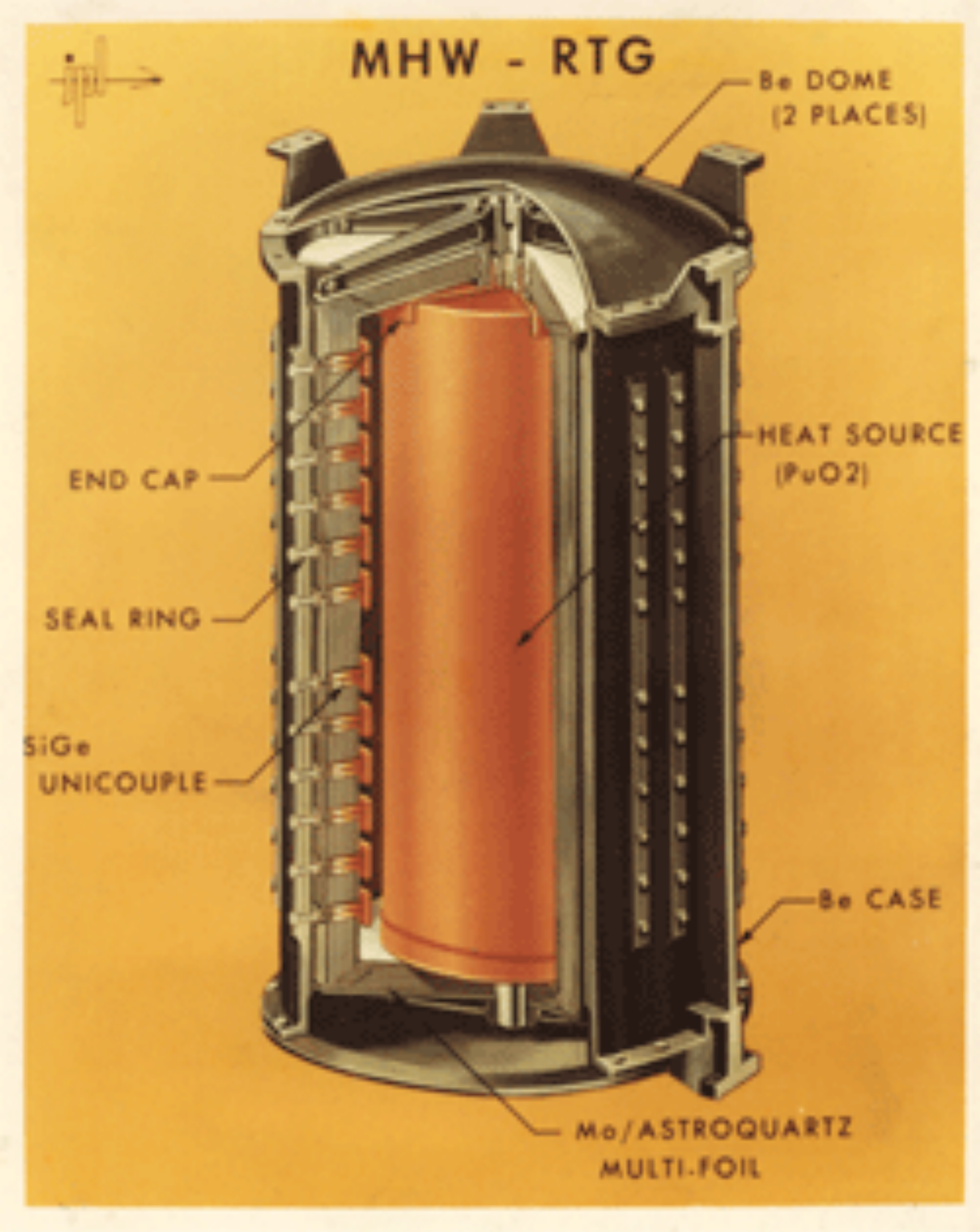
Advances in materials science

J. He, T. M. Tritt, Science 357, 6358,



Interesting application

mars.nasa.gov/mars2020

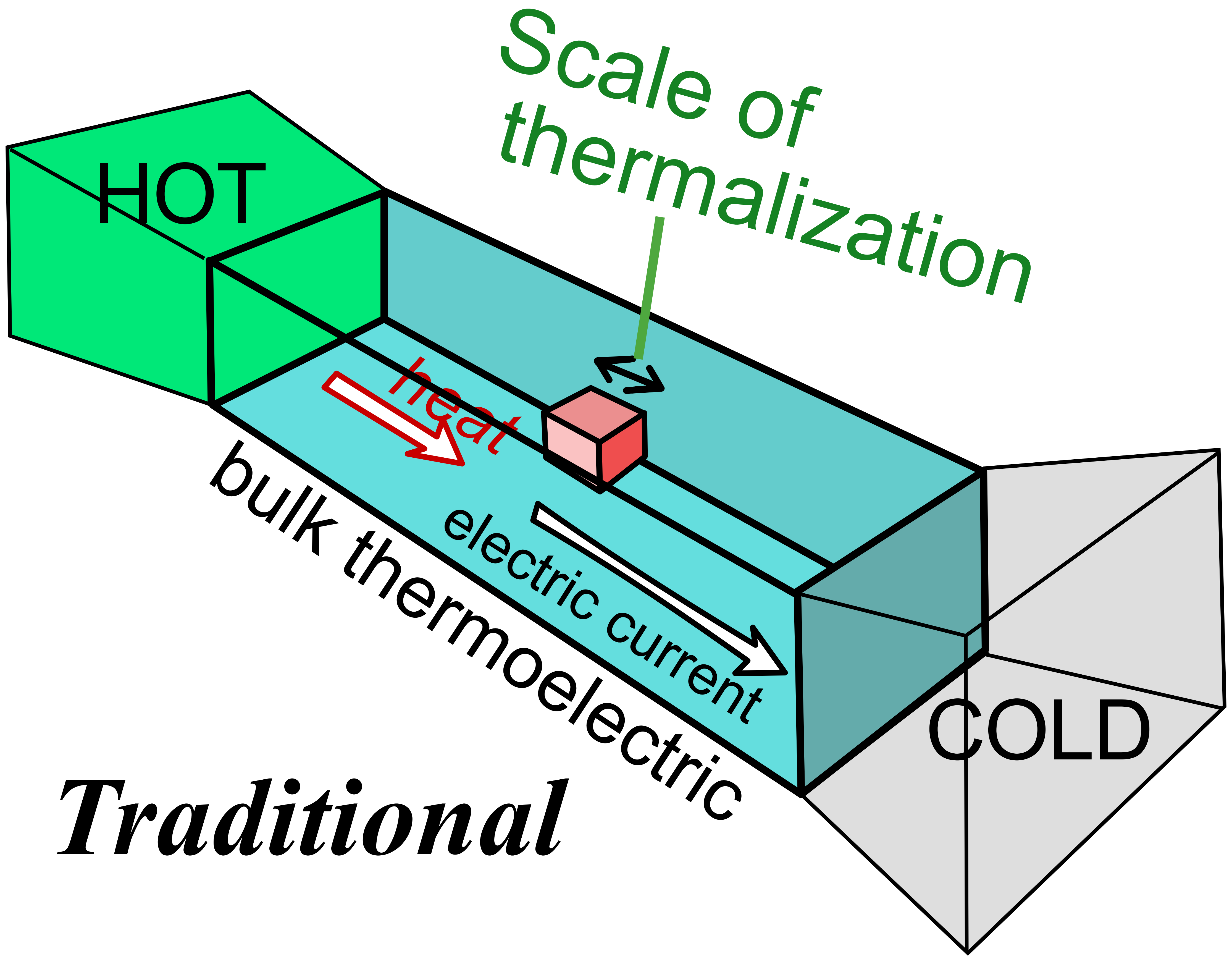


Radioisotope Thermoelectric Generator (RTG) Used on Voyager 1 & 2

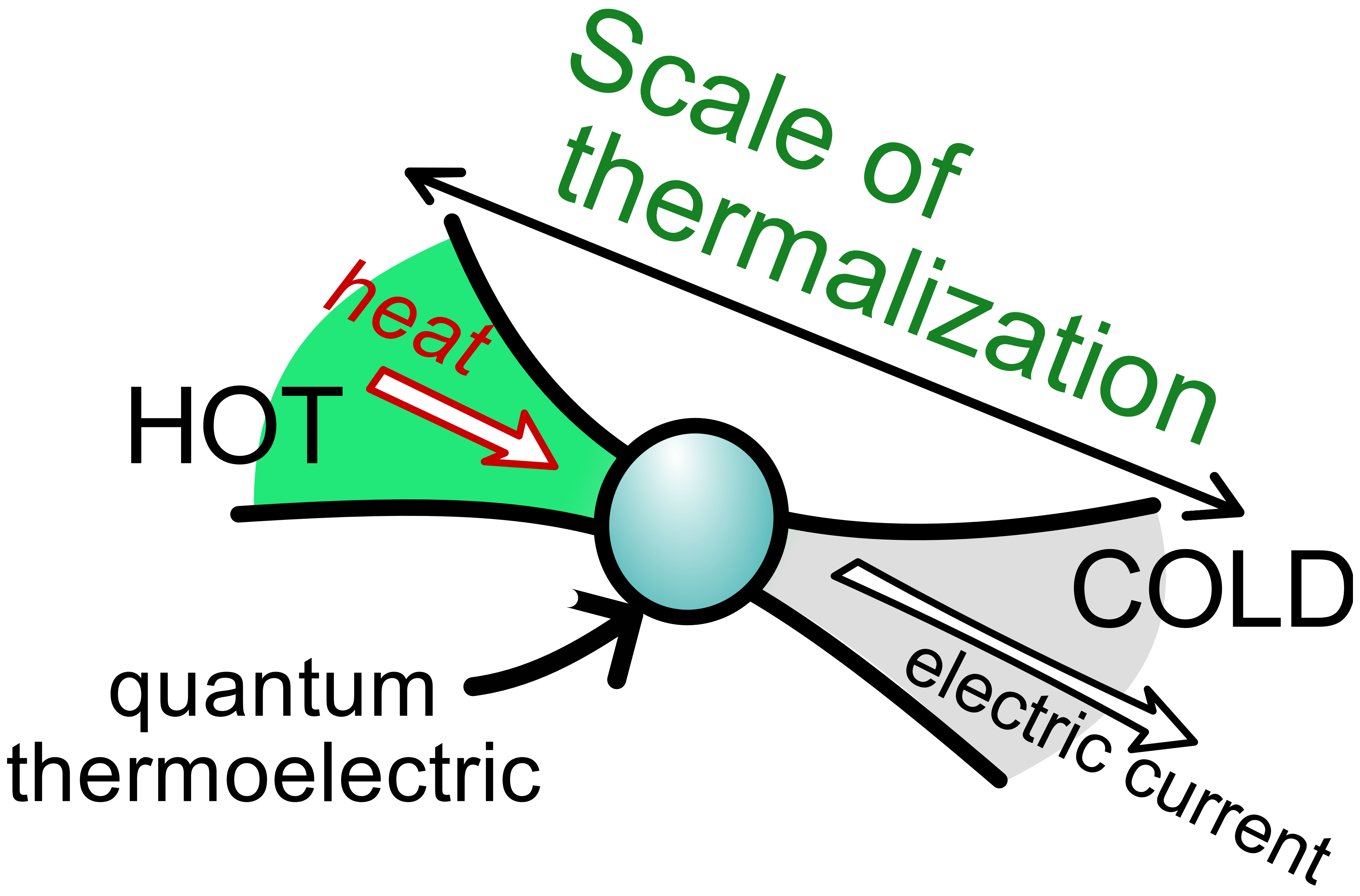
Thermoelectric Generators for Space
For Space Exploration missions, particularly beyond the planet Mars, the light from the sun is too weak to power a spacecraft with solar panels. Instead, the electrical power is provided by converting the heat from a Pu238 heat source into electricity using thermoelectric couples. Such Radioisotope Thermoelectric Generators (RTG) have been used by NASA in a variety of missions such as Apollo, Pioneer, Viking, Voyager, Galileo and Cassini. With no moving parts, the power sources for Voyager are still operating, allowing the spacecraft to continue to make scientific discoveries after over 35 years of operation. The Curiosity rover on Mars is the first rover powered by thermoelectrics using a Multi-Mission RTG (MMRTG).

Quantum regime?

