Small self-contained quantum fridges

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FNSNF
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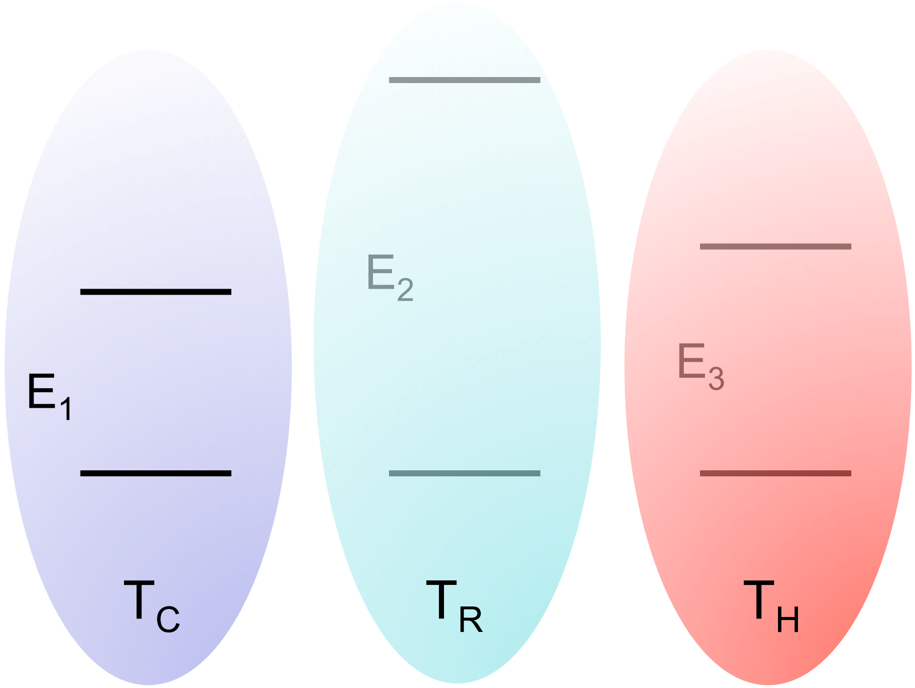
3-qubit fridge



$T_C < T_R < T_H$

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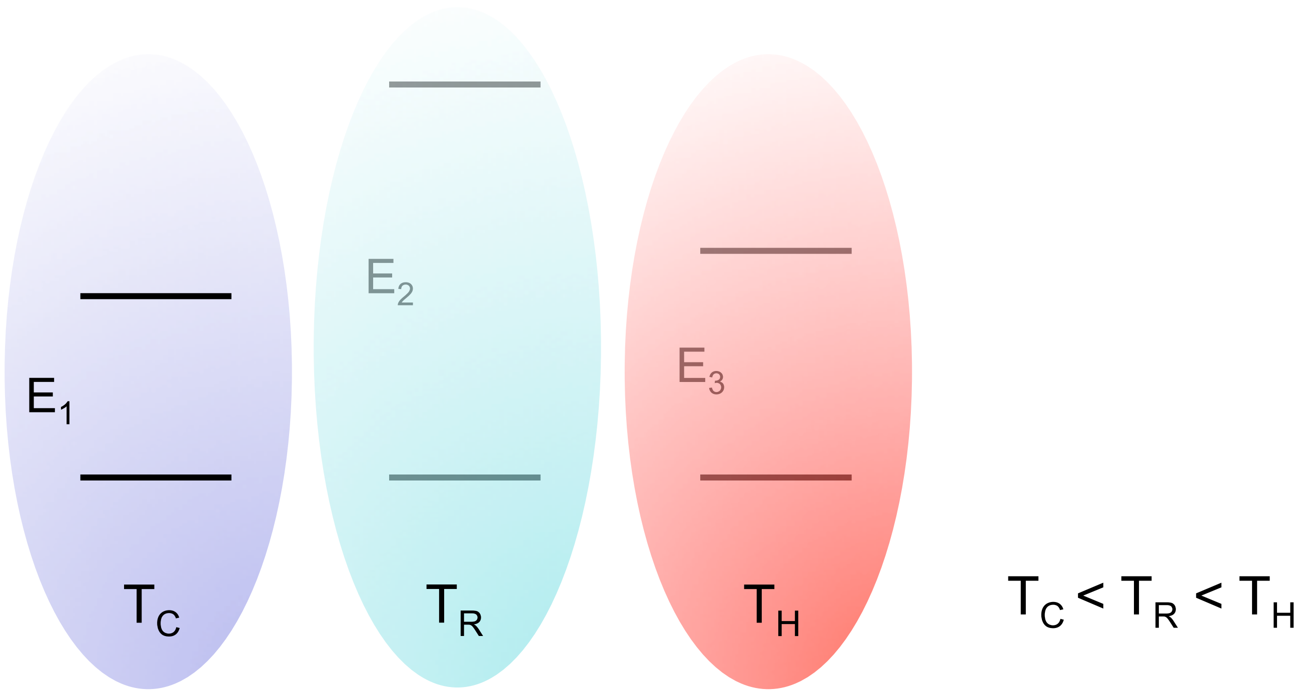
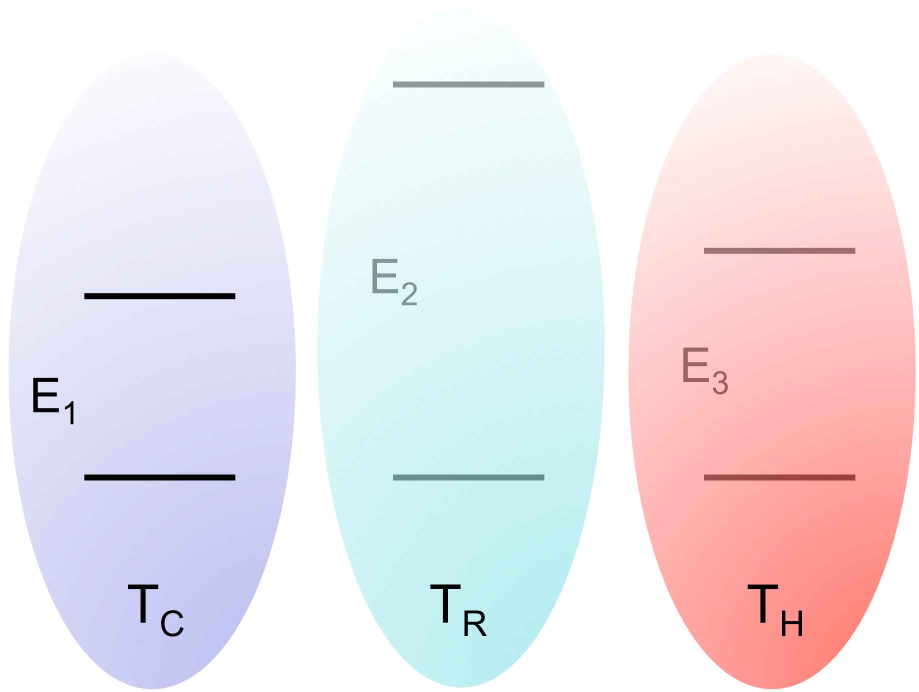


