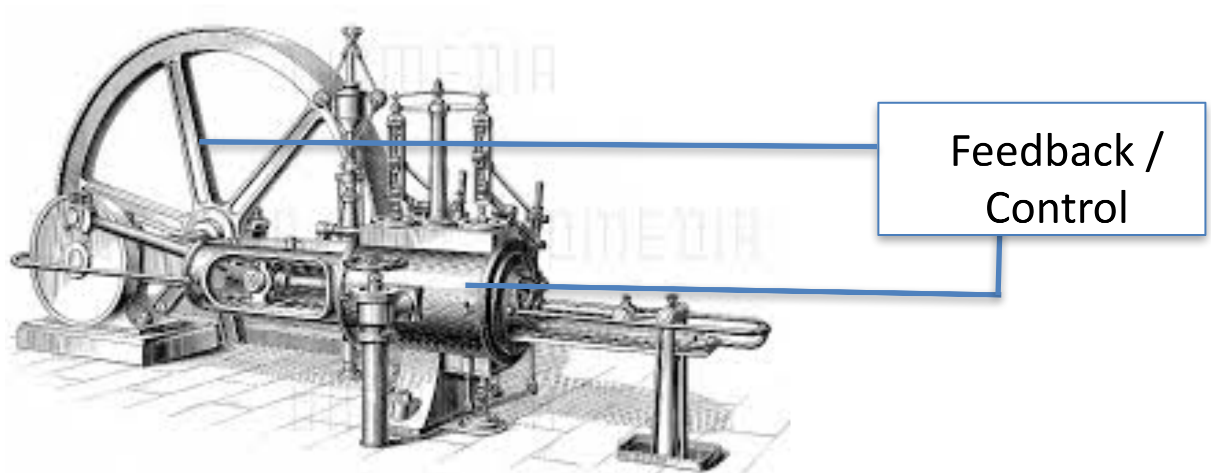
Information
in mesoscopic quantum thermal machines

Géraldine Haack

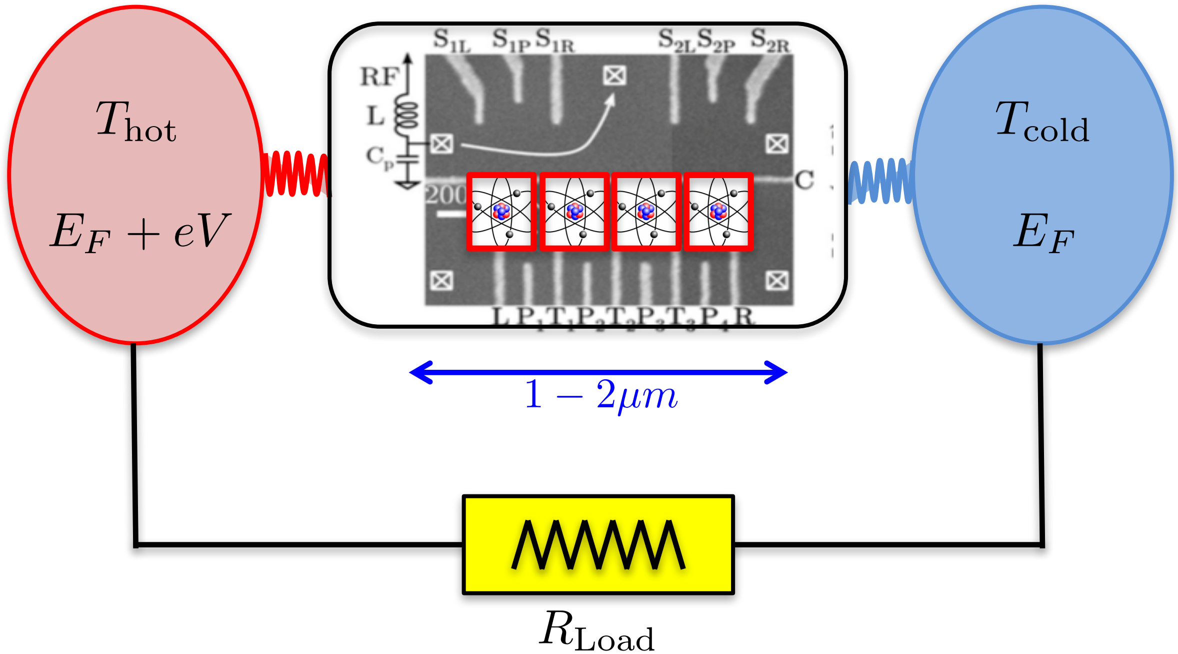
FNS Prima fellow, University of Geneva



Quantum Thermodynamics Conference

Espoo, 27.06.2019

What is a mesoscopic quantum thermal machine?



(Classical) outputs : Power (heat engine), cooling ratio (fridge)

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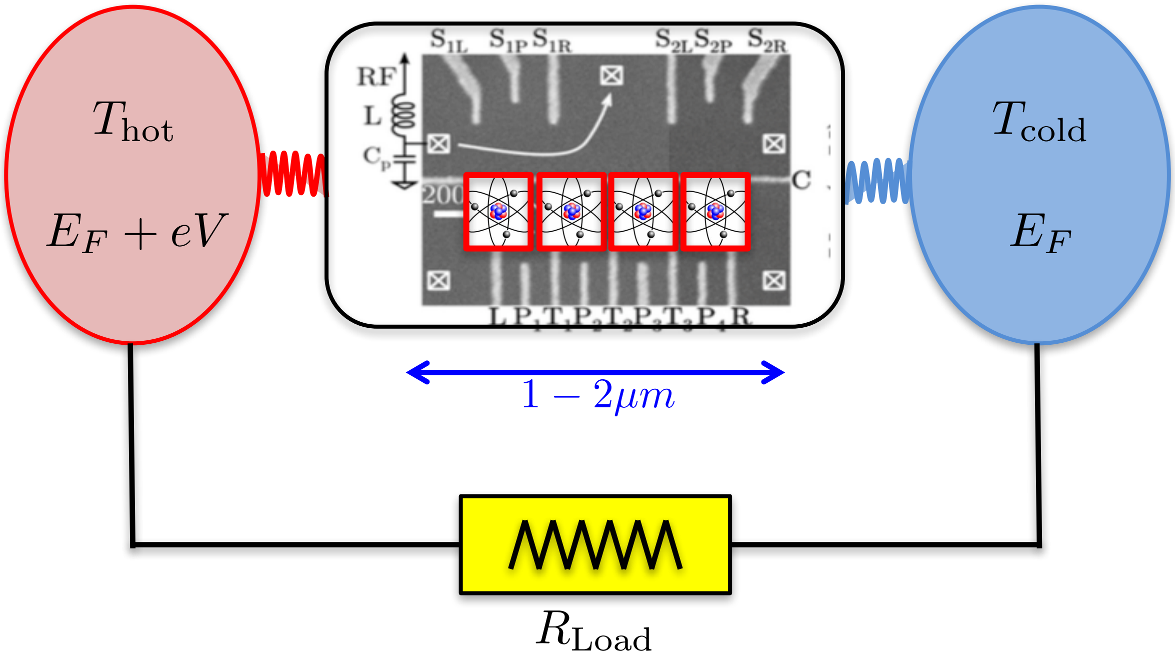
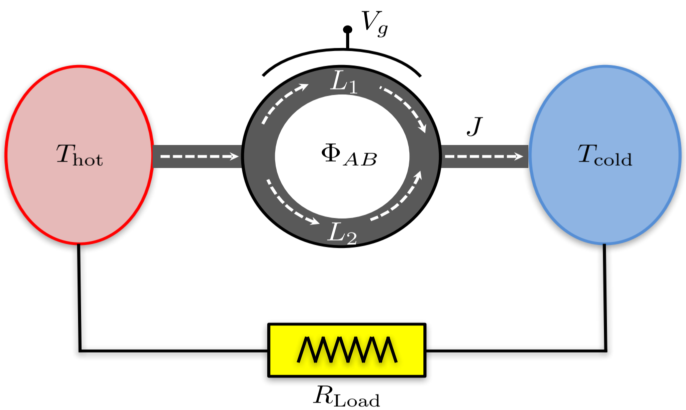


(Classical) outputs : Power (heat engine), cooling ratio (fridge)

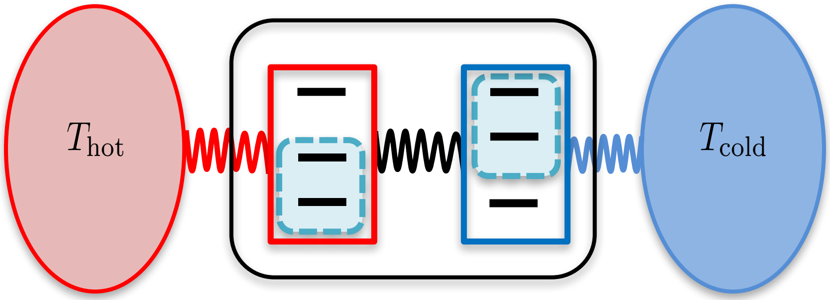
- Take advantage of quantum properties to enhance efficiency
- Fundamental bounds set by QM? -> see Fabien Clivaz' talk
- Generate quantum resources for QIP : no classical counterpart

Information in mesoscopic quantum thermal machines



Aharonov-Bohm heat engine

Classical information is detrimental



Entanglement engines

Quantum information is the output

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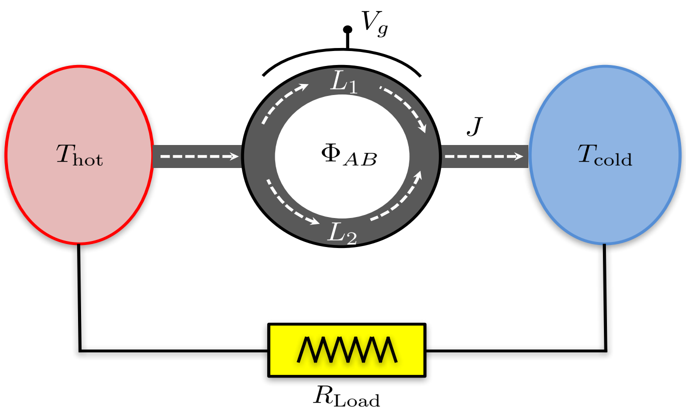
Information in mesoscopic quantum thermal machines



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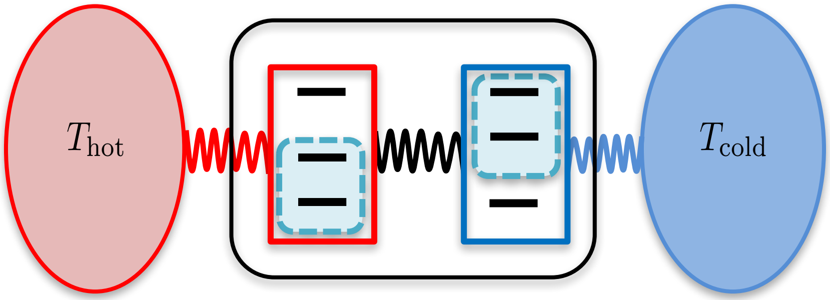


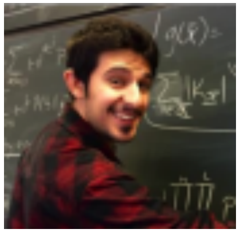
Entanglement engines

Quantum information is the output

Francesco Giazotto
(CNR Pisa)

Jonatan B. Brask
(DTU, Denmark)

