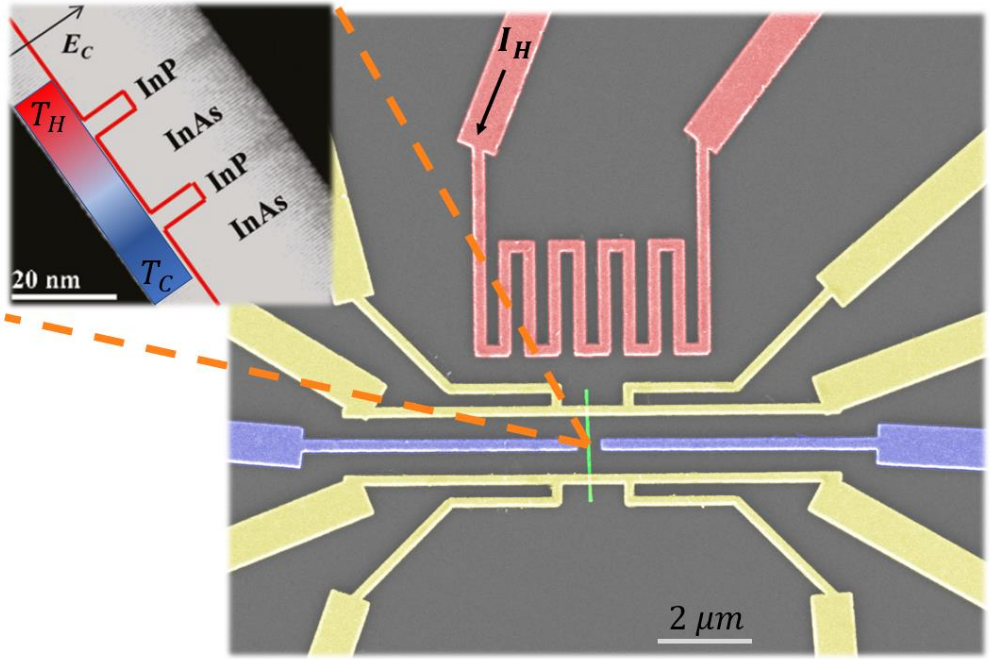
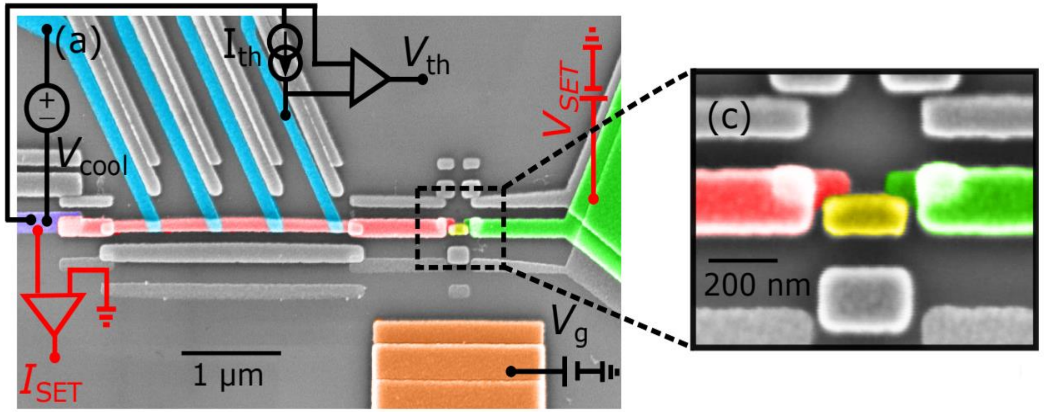
Charge, Heat and Work in Nanoscale Systems