Design: $E_2 = E_1 + E_3$

3-qubit fridge



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$|101\rangle$ $|010\rangle$

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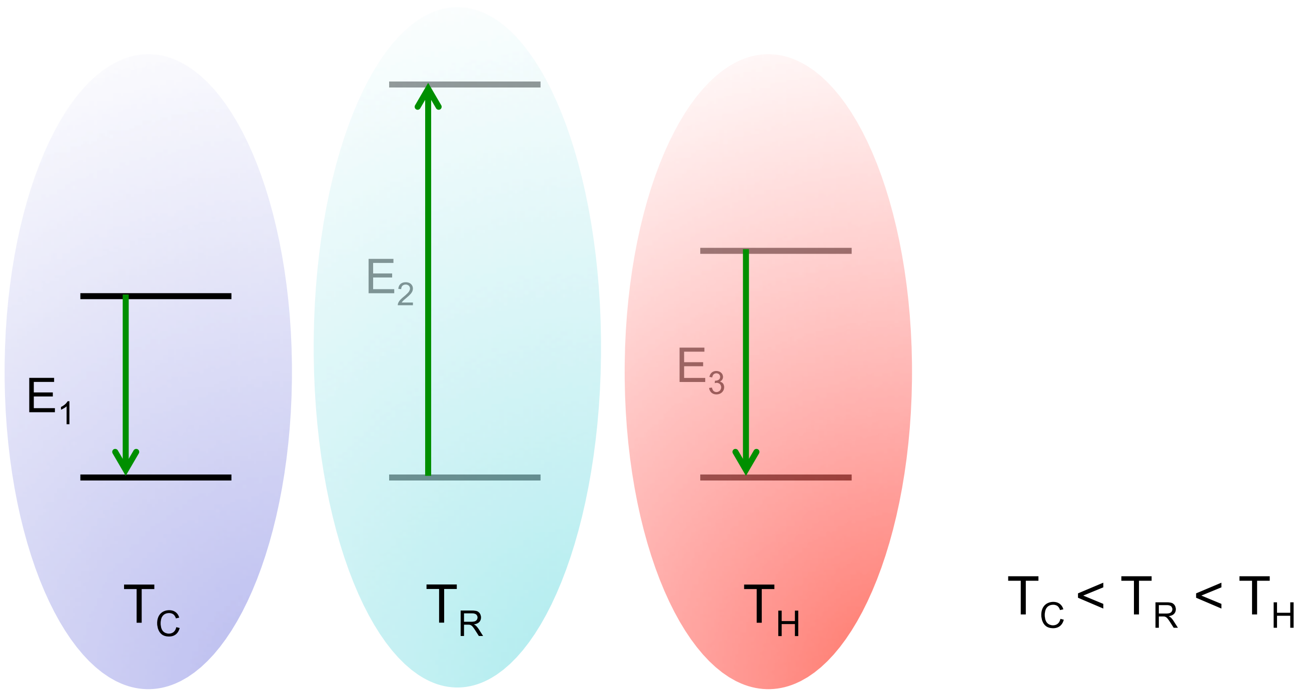