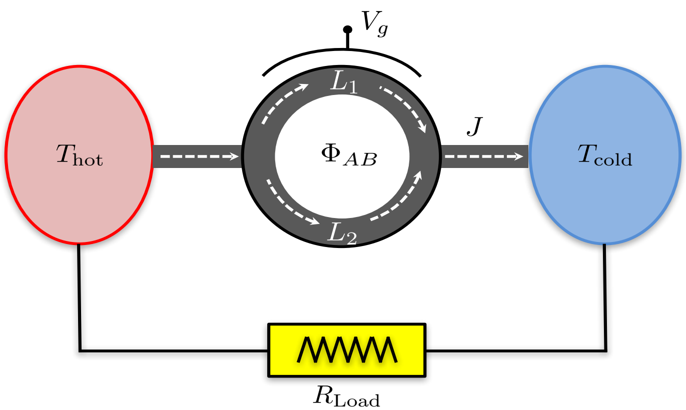
Nicolas Brunner
(Uni Geneva)



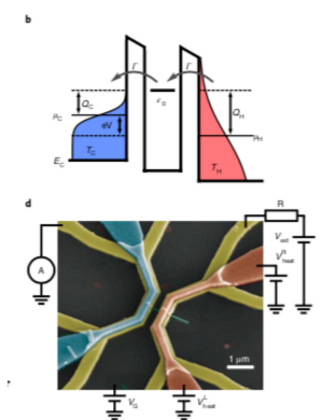
Armin Tavakoli
(Uni Geneva)

Marcus Huber
(IQOQI Vienna)

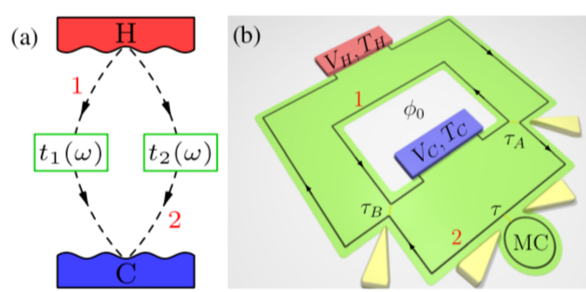
Part 1: Aharonov-Bohm quantum heat engine



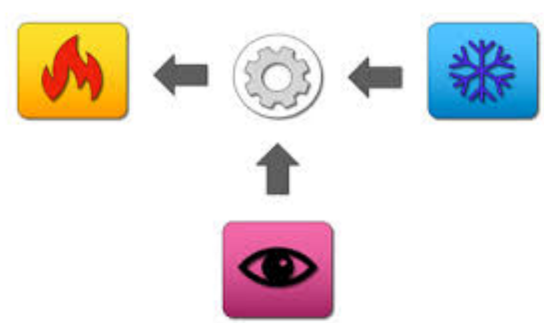
Some examples



Josefsson et al., Nat. Nano. 13 (2018)



Samuelsson et al., PRL 118 (2017)



Elouard, Jordan, PRL 120 (2018)
Buffoni et al., PRL 122 (2019)

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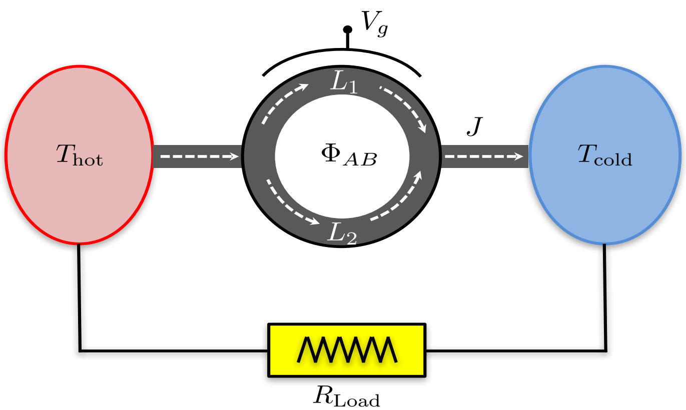


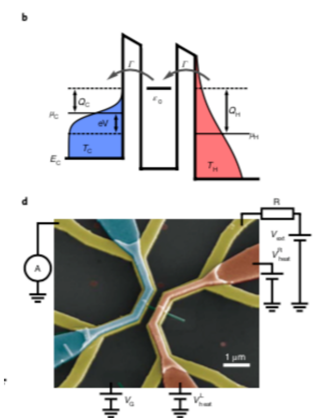
Efficient and highly tunable

Phase-coherent mesoscopic engine

Promising towards experiments

arXiv:1905.12672

Some examples



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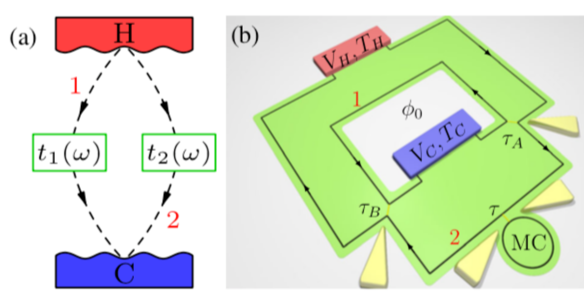
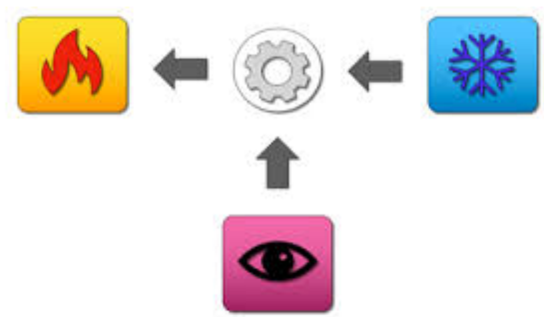


Samuelsson et al., PRL 118 (2017)



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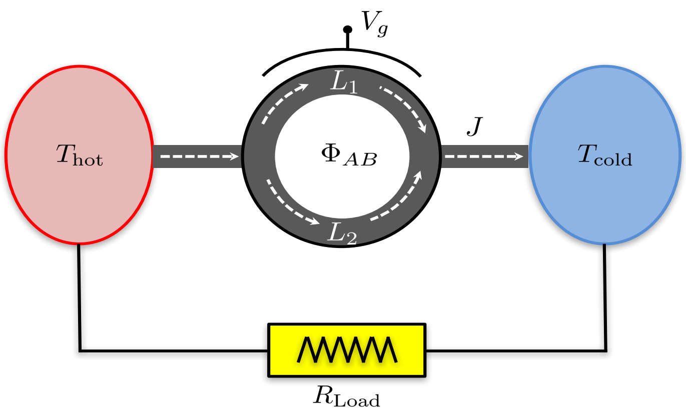


- Linear response regime, Landauer-Büttiker approach
- Transmission probability

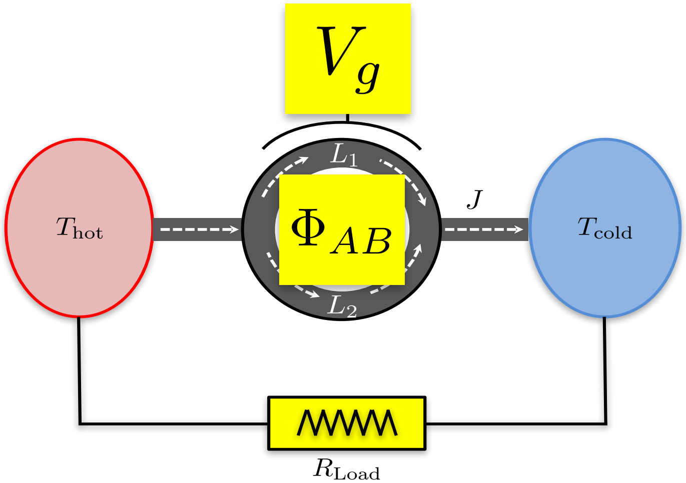
$$\begin{pmatrix} I \\ J \end{pmatrix} = \begin{pmatrix} G & L \\ M & K \end{pmatrix} \begin{pmatrix} \Delta V \\ \Delta T \end{pmatrix}$$

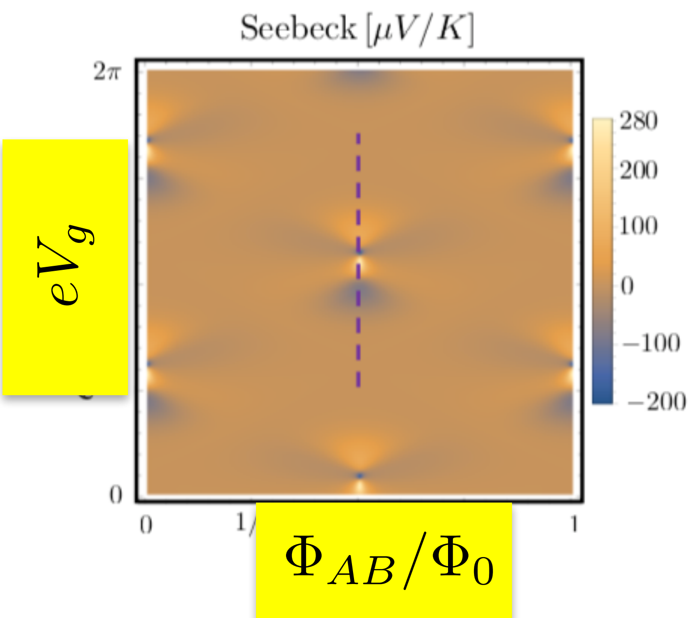
With thermopower $S = \left.\frac{\Delta V}{\Delta T}\right|_{I=0} = -\frac{L}{G}$

$$L = \frac{2e}{hT} \int_{-\infty}^{\infty} dE\,(E-\mu)\,T_{AB}(E) \left(-\frac{\partial f}{\partial E}\right)$$

Haack, Giazotto, arXiv:1905.12672

Part 1: Aharonov-Bohm quantum heat engine





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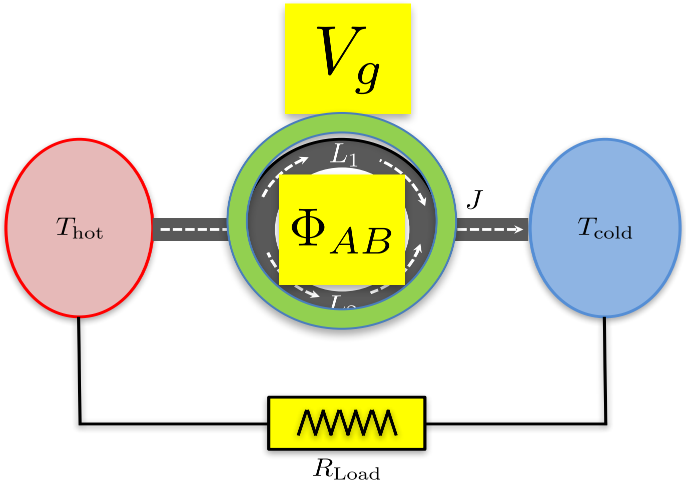
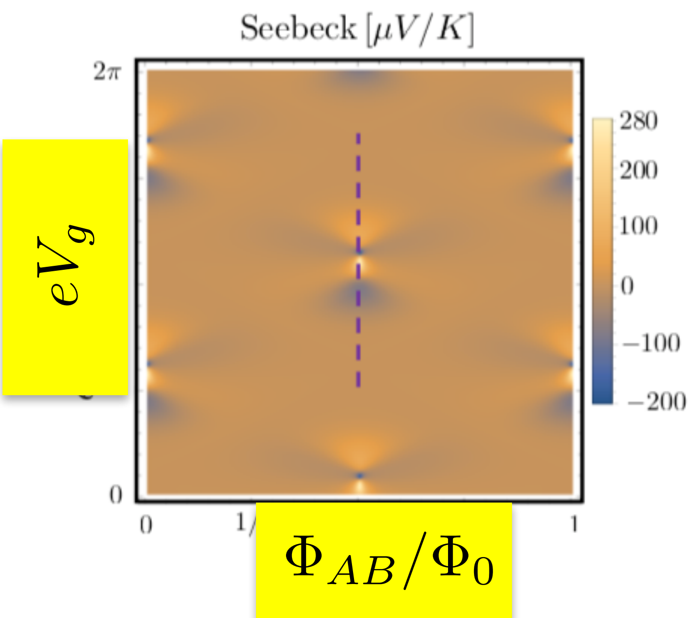