PAOLO ANDREA ERDMAN

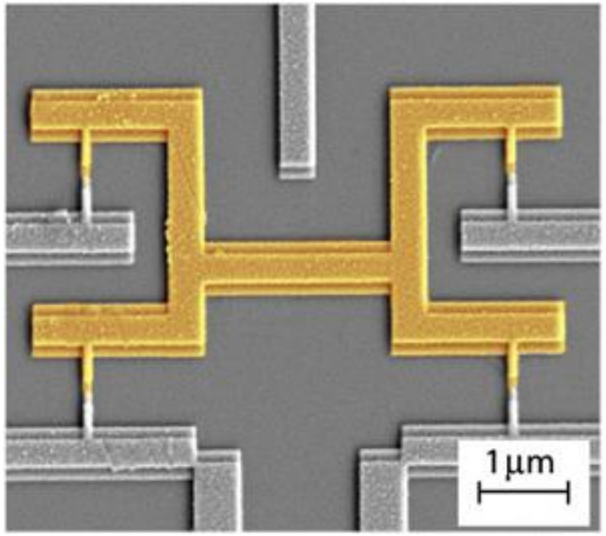
Single-Electron System



Quantum Dots



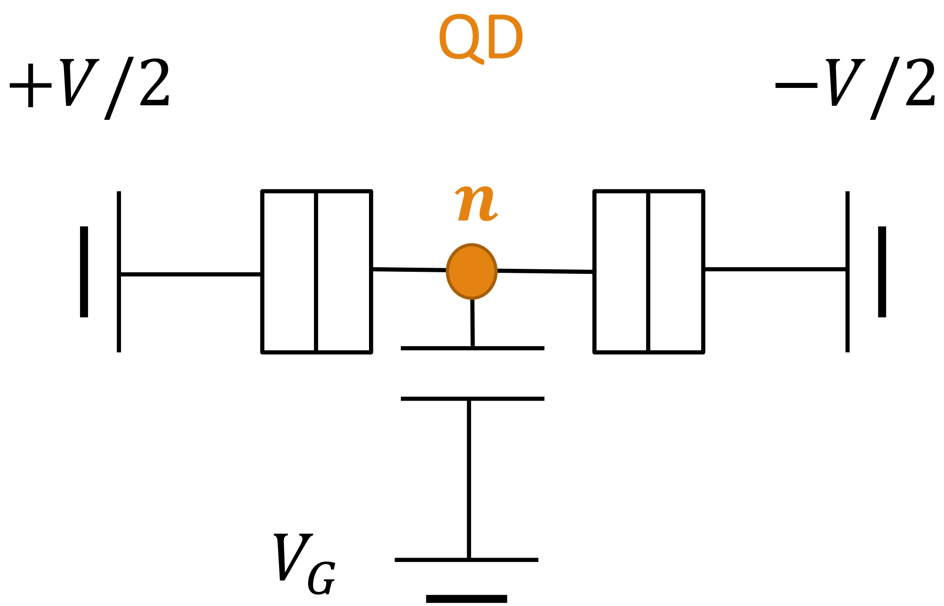
Metallic Supercoducting Islands



Supercunducting Circuits

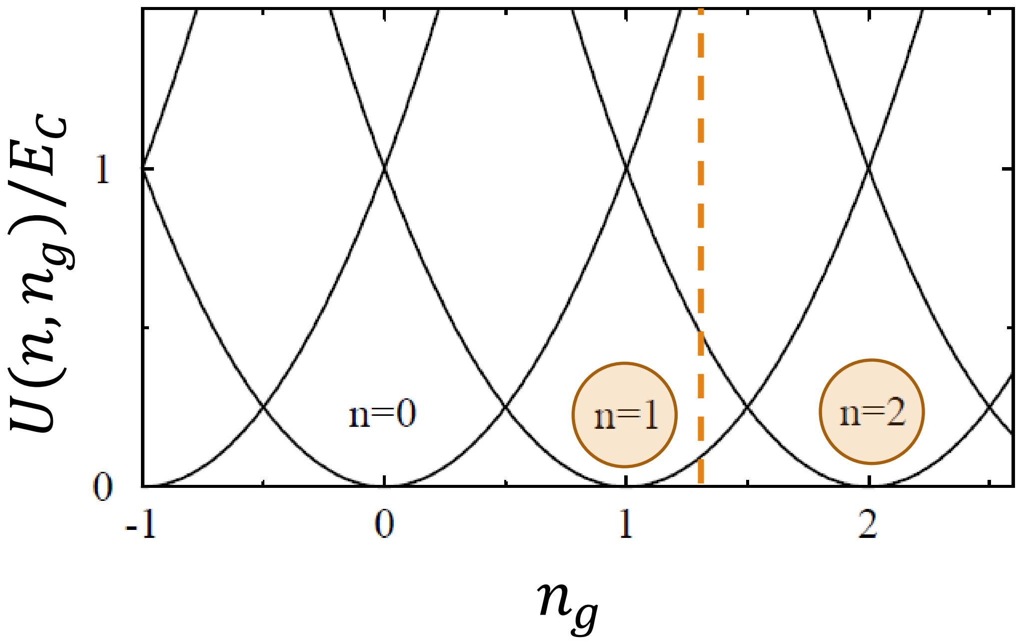
Charging Energy $E_C \gg k_B T, E_j$

Coulomb Blockade



Electrostatic energy $\propto Q^2$

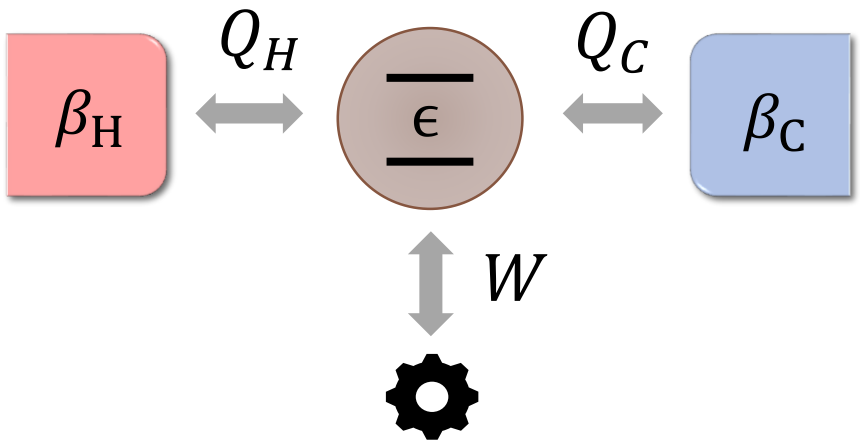
$$U(n, n_g) = E_C(n - n_g)^2$$



Projects

P1: "Maximum power and corresponding efficiency for two-level quantum heat engines and refrigerators"