Electron transport in the quantum regime



Traditional



Quantum

Small devices
$nm - \mu m$

Low temperatures
$T < 1K$

- Phonons are not active
- Electrons propagate coherently: preserve the phase of their wave functions

Theoretical description: 2-terminals

Transmisión function

$$J_1 = \frac{e}{h}\int d\varepsilon \mathcal{T}(\varepsilon)\left[f_L(\varepsilon) - f_R(\varepsilon)\right]$$

Fermi-Dirac function

$$f_\alpha = \frac{1}{e^{(\varepsilon-\mu_\alpha)/(k_B T_\alpha)} + 1}, \quad \alpha = L, R$$

$$J_2 = \frac{1}{h}\int d\varepsilon \left(\varepsilon - \mu\right) \mathcal{T}(\varepsilon)\left[f_L(\varepsilon) - f_R(\varepsilon)\right]$$

Properties of the transmission function $\mathscr{T}(\varepsilon)$

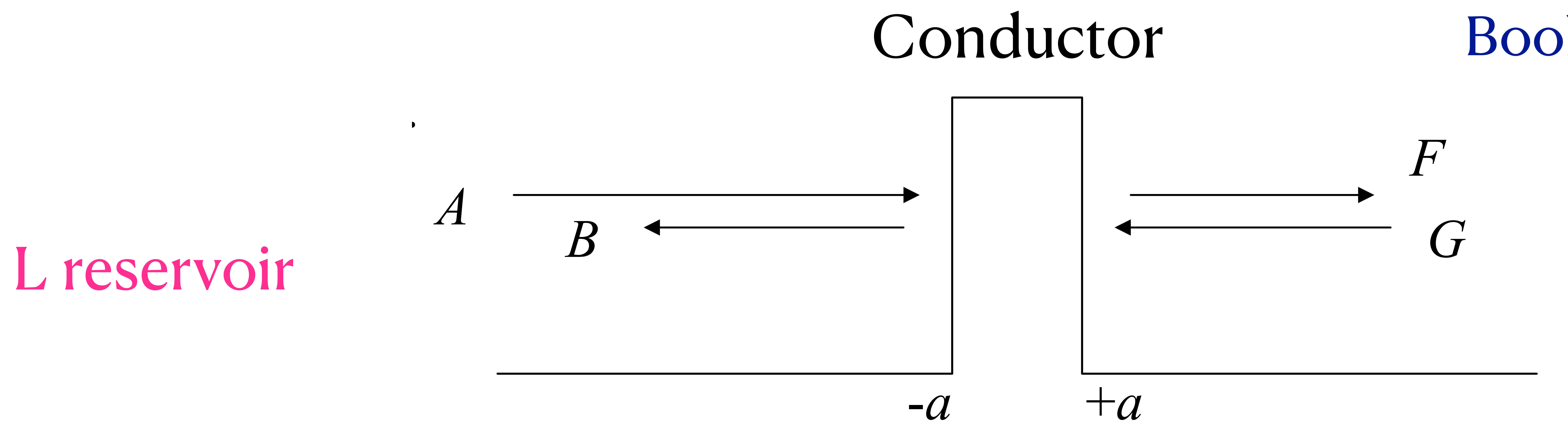
- Describes the "transparency" of the quantum conductor in a two-terminal configuration.
- Depends on the microscopic properties of the conductor and on the contacts to the reservoirs.
- $\mathscr{T}(\varepsilon) \geq 0$. Defines the probability of injecting an electron from one of the reservoirs with energy ε, transmitting it through the conductor and injecting it into the other reservoir. For a single quantum channel with perfect transmission: $\mathscr{T} = 1$.

Methods to calculate the transmission function in quantum devices

Landauer-Büttiker theory

A simple approach to calculate the transmission function

Books: Ferry, Datta, Moskalets



Transfer matrix M: relates both sides of the conductor

$$\begin{pmatrix} A \\ B \end{pmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{pmatrix} F \\ G \end{pmatrix}$$

Scattering matrix S: relates incoming with outgoing amplitudes

$$\begin{pmatrix} B \\ F \end{pmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{pmatrix} A \\ G \end{pmatrix}$$

Transmission Reflection

$$\mathcal{T}(\varepsilon) = |S_{12}|^2, \quad \mathcal{R}(\varepsilon) = 1 - \mathcal{T}(\varepsilon) = |S_{11}|^2$$

Non-equilibrium Green's functions

Hamiltonian approach Books: A-P. Jauho, Rammer

Example: Quantum dot

$$H = \sum_{\alpha=L,R} \left[H_\alpha + H_{c,\alpha}\right] + H_d$$

Reservoirs

$$H_\alpha = \sum_{k_\alpha} \varepsilon_{k_\alpha} c^\dagger_{k_\alpha} c_{k_\alpha}$$

$$T, \;\; \mu_L = \mu + eV, \;\; \mu_R = \mu$$

Quantum dot

$$H_d = \sum_\sigma \varepsilon_{d,\sigma} d^\dagger_\sigma d_\sigma$$

Contacts

$$H_{c,\alpha} = w \sum_{k_\alpha,\sigma} \left(c^\dagger_{k_\alpha,\sigma} d_\sigma + d^\dagger_\sigma c_{k_\alpha,\sigma} \right)$$

Transmission function of a quantum dot

Paradigmatic example

$$\mathscr{T}_\sigma(\varepsilon) = \Gamma_L(\varepsilon)\,|\,G^R_{d,d,\sigma}(\varepsilon)\,|^2\,\Gamma_R(\varepsilon)$$

Rates

$$\Gamma_\alpha(\varepsilon) = |\,w\,|^2\, 2\pi \sum_{k_\alpha} \delta(\varepsilon - \varepsilon_{k_\alpha}) \simeq \Gamma_\alpha$$

Retarded Green's function

$$G^R_\sigma(\varepsilon) = \frac{1}{\varepsilon - \varepsilon_{d,\sigma} + i(\Gamma_L + \Gamma_R)}$$

$$\mathscr{T}_\sigma(\varepsilon) = \frac{\Gamma_L \Gamma_R}{(\varepsilon - \varepsilon_0)^2 + (\Gamma_L + \Gamma_R)^2/4}$$

Comments

- Landauer-Büttiker = Schwinger-Keldysh non-equilibrium Green's functions for systems described by bilinear Hamiltonians.