$$ZT = GS^2T/\kappa_{th}$$



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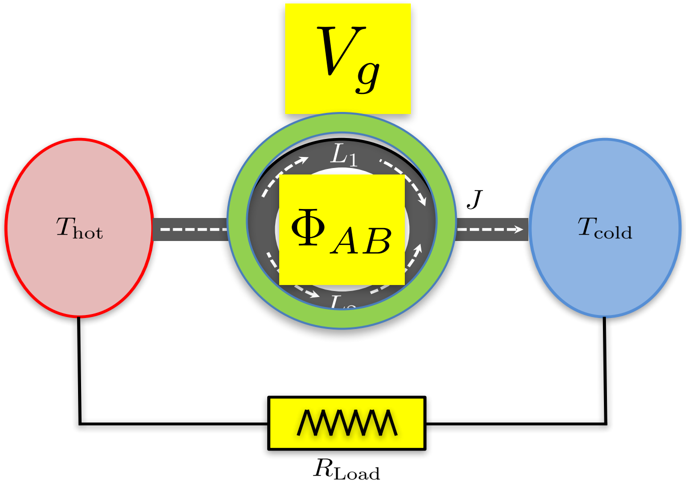

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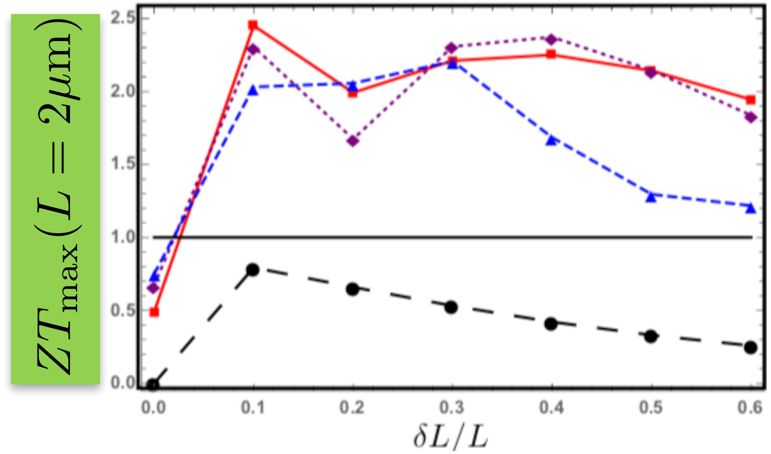
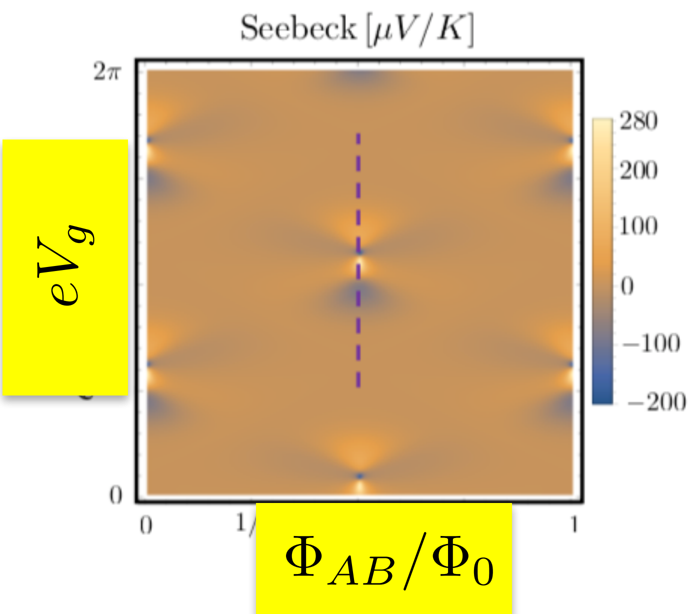
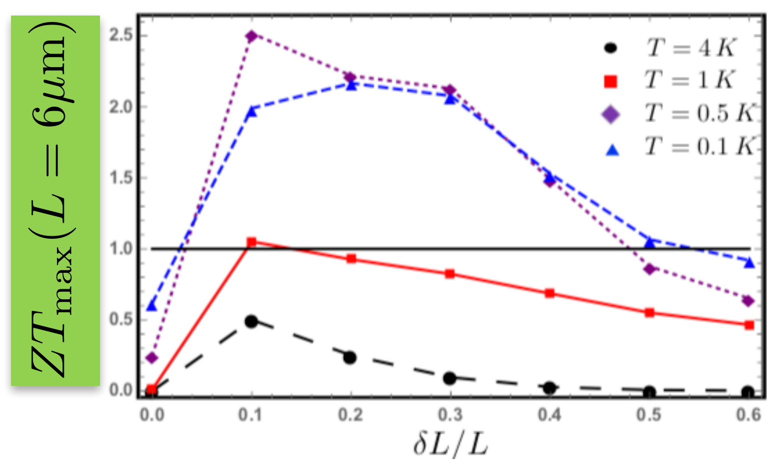


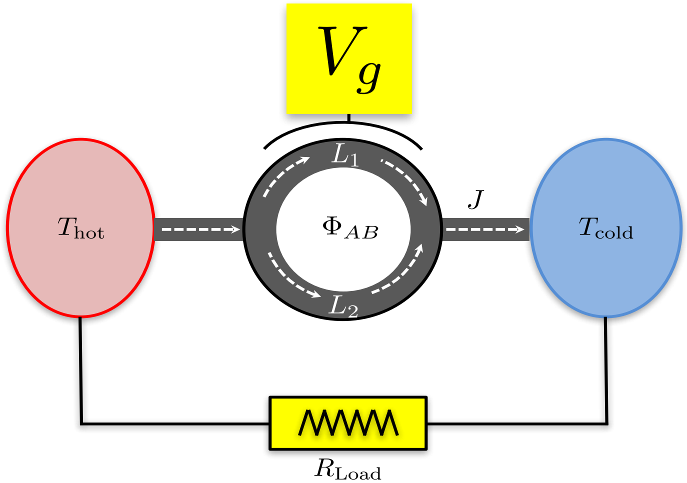




Thermoelectric properties: ZT coeff > 1

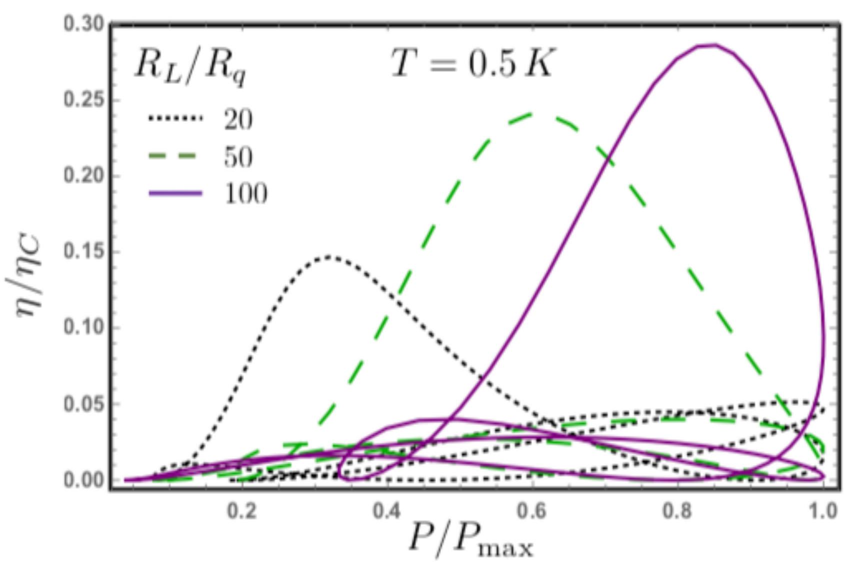
Haack, Giazotto, arXiv:1905.12672

Two-terminal engine close to optimal efficiency



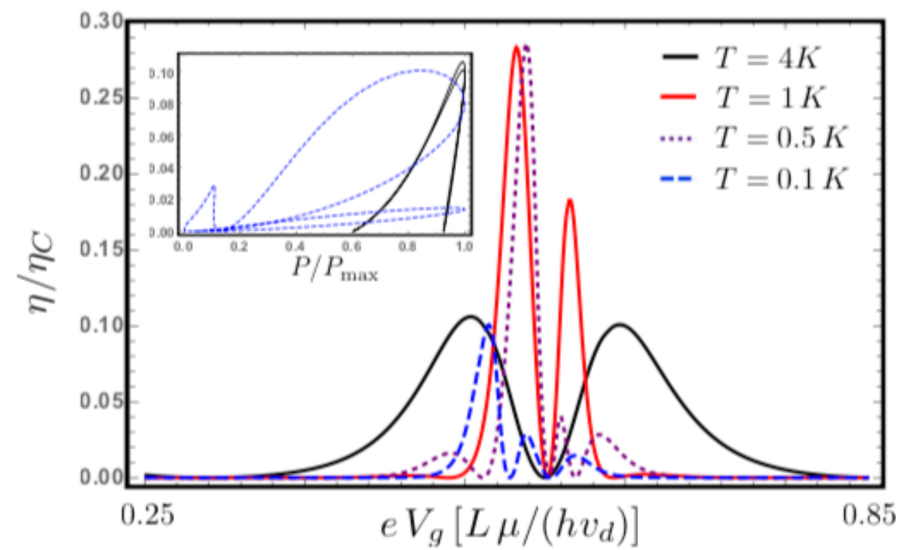
Emblematic phase-coherent mesoscopic device

Promising for experiments



$\eta_{\mathrm{max}} \neq \eta(P_{\mathrm{max}})$

Whitney, PRL 112 (2014)



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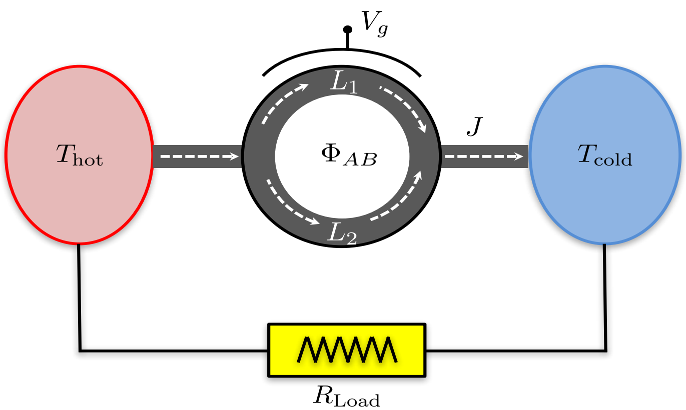

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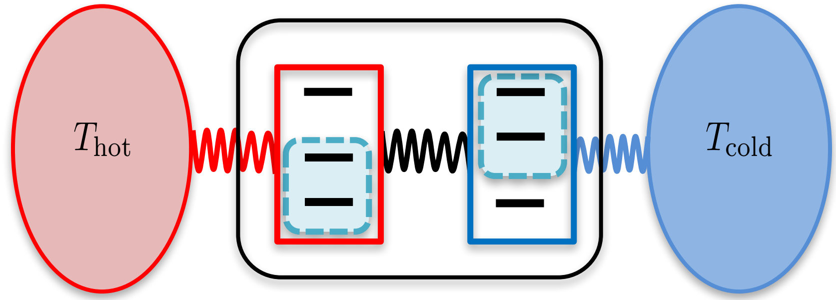

Entanglement engines

Quantum information is the output

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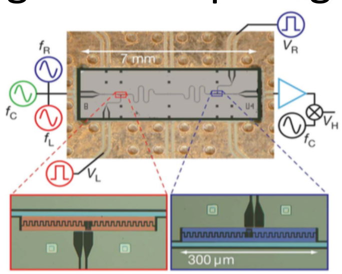
- Generate quantum resources for QIP : no classical counterpart

Part II: Entanglement engines

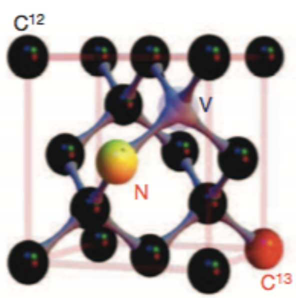
How to generate quantum correlations?