Finite-Time Thermodynamics



System Hamoltinian:

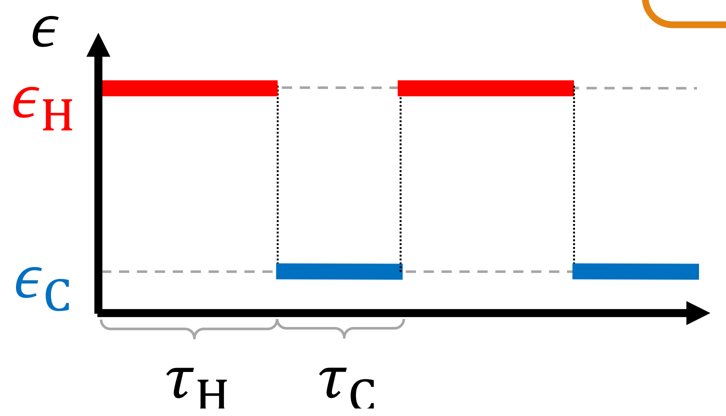
$$\hat{H} = \epsilon(t)\sigma^{+}\sigma^{-}$$

Lindblad Master Equation:

$$\frac{d\hat{\rho}}{dt} = -i[\hat{H}, \hat{\rho}] + D_H[\hat{\rho}] + D_C[\hat{\rho}]$$

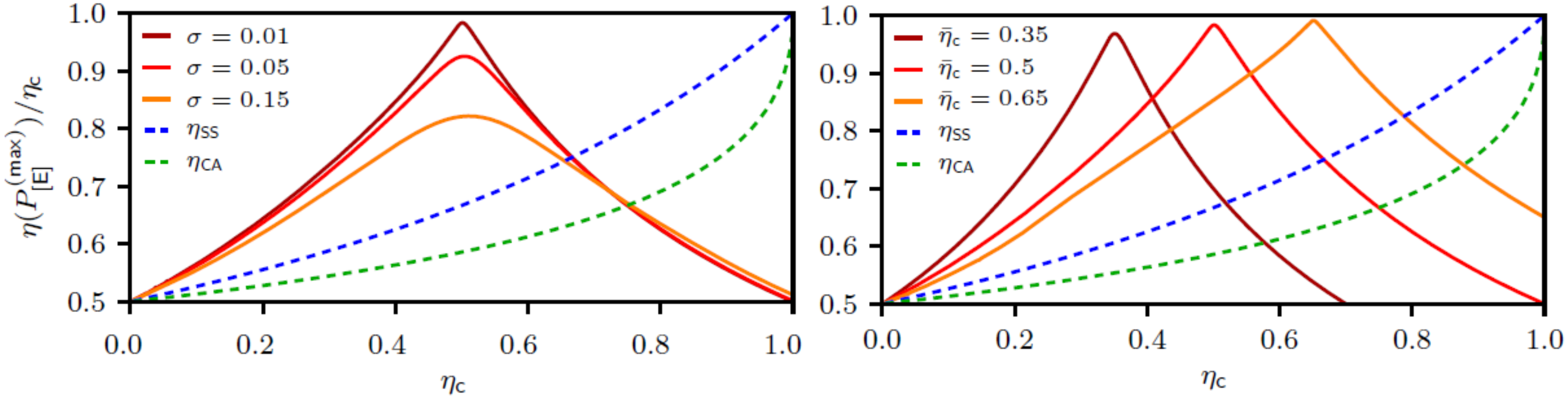
Maximum Efficiency:
Reversible Transformation

How to Maximize the *Power*?



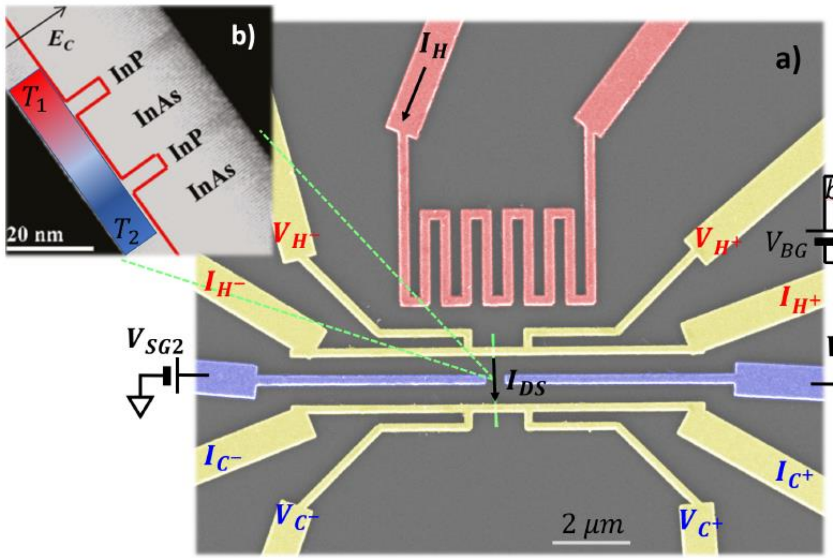
Universal Protocol:

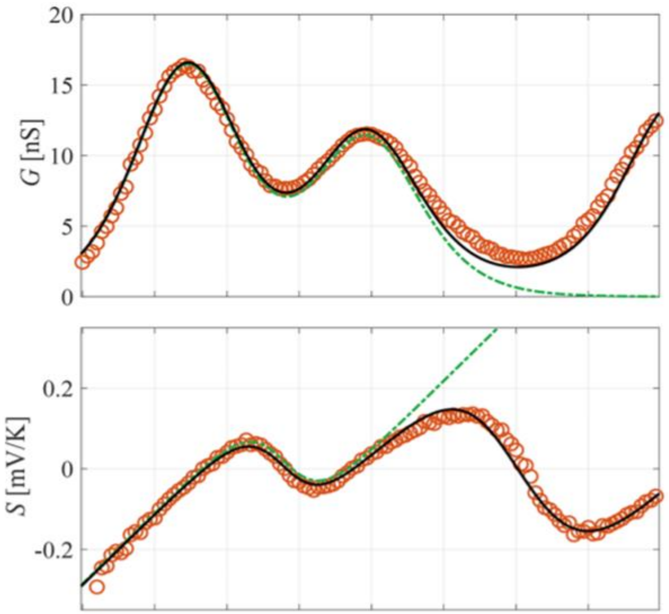
$$\tau_H + \tau_C \to 0$$



[P.A. Erdman, V. Cavina, R. Fazio, F. Taddei, and V. Giovannetti arXiv:1812.05089 (2018)]

P2: "Thermoelectric conversion at 30K in InAs/InP nanowire quantum dots"





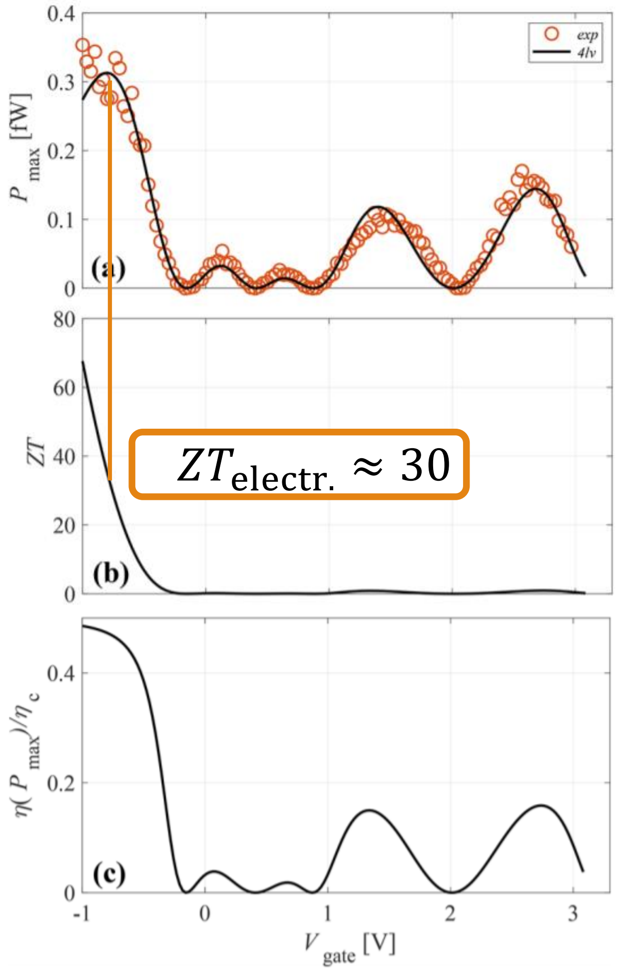


Figure of Merit: $ZT = GS^2T/K$

$$\eta_{\max} = \eta_C \; \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}-1}, \qquad \eta(P_{\max}) = \frac{\eta_C}{2} \; \frac{ZT}{ZT+2}$$

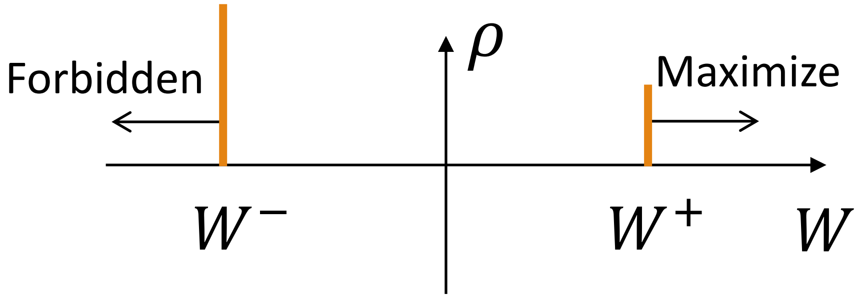
In single-level sequential QD
$ZT \to +\infty$

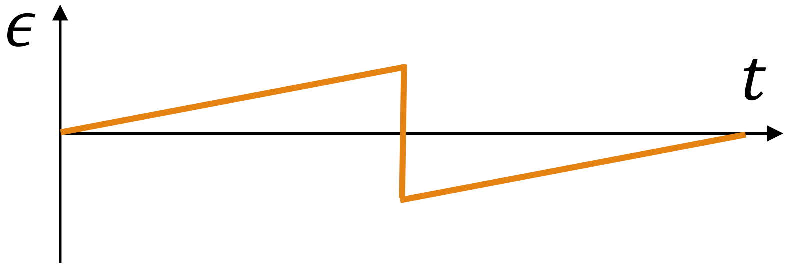
*[G. D. Mahan and L. O. Sofo, PNAS **93**, 7436 (1996).]*