- For bosonic systems (phononics, photonics):

Heat flux: $$J_2 = \frac{1}{h}\int_0^\infty d\varepsilon\varepsilon\mathcal{T}(\varepsilon)\left[n_L(\varepsilon) - n_R(\varepsilon)\right]$$

$$n_\alpha = \frac{1}{e^{\varepsilon/(k_B T_\alpha)} - 1}, \quad \alpha = L, R$$

Exercise

For a system with perfect transmission: $\mathcal{T} = 1$, verify that the quantum of thermal conductance is independent of the particle statistics and is given by:

$$\kappa_{\mathrm{th}} = \frac{\pi^2 k_B^2 T}{3h}$$

Pendry [J. Phys. A 16, 2161 (1983)] y Bekenstein [PRL 46, 623 (1981); PRD 30, 1669 (1984)]

Calculation of linear response

Expanding the Fermi functions at linear order in $\delta\mu,\ \delta T$

$$f_L(\varepsilon) = f(\varepsilon) - f'(\varepsilon)(\varepsilon - \mu)\frac{\delta T}{T}$$

$$f_R(\varepsilon) = f(\varepsilon) - f'(\varepsilon)eV$$

Onsager coefficents

Substituting in J_1, J_2 .....

$$L_{11} = e^2 T\, I_0 \qquad L_{12} = L_{21} = eT\, I_1 \qquad L_{22} = T\, I_2$$

$$I_n = -\frac{1}{h}\int_{-\infty}^{\infty} d\varepsilon\, \left(\varepsilon - \mu\right)^n\, \mathcal{T}(\varepsilon)\, f'(\varepsilon)$$

The thermoelectric response depends on the properties of $\mathcal{T}(\varepsilon)$

Bounds for the conductance

Achieved for $\mathscr{T}(\varepsilon) = 1$

$$G \leq \frac{e^2}{h}$$

Quantum of electrical conductance per channel

$$\kappa \leq \frac{\pi^2 k_B^2 T}{3h}$$

Universal quantum of thermal conductance per channel.

Independent of the statistics!

Bekenstein, PRL 46, 923 (1981) - Pendry, JPA 16, 2161 (1983)

$$\frac{\kappa}{GT} = \frac{\pi^2 k_B^2}{3e^2}$$

Wiederman-Franz law

The thermoelectric response depends on the properties of $\mathscr{T}(\varepsilon)$

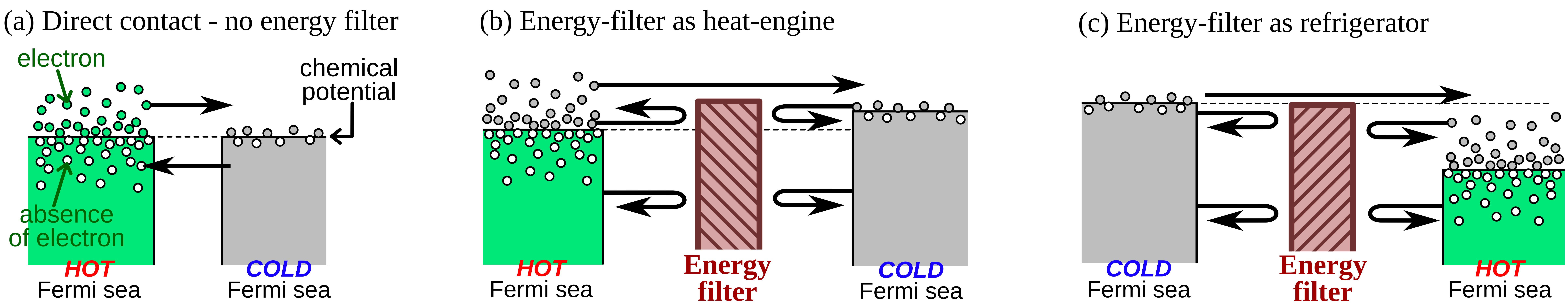
Odd in $(\varepsilon - \mu)$

Even in $(\varepsilon - \mu)$

$$L_{12} = -\frac{1}{h}\int_{-\infty}^{\infty} d\varepsilon \left(\varepsilon - \mu\right) \mathscr{T}(\varepsilon) f'(\varepsilon)$$