Controlled unitary processes

Logical two-qubit gates



DiCarlo et al., Nature 460 (2009)

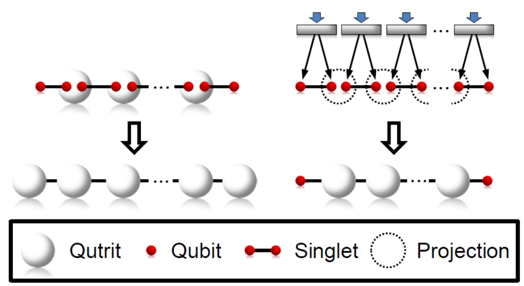


Zu et al., Nature 514 (2014)

Dissipation is detrimental

Equilibrium systems

Cooling to the ground state

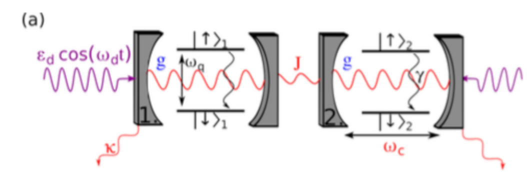


Kaltenbaek et al., Nat. Phys. 6 (2010)

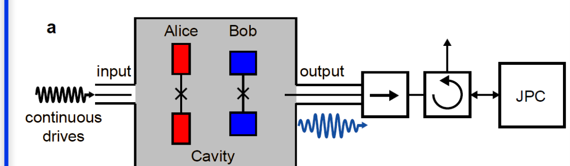
Complex Hamiltonians

Quantum engineering

Bath & coupling engineering



Aron et al., PRA 90 (2014)



Lin et al., Nature 504 (2013)
Shankar et al., Nature 504 (2013)

Lots of external control

Can we use thermal machines?

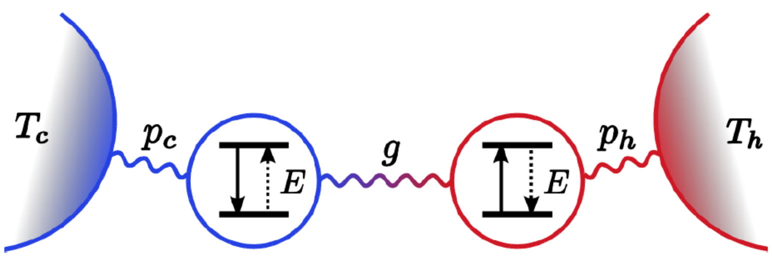
Out-of-equilibrium thermal machines

- Various systems:
  - Atom coupled to cavities driven by incoherent light
  - Qubits subject to noisy channel
  - Mechanical oscillators

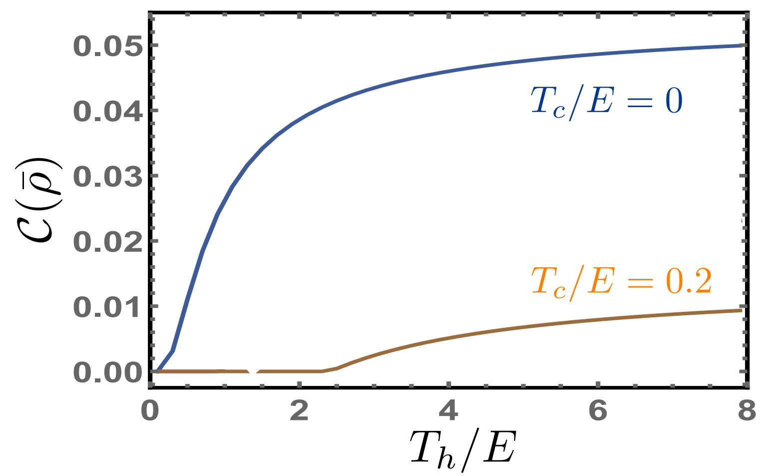
Plenio, Huelga, PRL 88 (2002)
Eisler, Zimboras, PRA 71 (2005)
Hartmann et al., NJP 9 (2007)
Quiroga et al., PRA 75 (2007)
Linden et al., PRL 105 (2010)
Bellomo et a., NJP 15 (2013)
Brunner et al., PRE 89 (2014)
Brask et al., NJP 17 (2015)
Boyanovsky et al., PRA 96 (2017)

- Specific interaction Hamiltonian (Ising-type, XX-type, …)

- Simple model



$$H_{int} = g\,(|01\rangle\langle 10| + h.c.)$$



Brask, Haack, Brunner, Huber, NJP 17 (2015)

Generation of steady-state entanglement
Using only incoherent couplings to thermal baths

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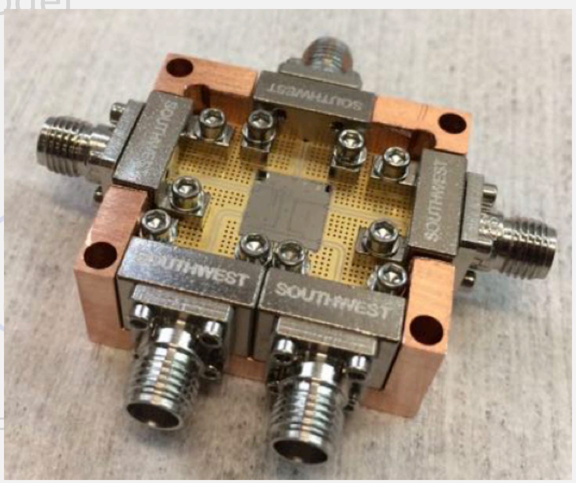
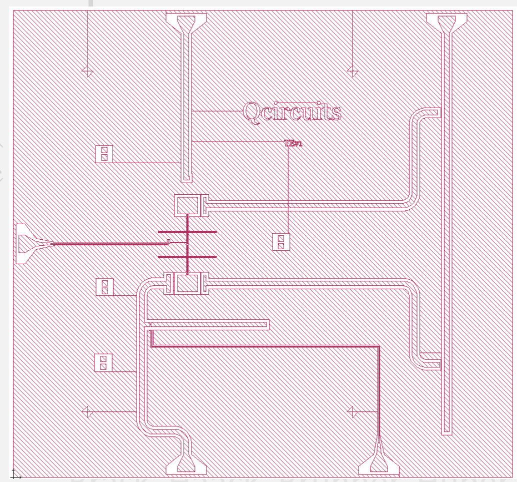
- Simple model

On-going Circuit QED experiment : Group of Benjamin Huard (ENS Lyon)





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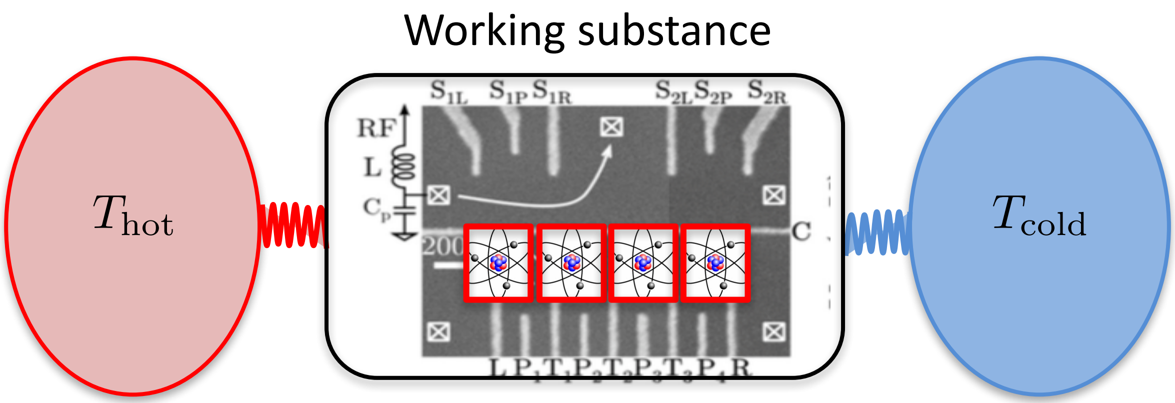
Heralded entanglement engine



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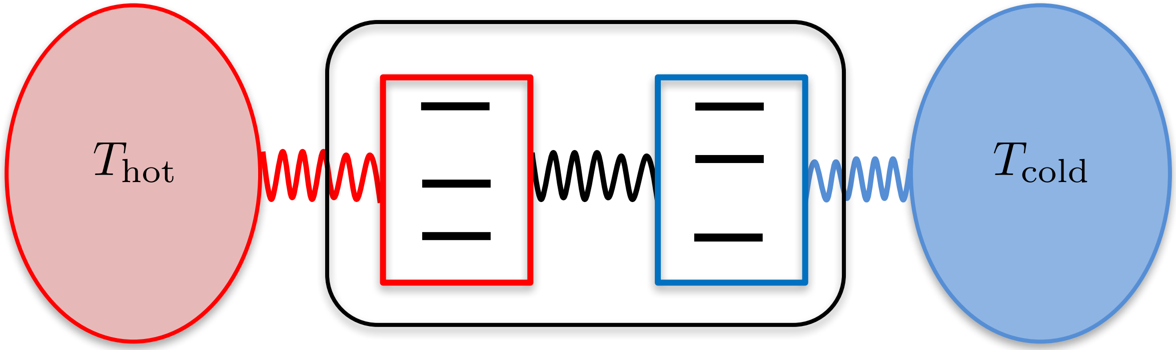

Tavakoli, Haack, Huber, Brunner, Brask, Quantum 2 (2018)

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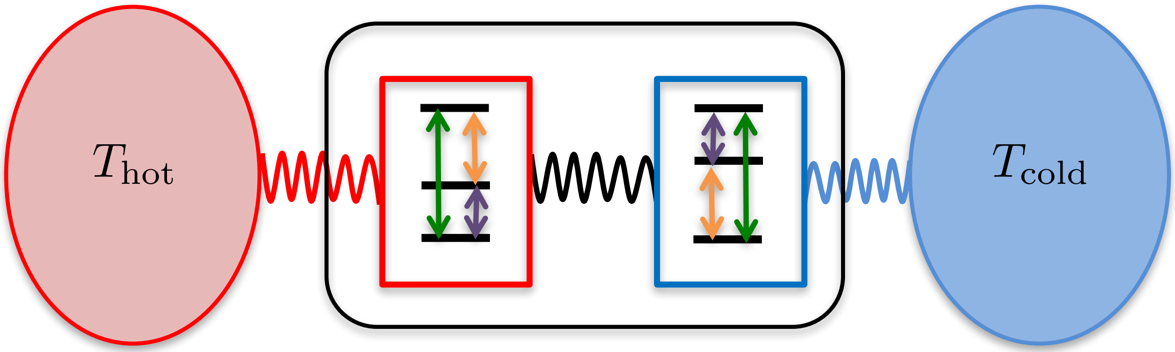