[D. Prete, P.A. Erdman, V. Demontis, L. Sorba, V. Zannier, D. Ercolani, F. Beltram, F. Rossella, F. Taddei, and S. Roddaro, Nano Lett. 19, 3033 (2019)]

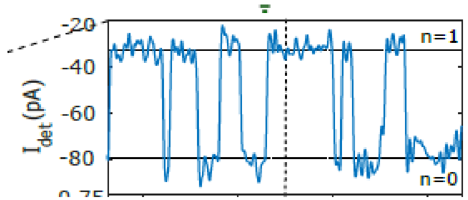
P3: "Optimal probabilistic work extraction beyond the free energy difference with a single-electron device"

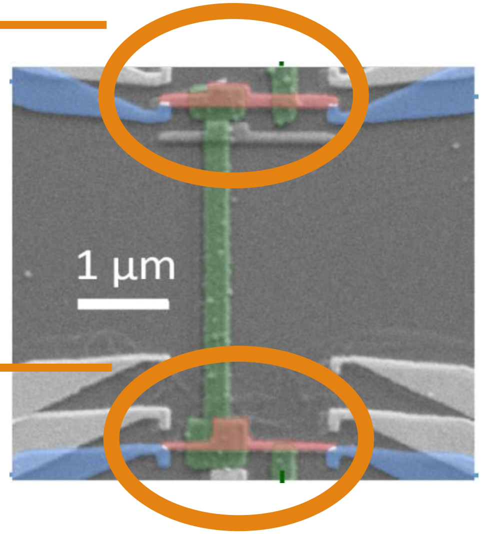
- Second law: $\langle W \rangle < 0$ (closed cycle).
- Exploiting fluctuations, $W > 0$ is possible.
- What is the optimal driving sequence?
  [V. Cavina, A. Mari, and V. Giovannetti, Sci. Rep. 6, 29282 (2016)]