Must not be even in $(\varepsilon - \mu)$

Thermoelectricity: no Wiederman-Franz law

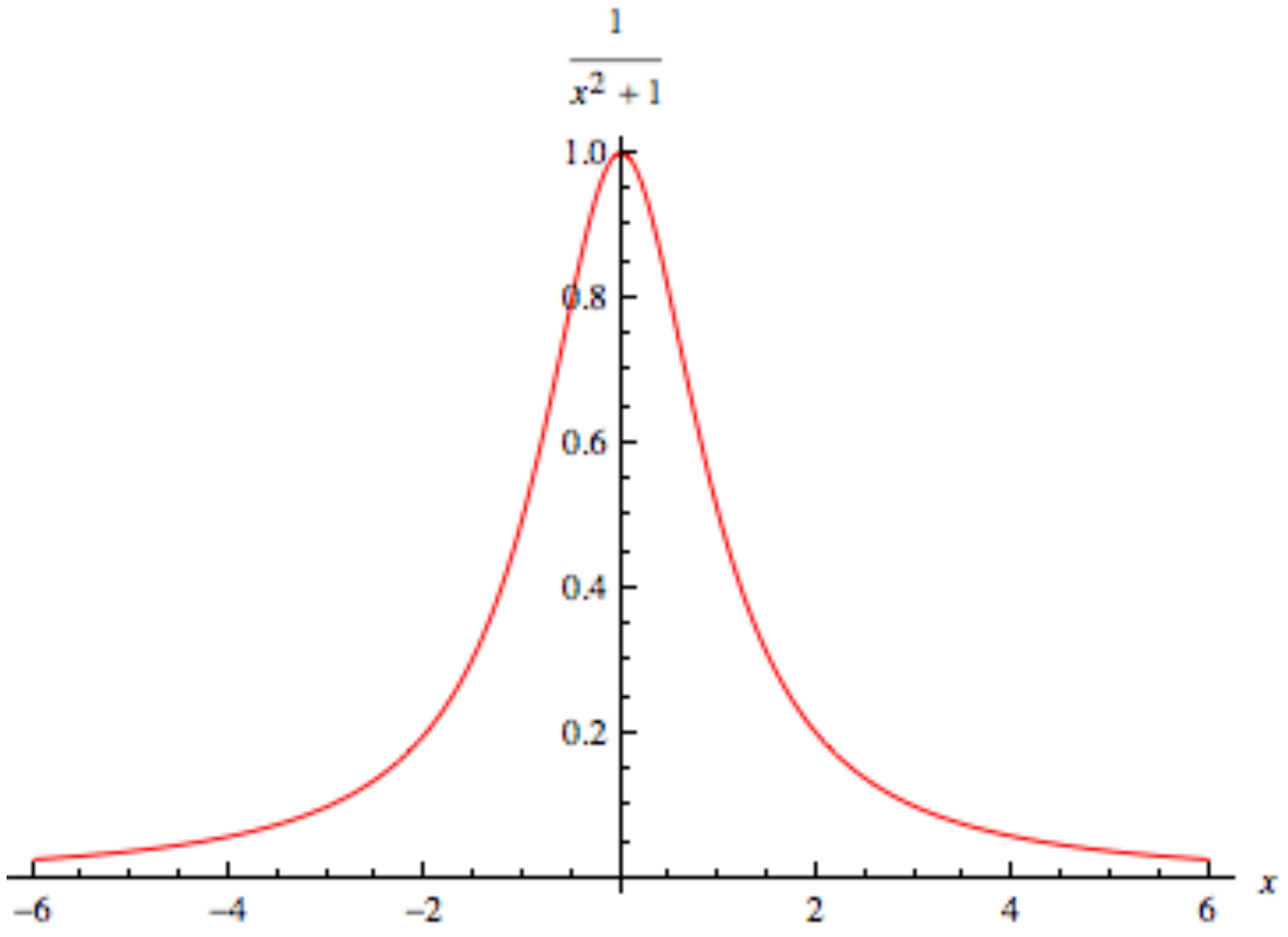


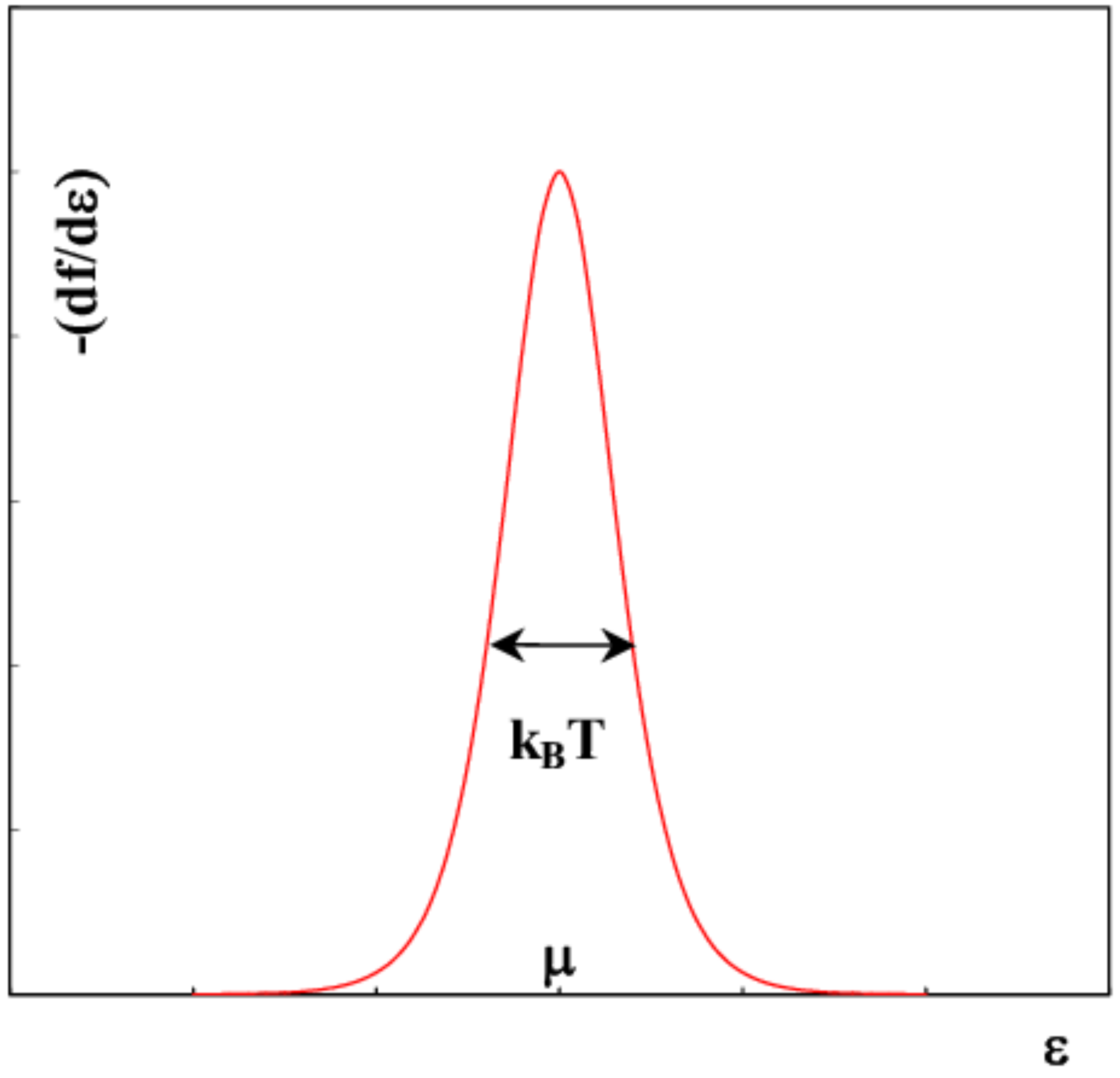
Quantum dot

Paradigmatic example

$$\mathcal{T}_\sigma(\varepsilon) = \frac{\Gamma^2}{(\varepsilon - \varepsilon_0)^2 + \Gamma^2}$$

Lorenzian





Limit of very low temperatures

Electrical conductance

$$G = -\frac{e^2}{h}\int_{-\infty}^{\infty} d\varepsilon\ \mathcal{T}(\varepsilon)\, f'(\varepsilon)$$