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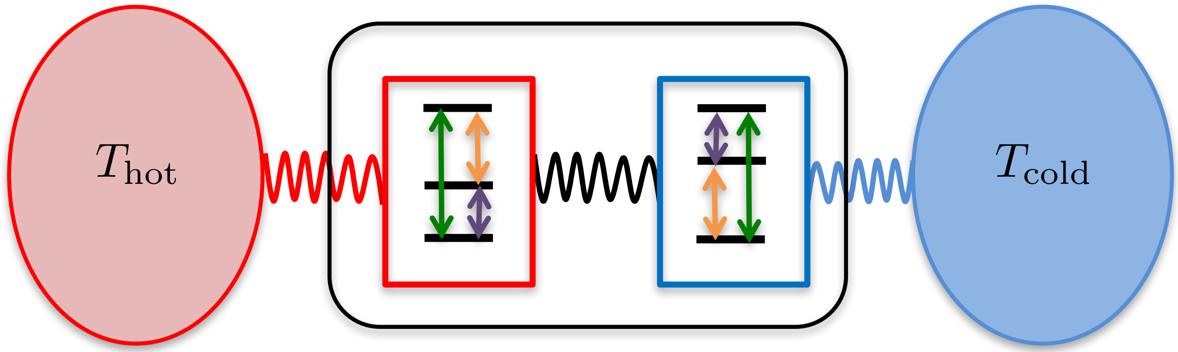

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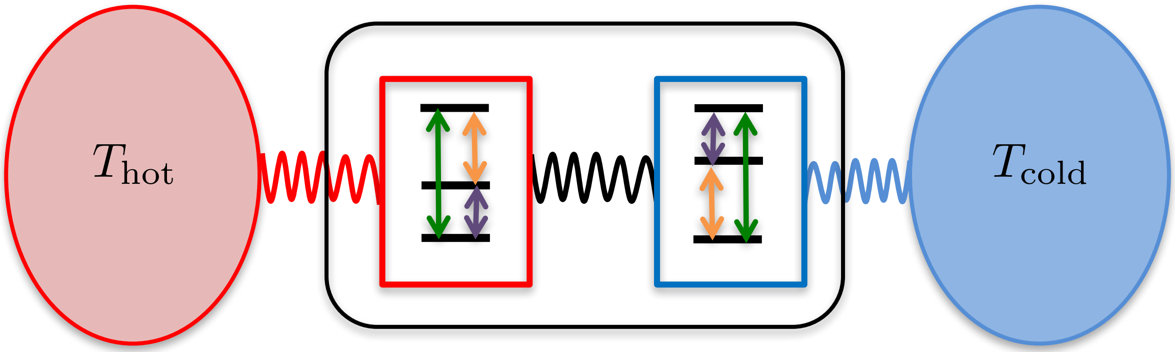
- Dynamics : Reset master equation $\dot{\rho}(t) = -i[H, \rho(t)] + p\left(\tau - \rho(t)\right)$
- Local probabilistic reset: $\rho(t+dt) = -i[H, \rho(t)]dt + p\, dt\, \tau + (1 - p\, dt)\rho(t)$

Thermal state

Heralded entanglement engine



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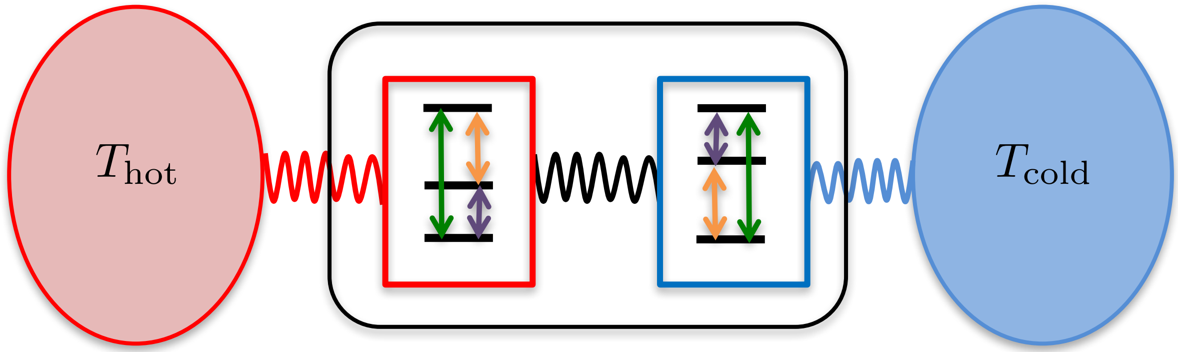
  Thermal state
- Exact mapping with Lindblad-type ME Haack et al., in preparation
- Local vs global ME Hofer et al., NJP 19 (2017)
  Gonzales et al., Open Syst. Inf. Dyn. 24 (2018)
  Mitchison, Plenio, NJP 20 (2018)
  De Chiara et al., NJP 20 (2018)
  Cattaneo et al., arXiv:1906.08893

Heralded entanglement engine



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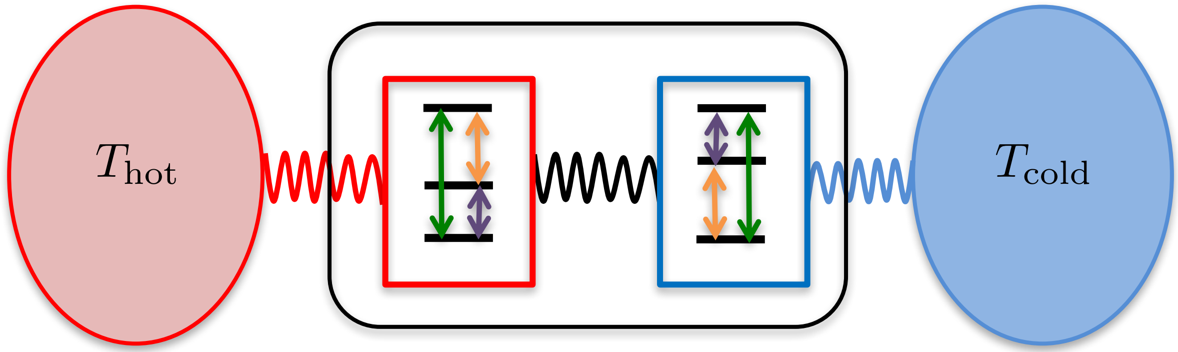
Mitchison, Plenio, NJP 20 (2018)
De Chiara et al., NJP 20 (2018)
Cattaneo et al., arXiv:1906.08893
- Steady-state is weakly entangled

Heralded entanglement engine



Tavakoli, Haack, Huber, Brunner, Brask, Quantum 2 (2018)

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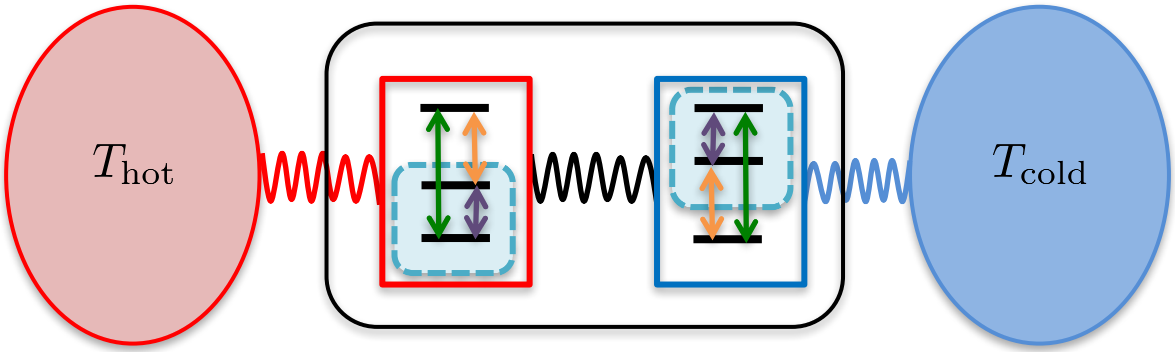

Filtering
Π

Tavakoli, Haack, Huber, Brunner, Brask, Quantum 2 (2018)

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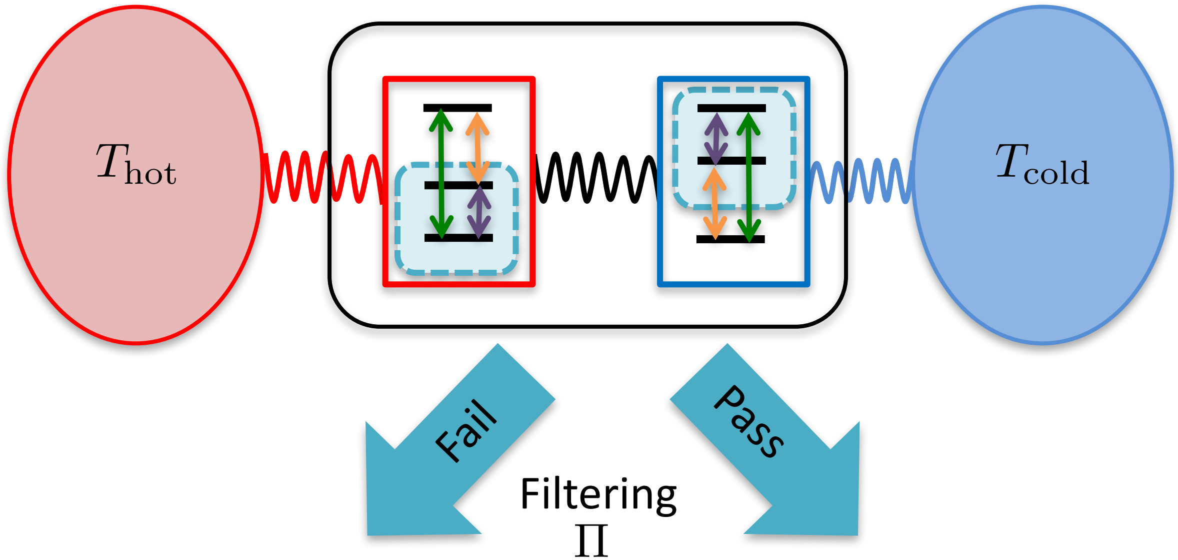