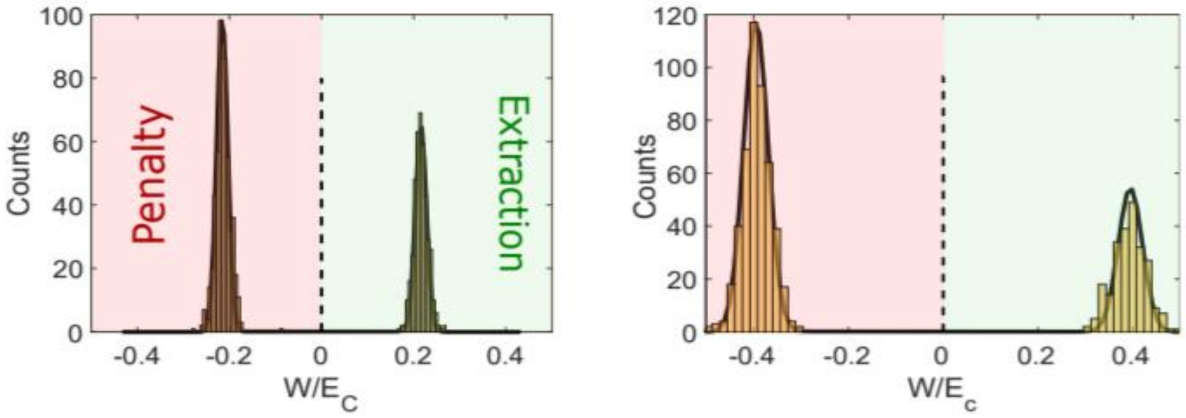


Single-Electron system
2 level system



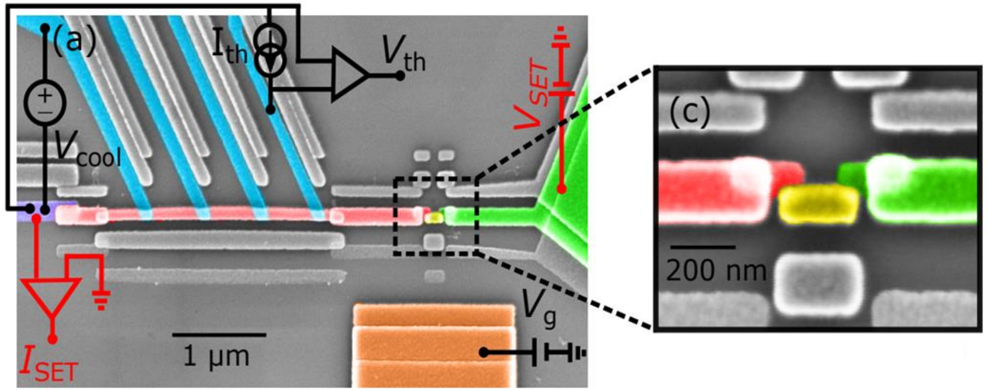


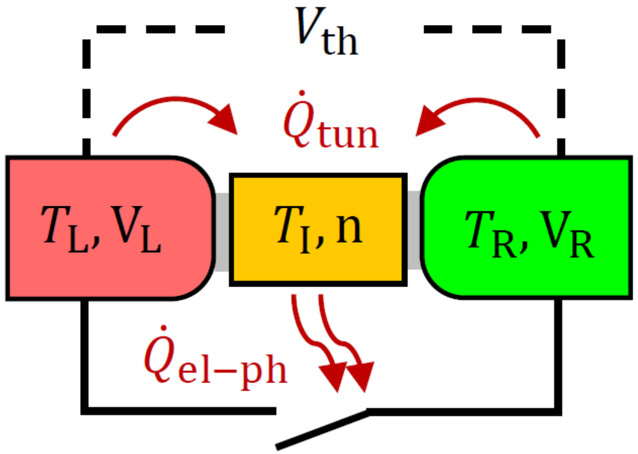
Real-Time Charge Detector:
Measurement of Q

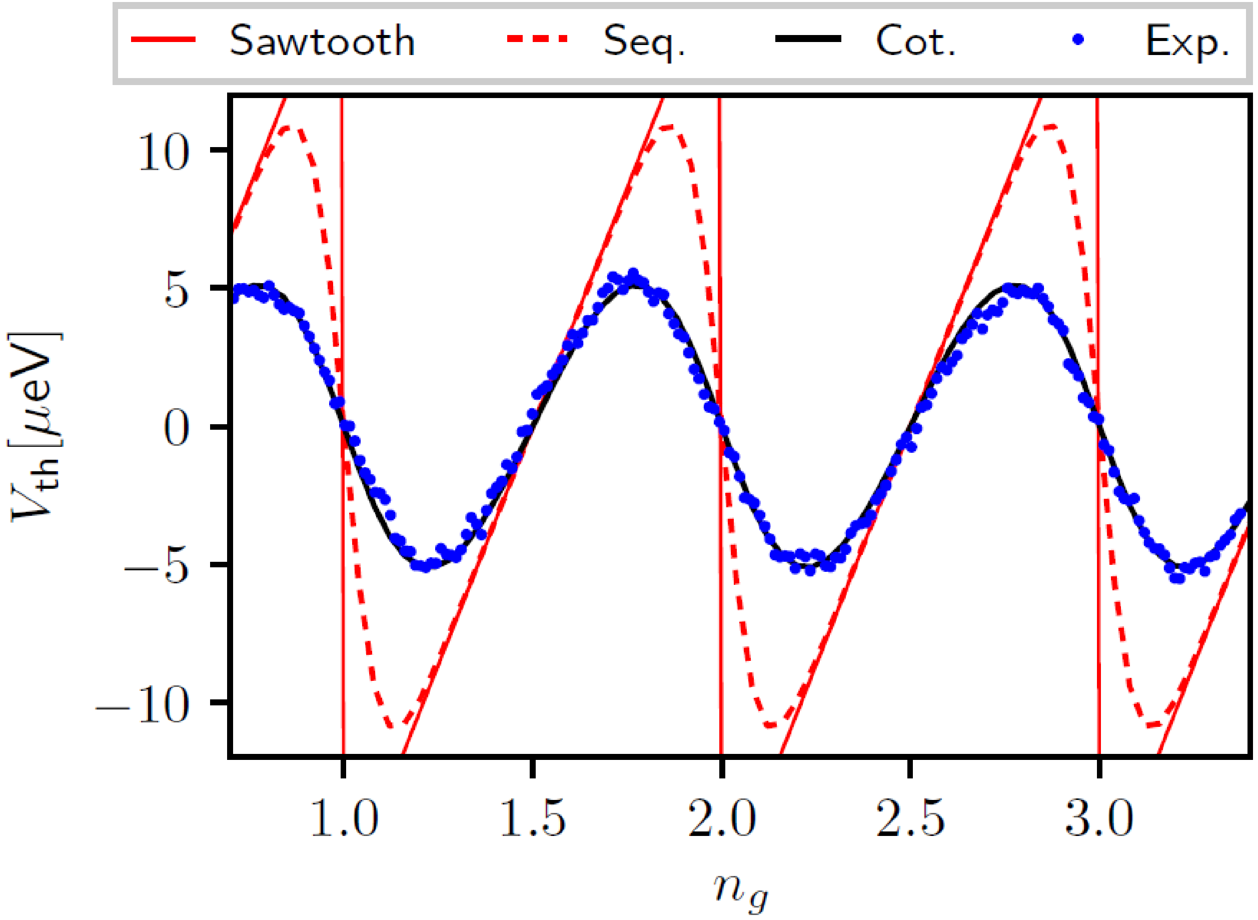


[O. Maillet, P.A. Erdman, V. Cavina, B. Bhandari, E.T. Mannila, J.T. Peltonen, A. Mari, F. Taddei, C. Jarzynski, V. Giovannetti, and J.P. Pekola, Phys. Rev. Lett. 122, 150604 (2019)]

P4: "Non-Linear Thermovoltage in a Single-Electron Transistor"