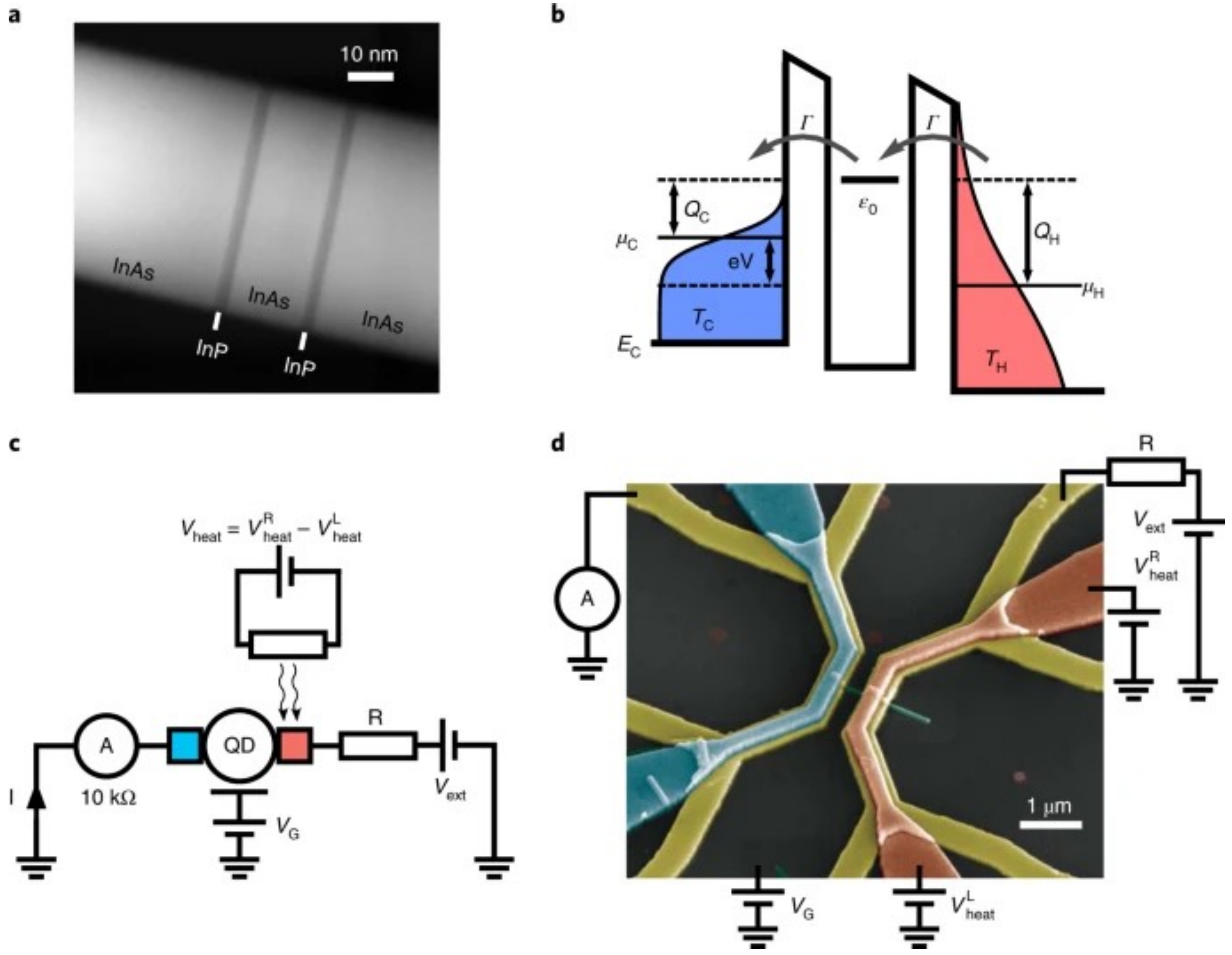
$$-f'(\varepsilon) \rightarrow_{T\rightarrow 0} \delta(\varepsilon - \mu)$$

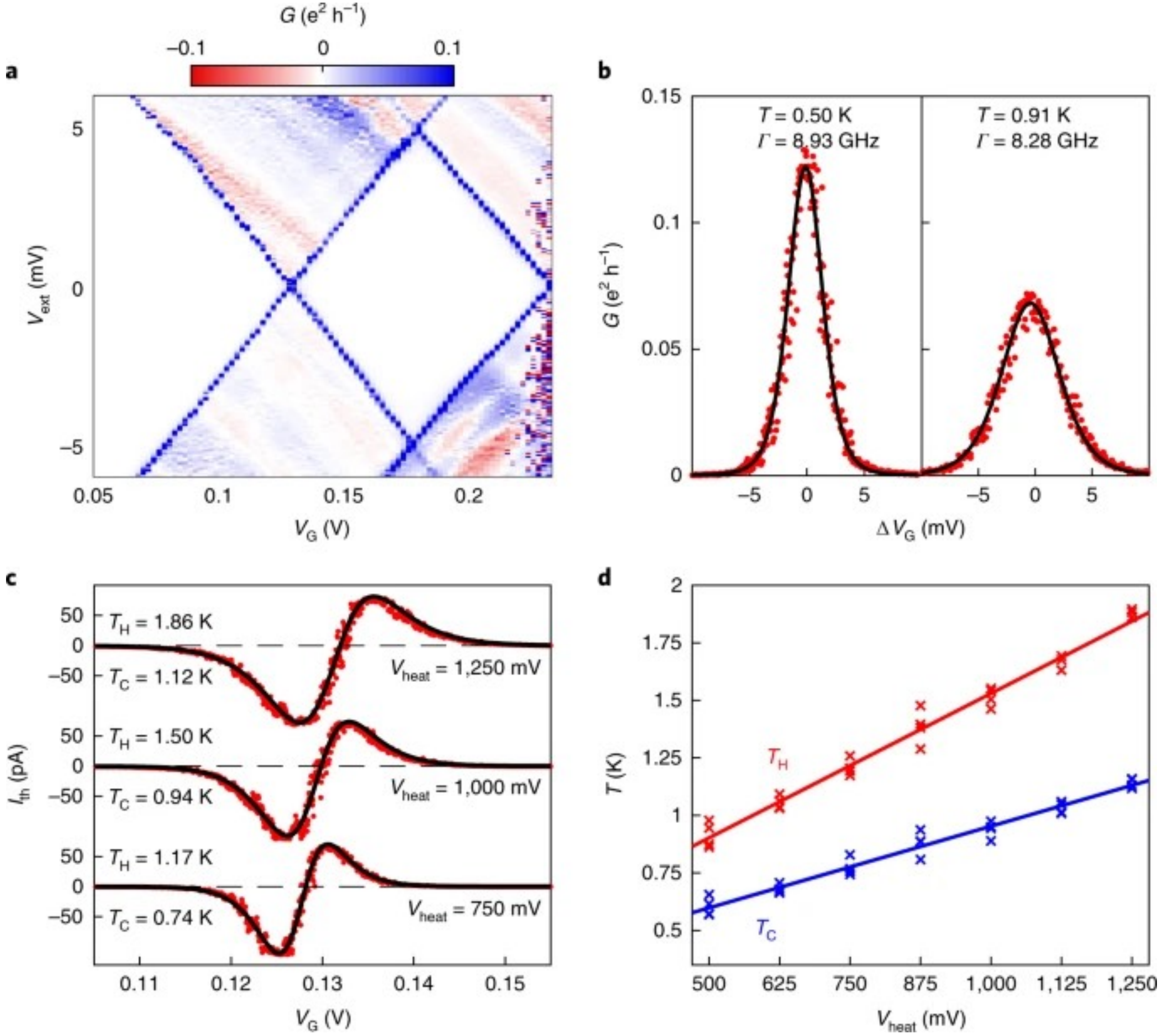
$$G(\mu) \simeq \mathcal{T}(\mu)$$

Experiments on the electrical conductance provide information on the transmission function