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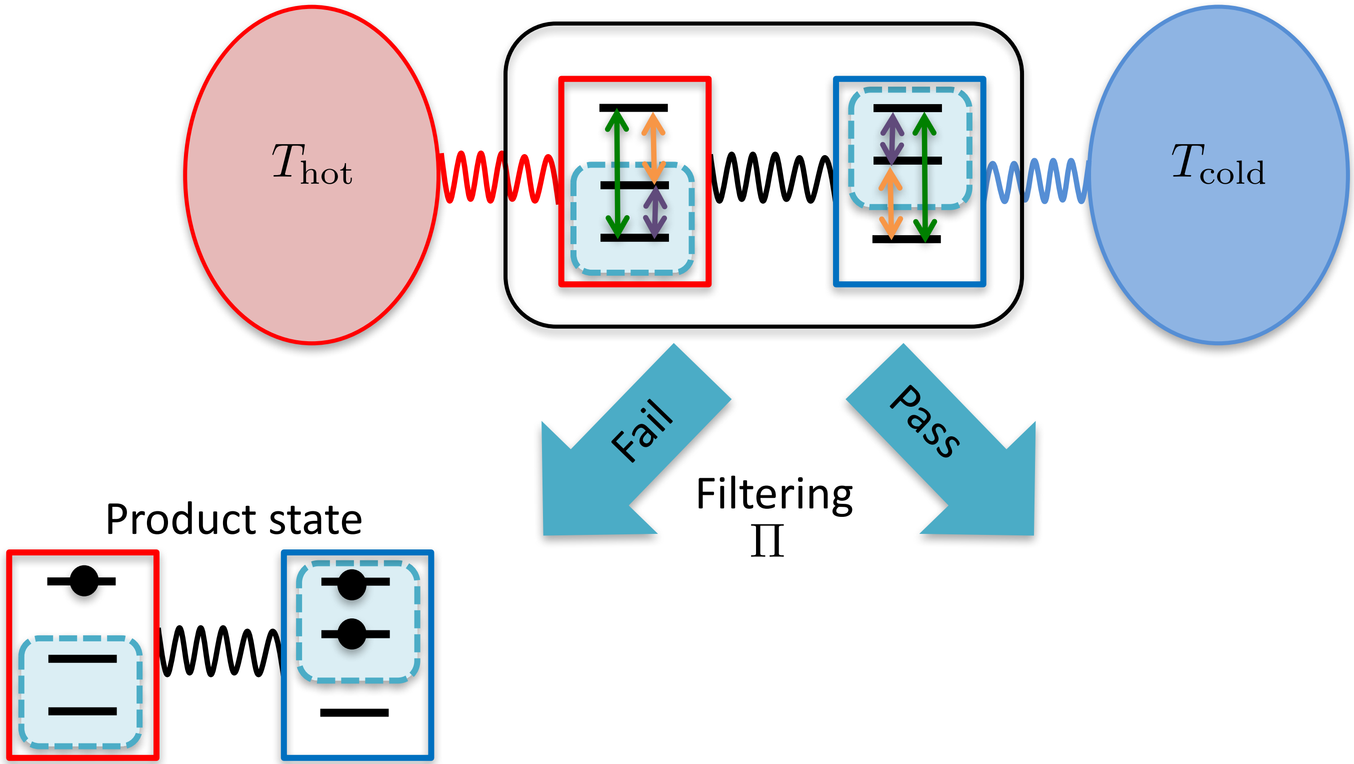

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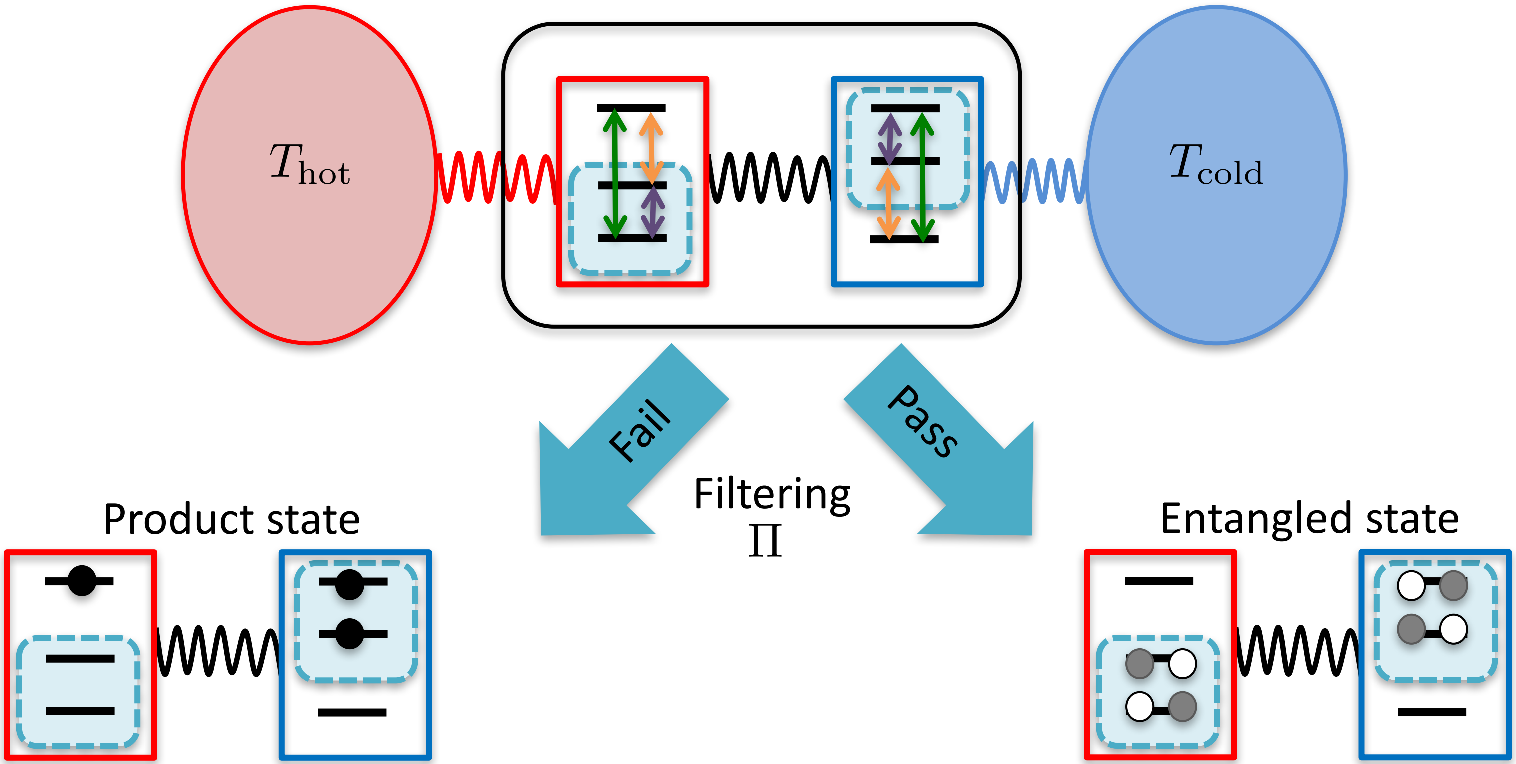

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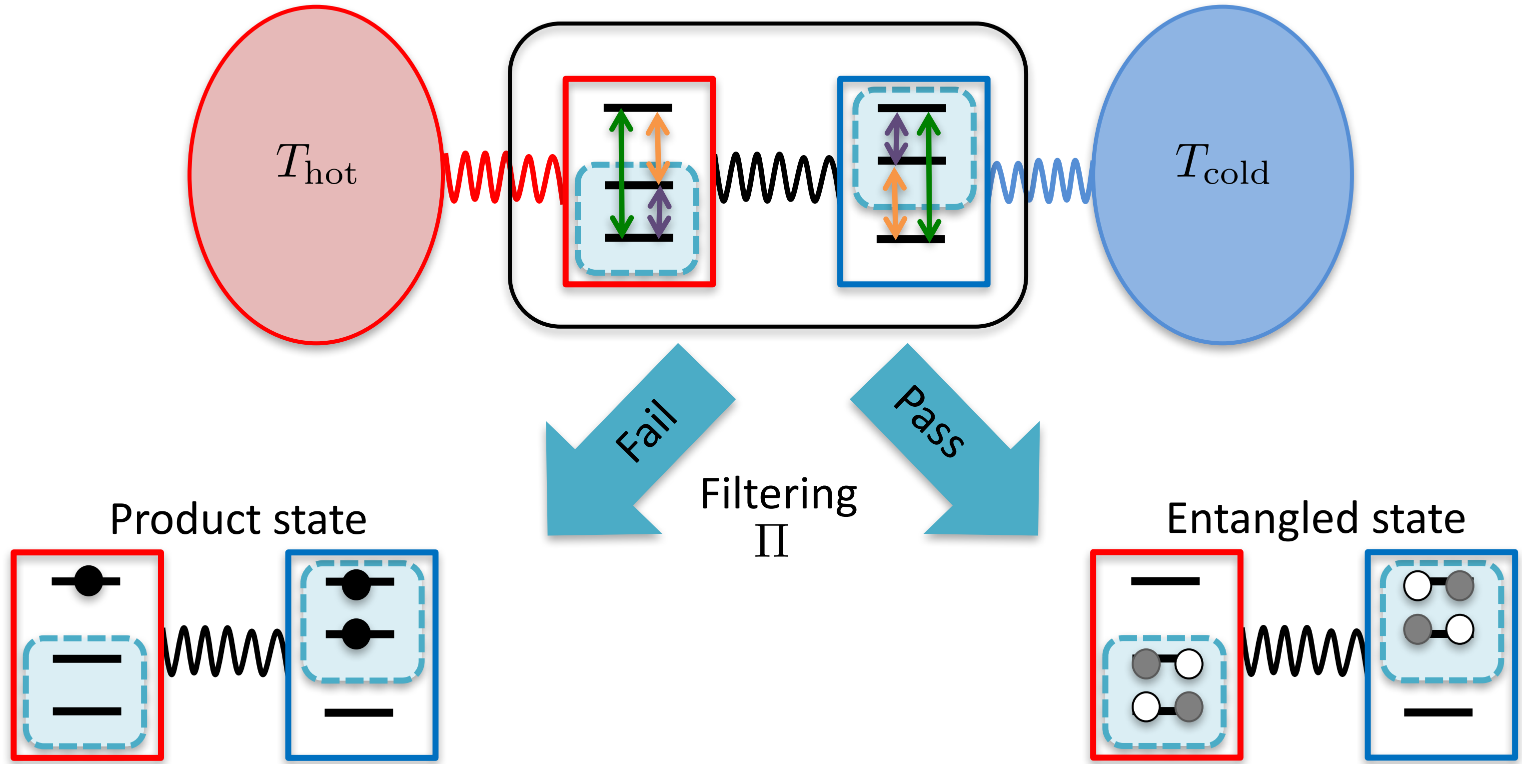
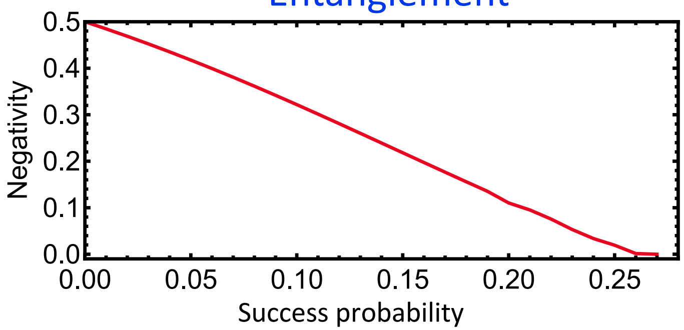
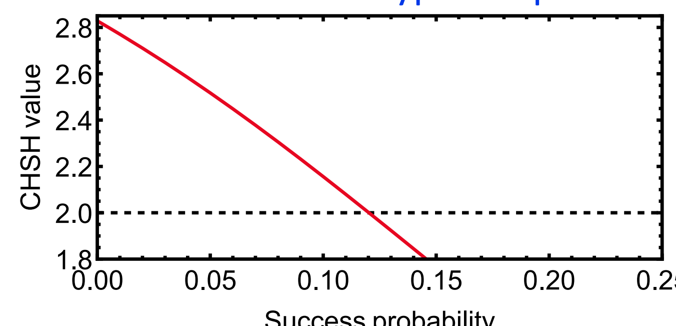


Entanglement



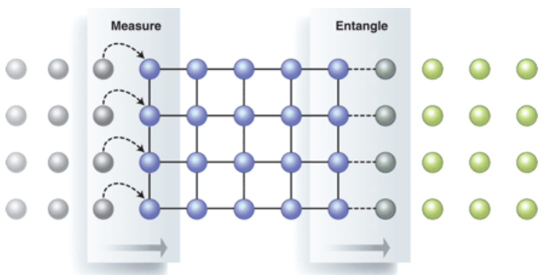
Violation of Bell-type inequalities



Tavakoli, Haack, Huber, Brunner, Brask, Quantum 2 (2018)

Multipartite entanglement?