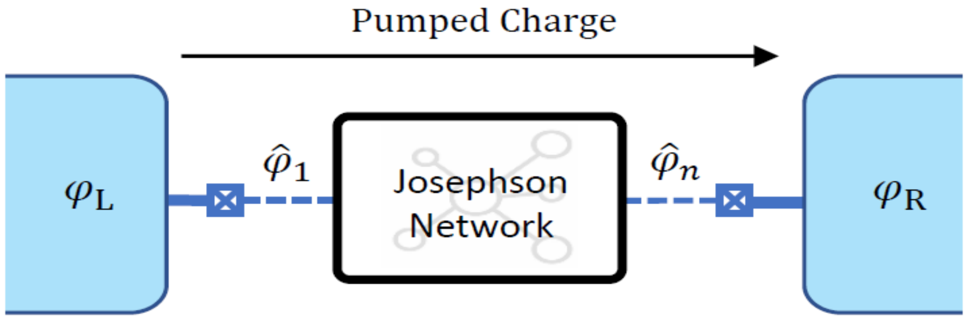


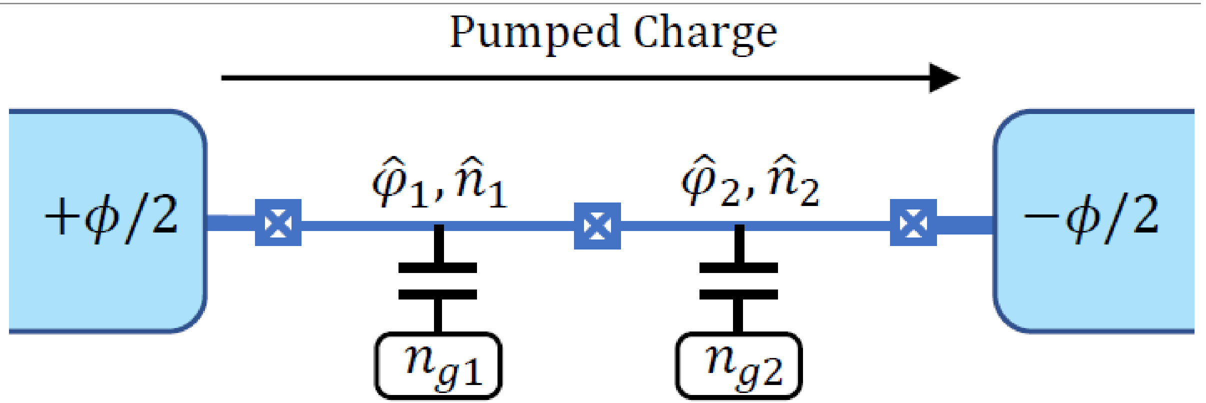




[P.A. Erdman, J.T. Peltonen, B. Bhandari, B. Dutta, H. Courtois, R. Fazio, F. Taddei, and J.P. Pekola, Phys. Rev. B 99, 165405 (2019)]

P5: "A Fast and Accurate Cooper Pair Pump"



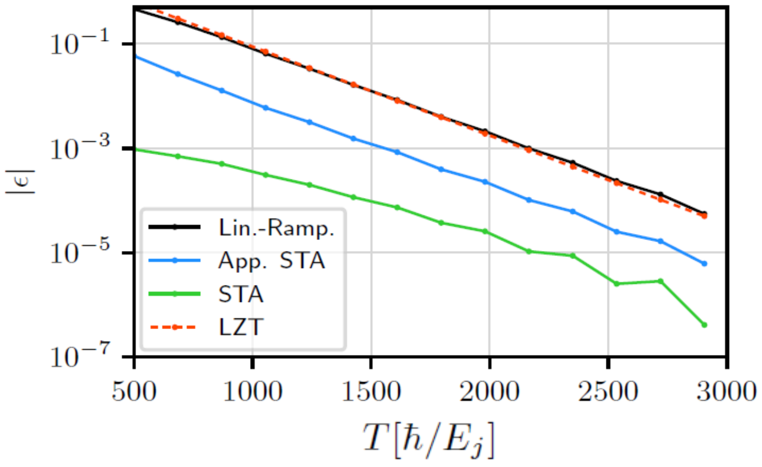


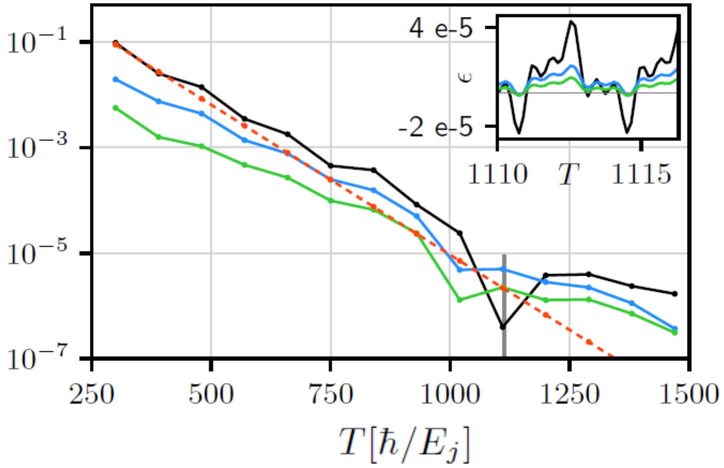
- Charge Pumping: $I = (ne)\,f$.
- Metrological applications: low errors.