Experimental example on thermoelectricity in quantum dots

M. Josefsson, A. Svilans, et al. Nature Nanotechnology **13**, 920 (2018)

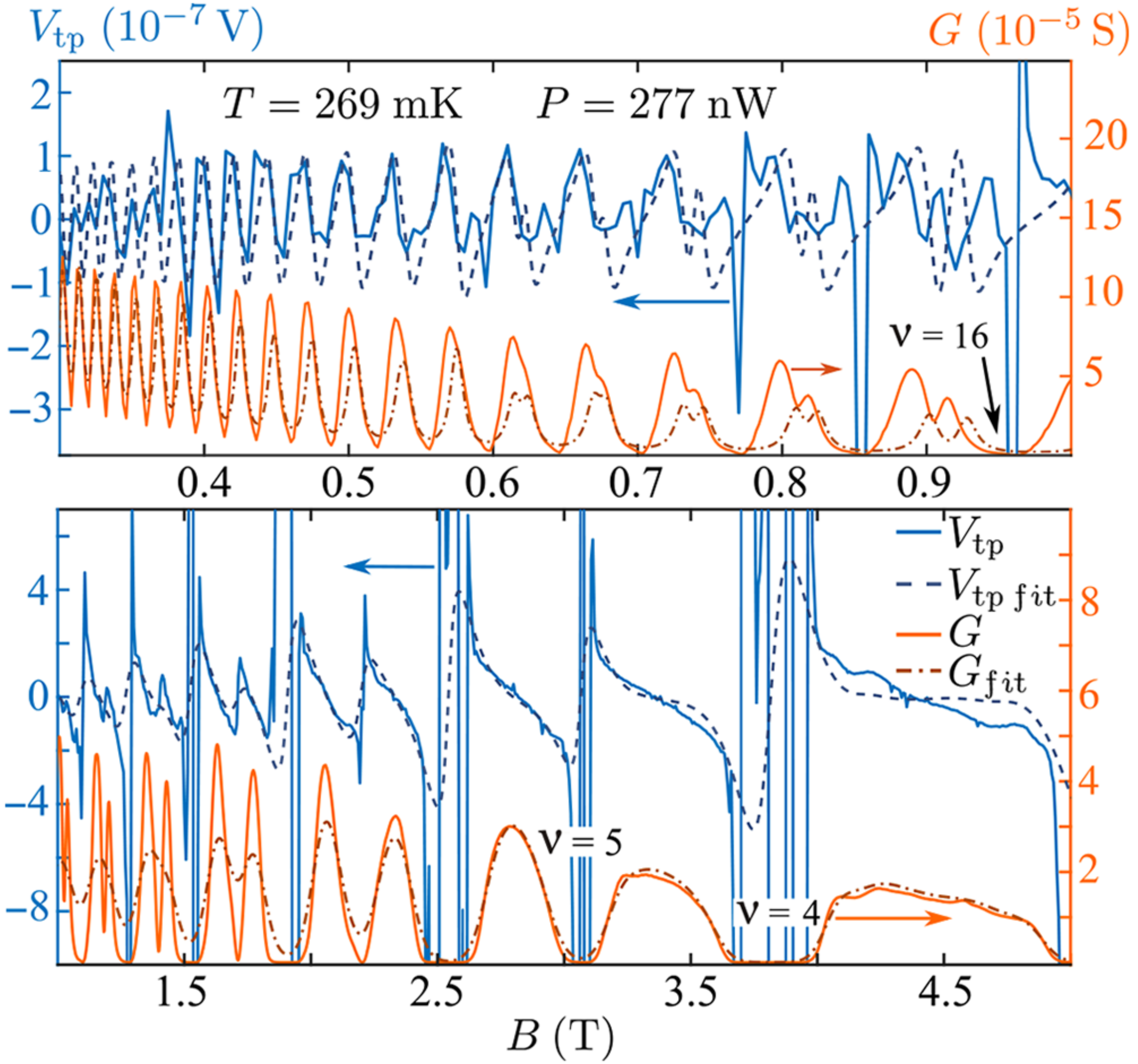




PHYSICAL REVIEW APPLIED **14,** 034019 (2020)

Thermoelectricity in Quantum Hall Corbino Structures

Mariano Real,[1,*] Daniel Gresta,[2] Christian Reichl,[3] Jürgen Weis,[4] Alejandra Tonina,[1] Paula Giudici,[5]
Liliana Arrachea,[2] Werner Wegscheider,[3] and Werner Dietsche[3,4]