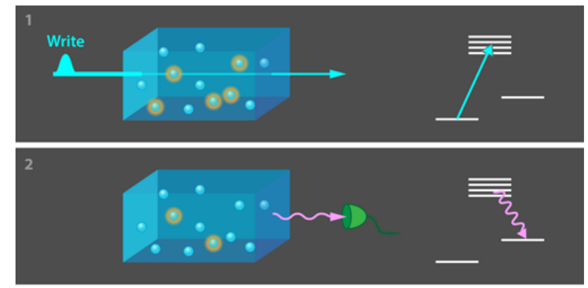
Cluster states



O'Brien, Science 318 (2007)

Quantum Computing

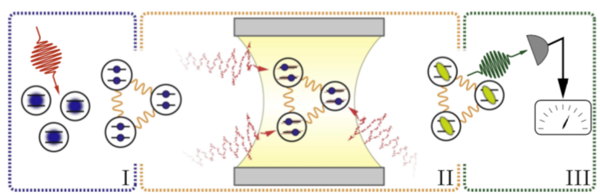
Dicke states / W-states



Nunn, Physics 10 (2017)

Quantum repeaters

GHZ states

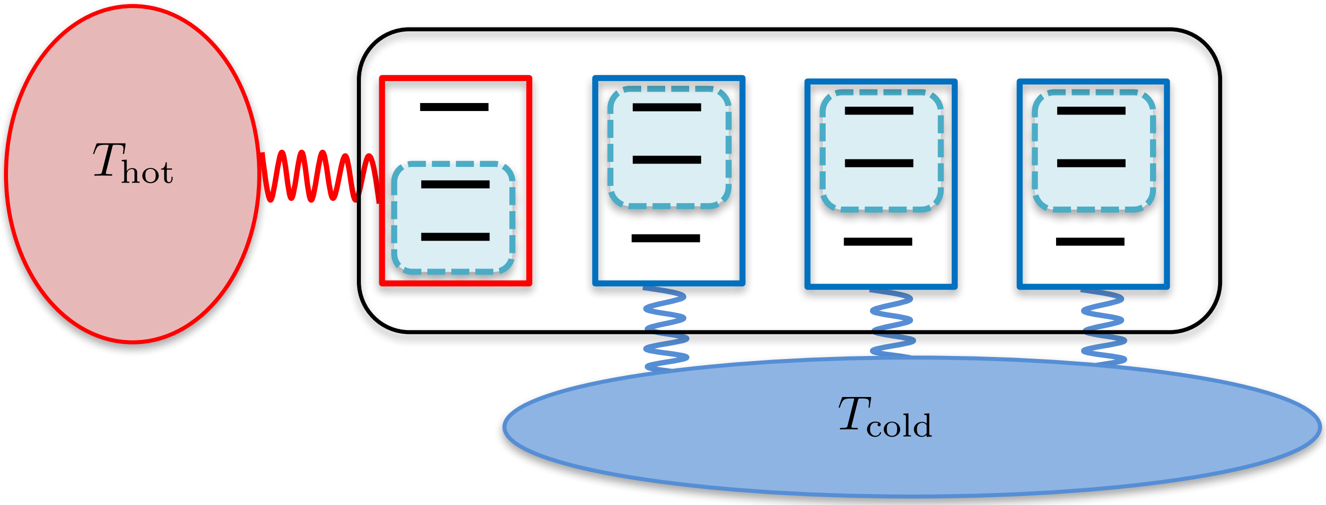


Haase *et al.*, NJP 20 (2018)

Quantum metrology

Which quantum states can be generated via an autonomous thermal machine?

Generalize to multipartite entanglement



Tavakoli, Haack, Brunner, Brask, arXiv:1906.00022

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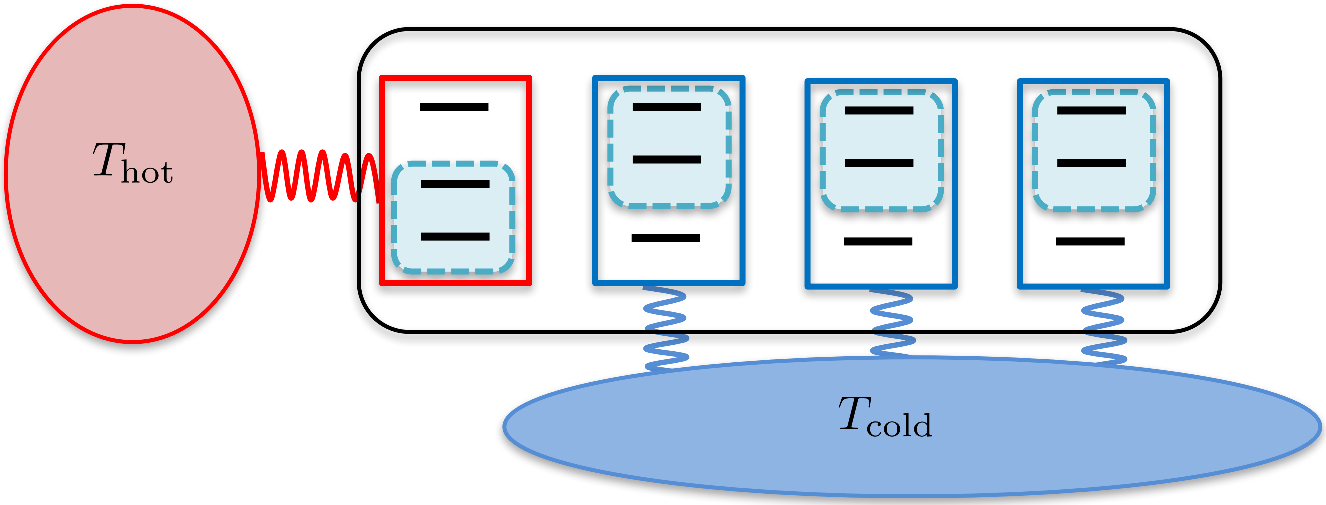
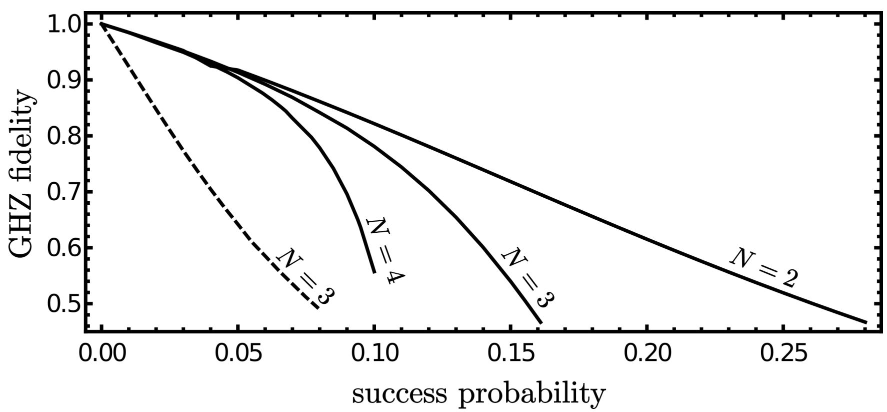
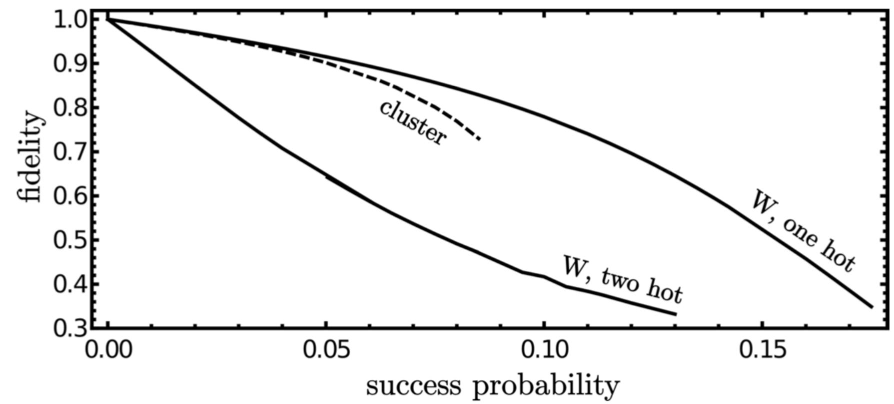


For a GHZ state



For cluster and W-states



Tavakoli, Haack, Brunner, Brask, arXiv:1906.00022

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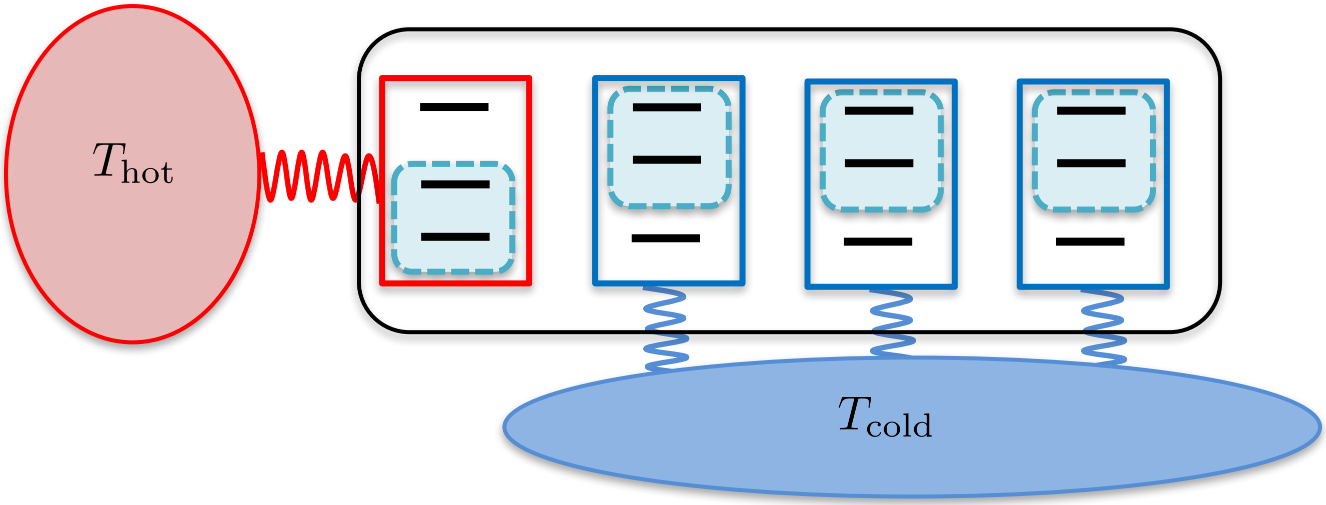

- Target state $|\Psi\rangle$
- $H_{\rm free} = \sum_{k=1}^{N} \left(\sum_{l=1}^{2} \Delta_k^{(l)} |l\rangle_k \langle l| \right)$
- Discarded state for qutrit k : R_k
- $|R\rangle = |R_1, R_2, \ldots, R_k\rangle$
- $H_{int} = g\big(|R\rangle\langle\bar{\Psi}| + h.c.\big)$