We evaluate the error due to the difficulty of implementing optimal control

Error Sources:

- Pumped charge not quantized (error $\sim E_j/E_C$)
- Finite-time effects (Landau-Zener Transitions)



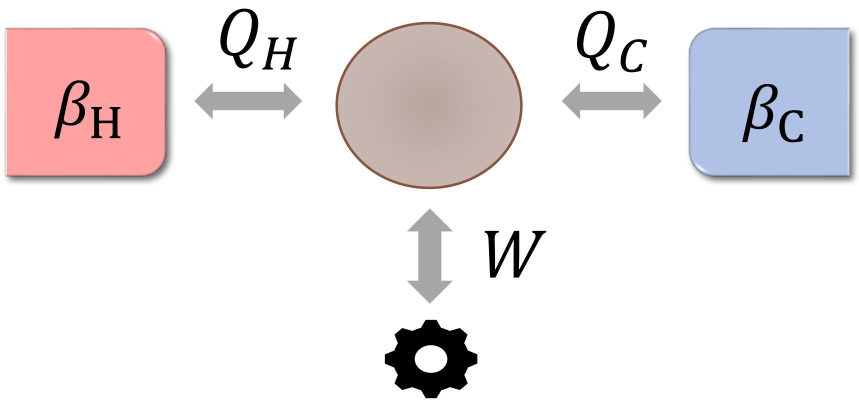


We present fast and accurate pump using:

- *Topological properties* (phase averaging)
- *Optimal control* (shortcuts to adiabaticity)

[P. A. Erdman, F. Taddei, J. T. Peltonen, R. Fazio and J. P. Pekola, arXiv:1909.13627]

P6: "Heat Engines in the Fast Driving Regime: Optimality of Sudden Quenches"



Arbitrary periodic protocol: $\vec{\lambda}(t) = \vec{\lambda}(t+T), \quad \hat{\rho}(t) = \hat{\rho}(t+T)$

Fast Driving Regime: $T \ll \Gamma^{-1}$ → $\hat{\rho}(t) \approx \hat{\rho}_0$

Master Equation written as: $\frac{d\vec{p}(t)}{dt} = -\Gamma \cdot \left[\vec{p}_0 - \vec{p}_{eq}\left(\vec{\lambda}(t)\right)\right]$

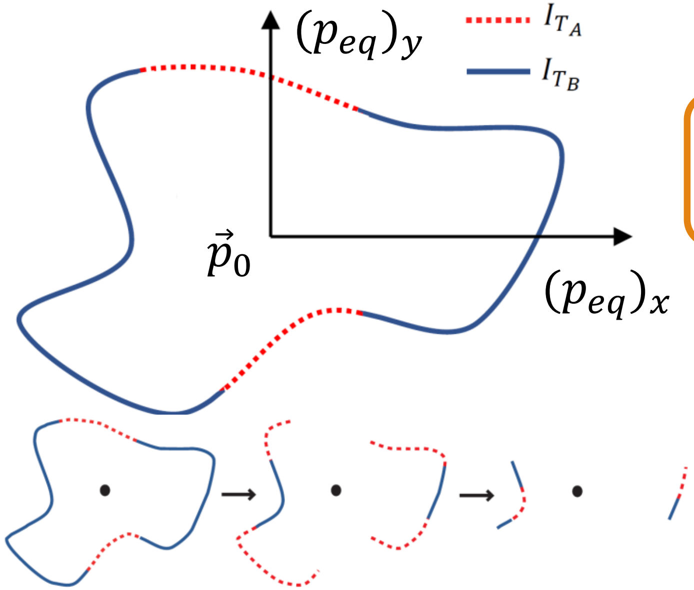
How to Maximize the *Power* using an arbitrary system?

System Hamiltonian:

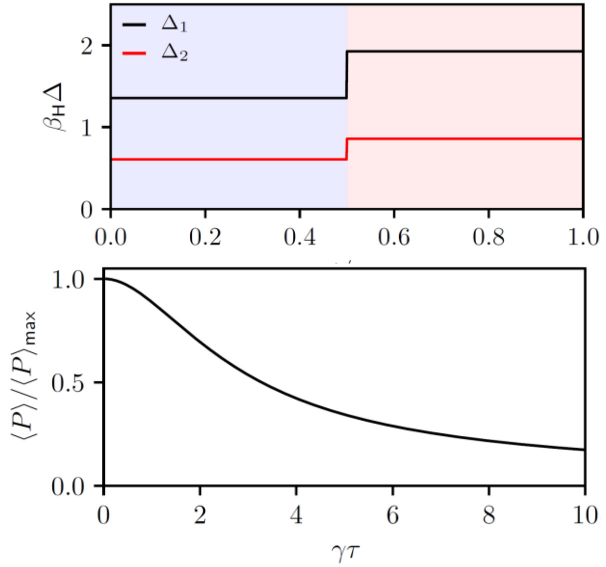
$$\hat{H}\left(\vec{\lambda}(t)\right)$$

Lindblad Master Equation:

$$\frac{d\hat{\rho}}{dt} = -i\left[\hat{H}, \hat{\rho}\right] + D_{\mathrm{H}}[\hat{\rho}] + D_{\mathrm{C}}[\hat{\rho}]$$



Sudden Jumps



[V. Cavina, P. A. Erdman, L. Tolomeo, F. Taddei, and V. Giovannetti, *work in progress*]