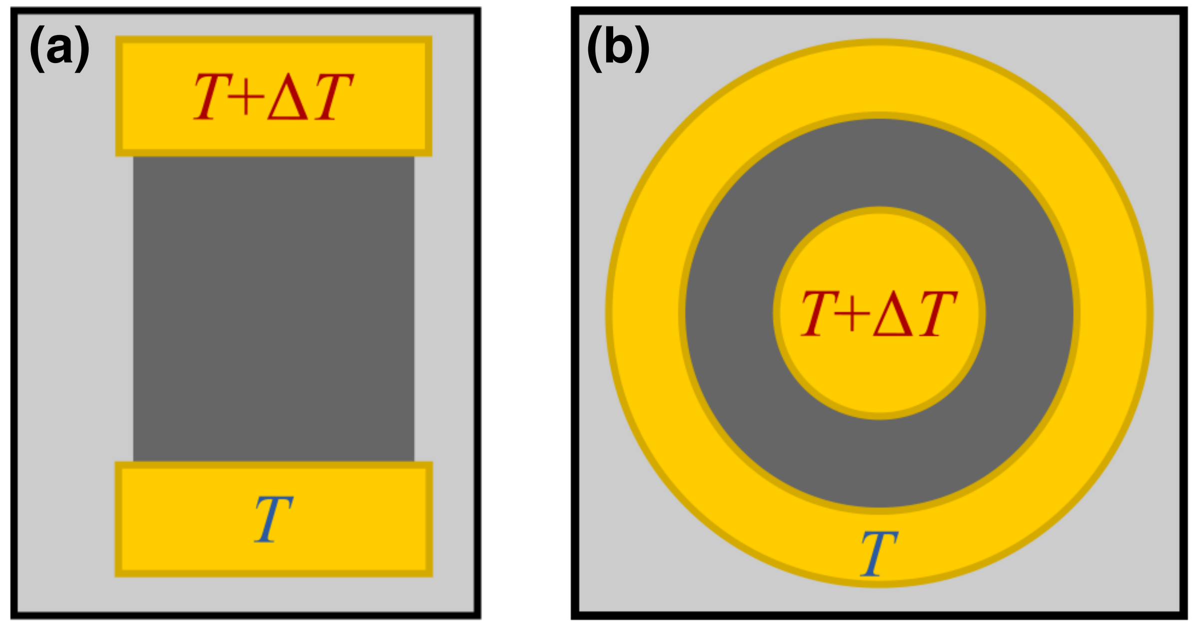
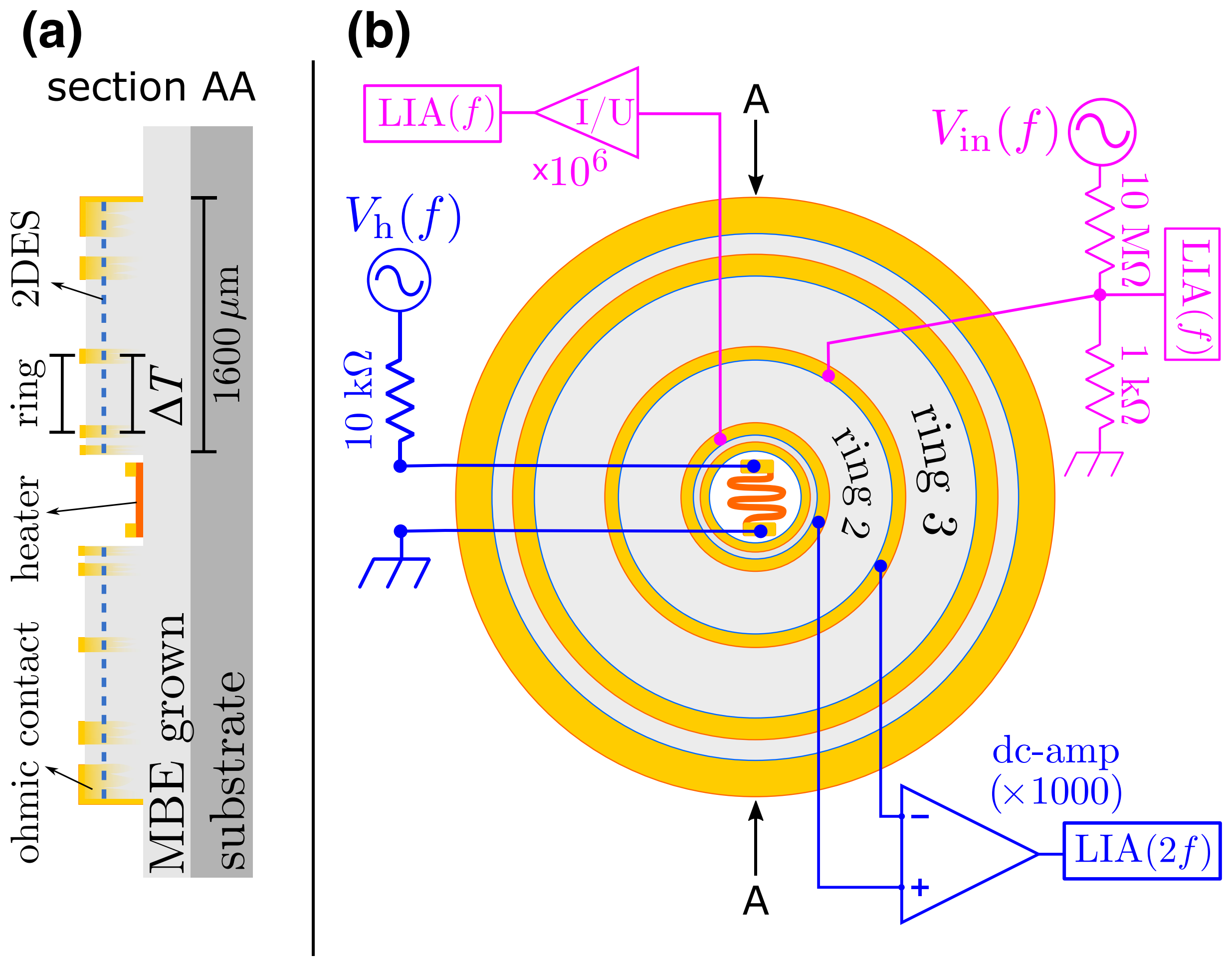


FIG. 1. The two sample designs to investigate thermoelectric effects: (a) the Hall bar; (b) the Corbino. The dark-gray areas are the 2DES. The hot and the cold contacts for measuring the thermovoltage are at the two ends of the rectangular-shaped Hall bar. For the Corbino, the hot contact is in the center of the 2DES, which is surrounded by the cold contact.



Role of many-body interactions?

PHYSICAL REVIEW B **95**, 245432 (2017)

Thermoelectric properties of an interacting quantum dot based heat engine

Paolo Andrea Erdman,[1,*] Francesco Mazza,[1] Riccardo Bosisio,[1] Giuliano Benenti,[2,3,4] Rosario Fazio,[5,1] and Fabio Taddei[6]

PHYSICAL REVIEW B **97**, 081104(R) (2018)

Rapid Communications

Enhanced thermoelectric response in the fractional quantum Hall effect

Pablo Roura-Bas,[1] Liliana Arrachea,[2,3] and Eduardo Fradkin[4]

PHYSICAL REVIEW B **101**, 241101(R) (2020)

Rapid Communications

Thermoelectric response and entropy of fractional quantum Hall systems

D. N. Sheng[1] and Liang Fu[2]

PHYSICAL REVIEW B **105**, L121405 (2022)

Letter

Thermoelectrics of a two-channel charge Kondo circuit: Role of electron-electron interactions in a quantum point contact

A. V. Parafilo,[1,*] T. K. T. Nguyen,[2] and M. N. Kiselev[3]

PHYSICAL REVIEW B **95**, 155131 (2017)

Thermoelectric transport in disordered metals without quasiparticles: The Sachdev-Ye-Kitaev models and holography

Richard A. Davison,[1] Wenbo Fu,[1] Antoine Georges,[2,3,4] Yingfei Gu,[5] Kristan Jensen,[6] and Subir Sachdev[1,7]

PHYSICAL REVIEW B **101**, 205148 (2020)

Editors' Suggestion

Thermoelectric power of Sachdev-Ye-Kitaev islands: Probing Bekenstein-Hawking entropy in quantum matter experiments

Alexander Kruchkov,[1] Aavishkar A. Patel,[2] Philip Kim,[1] and Subir Sachdev[1,*]

Main take-home message

- In order to have a thermal machine we need a mechanism for heat-work conversion.
- In steady-state quantum electron transport such a mechanism is associated to an energy filter breaking particle-hole symmetry.
- Heat-work conversion comes along with entropy production.

Thank you!

Xul Solar, Argentina, 1937-1963