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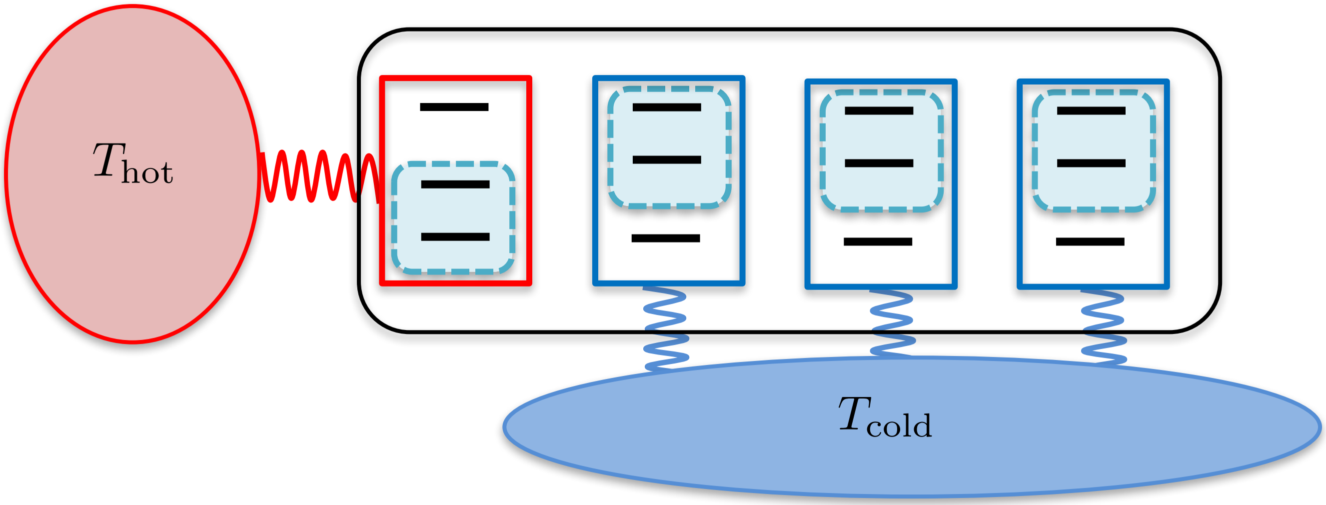

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Which target admits an entanglement engine?

$$[H_s, H_{int}] = 0$$

To be determined: $|R\rangle, \Delta_k$

Tavakoli, Haack, Brunner, Brask, arXiv:1906.00022

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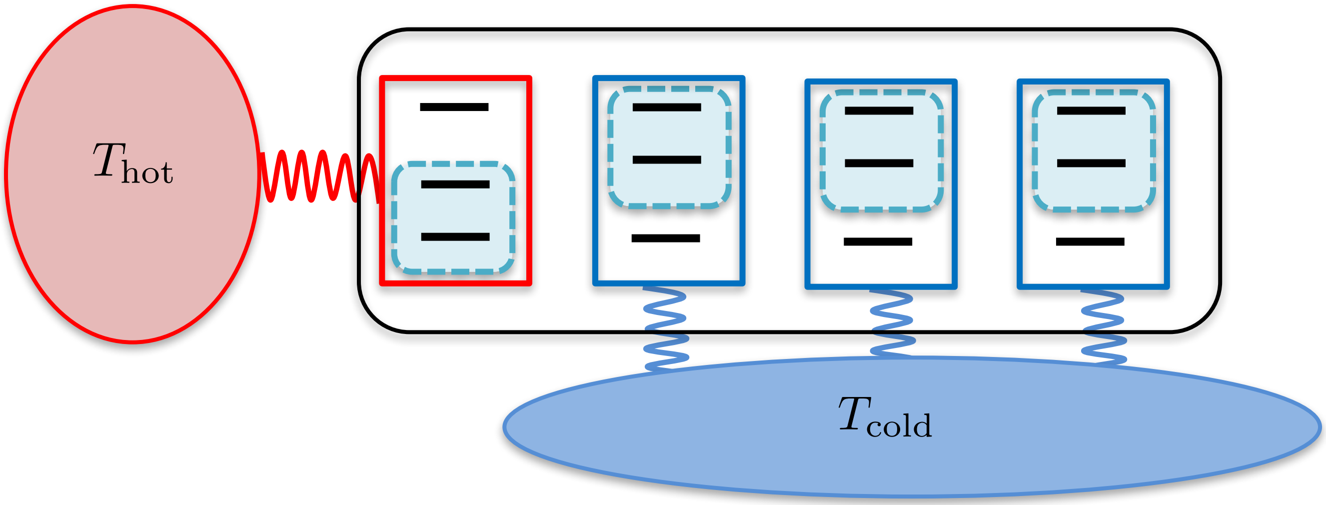

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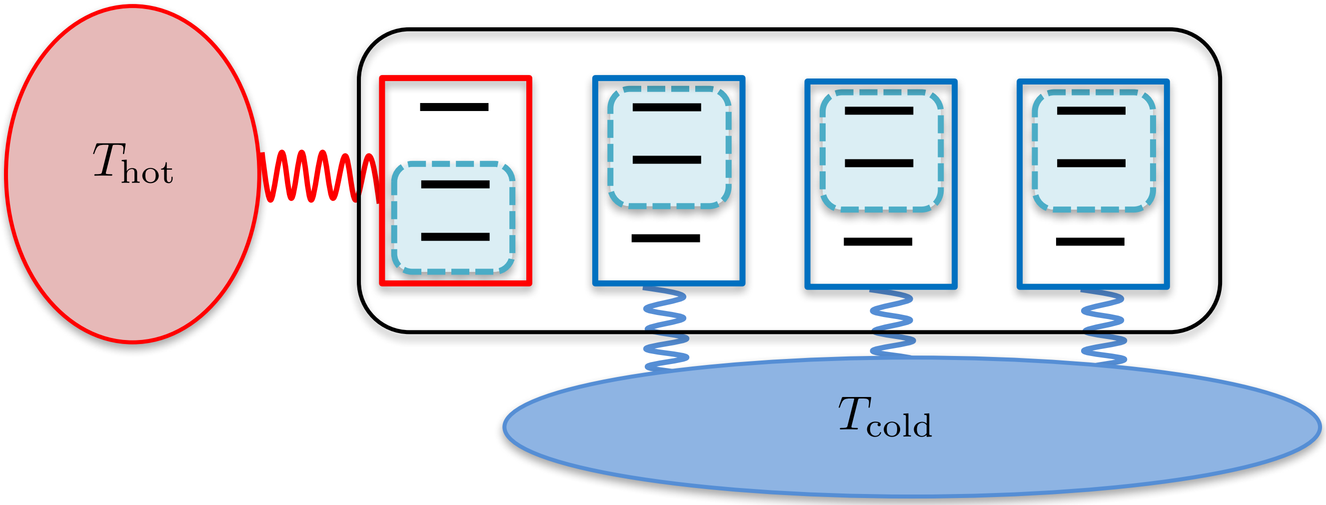

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Tavakoli, Haack, Brunner, Brask, arXiv:1906.00022

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Tavakoli, Haack, Brunner, Brask, arXiv:1906.00022

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Both $|R\rangle$ and $|\bar{\Psi}\rangle$ are eigenstate of H_{free} with eigenvalues E_R and $E_{\bar{n}}$

$$[H_s, H_{int}] = 0 \quad \Leftrightarrow \quad E_{\bar{n}} = E_R$$

$$\frac{1}{2}\sum_{k=1}^{N}\left[R_k n_k \Delta_k^{(1)} + (2-R_k)((1-n_k)\Delta_k^{(1)} + n_k\Delta_k^{(2)})\right] - \frac{1}{2}\sum_{k=1}^{N}\left[R_k\Delta_k^{(2)}\right] = 0$$

Tavakoli, Haack, Brunner, Brask, arXiv:1906.00022

Proof

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1. Energy conserving condition -> $|R\rangle, \Delta_k$

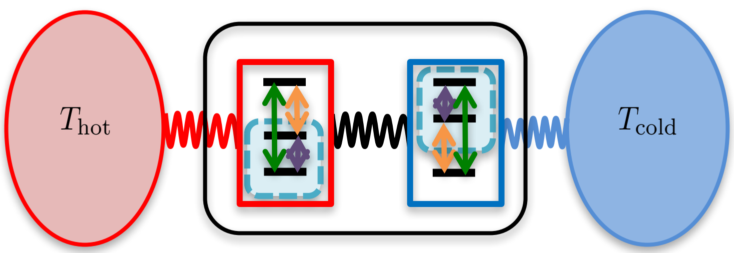
2. If this condition is satisfied for q hot qutrits and N-q cold qutrits, then it can also be satisfied for 1 hot qutrit and N-1 cold ones

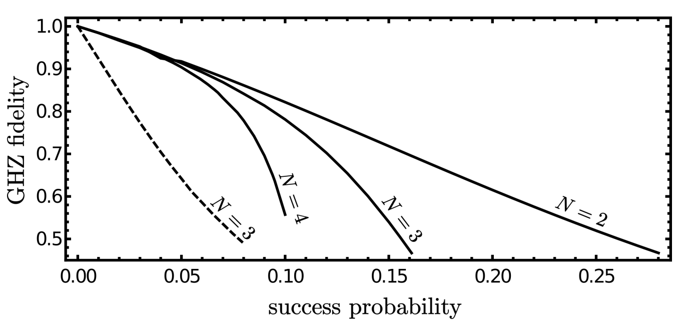
3. In the limit $T_h \to \infty \, , T_c = 0$, $\rho' = \dfrac{\Pi\rho_{ss}\Pi}{\mathrm{Tr}\{\Pi\rho_{ss}\}} = |\bar{\Psi}\rangle\langle\bar{\Psi}|$

Tavakoli, Haack, Brunner, Brask, arXiv:1906.00022

Next ?

- Deterministic machines for strong entanglement?
- Experimental platforms?
- Fundamental limits to thermal entanglement?
- Figures of merit for this family of machines?





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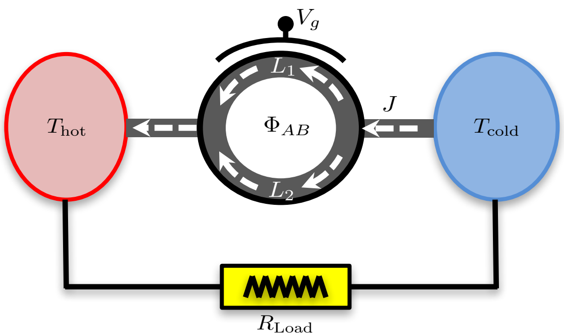
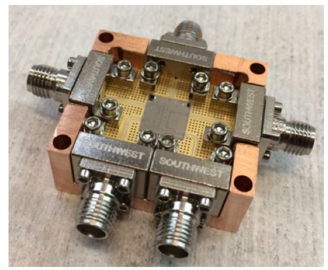
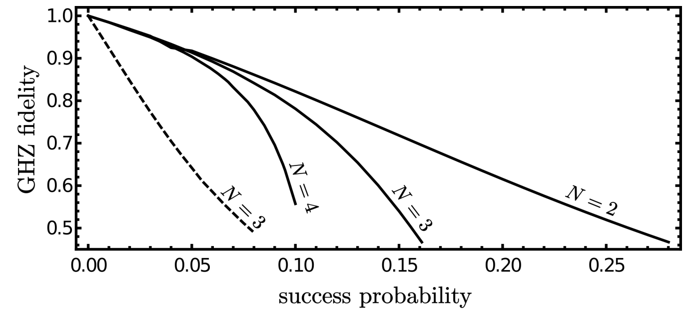
At the interplay between
quantum information, quantum thermodynamics and mesoscopic physics

Information in mesoscopic quantum thermal machines







Haack, Giazotto, arXiv:1905.12672

Brask, Haack, Brunner, Huber, NJP 17 (2015)

Tavakoli, Haack, Huber, Brunner, Brask, Quantum 2 (2018)

Tavakoli, Haack, Brunner, Brask, arXiv:1906.00022

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