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Interaction: $|101\rangle \longrightarrow |010\rangle$

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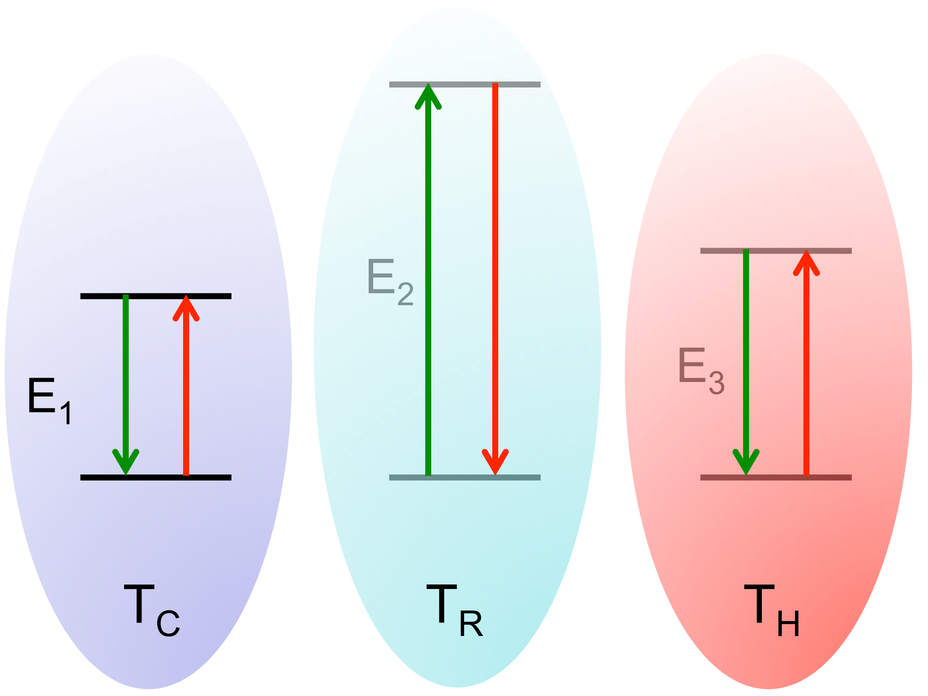

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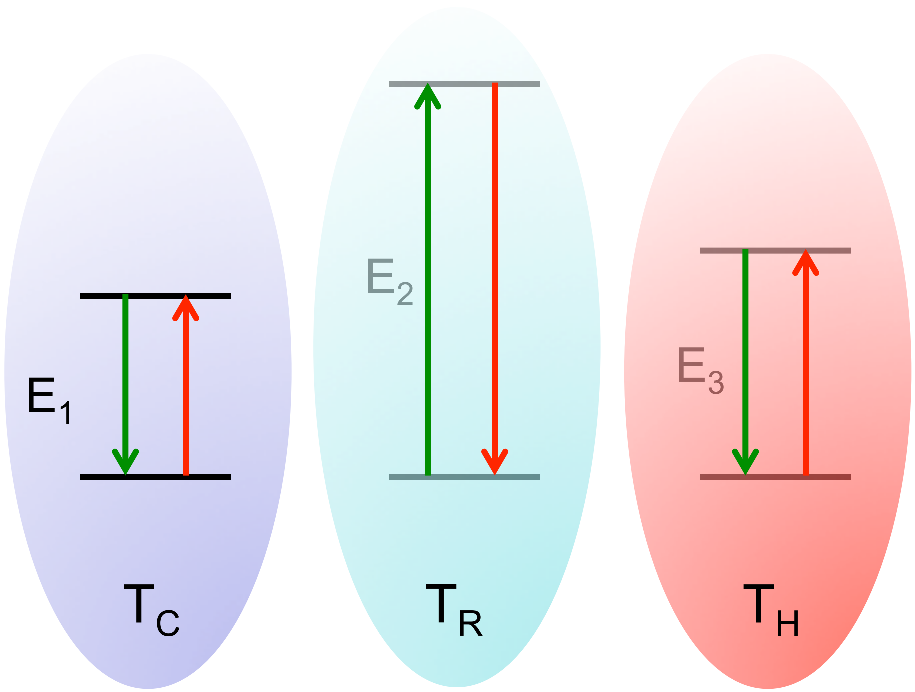


$T_C < T_R < T_H$

Design: $E_2 = E_1 + E_3$

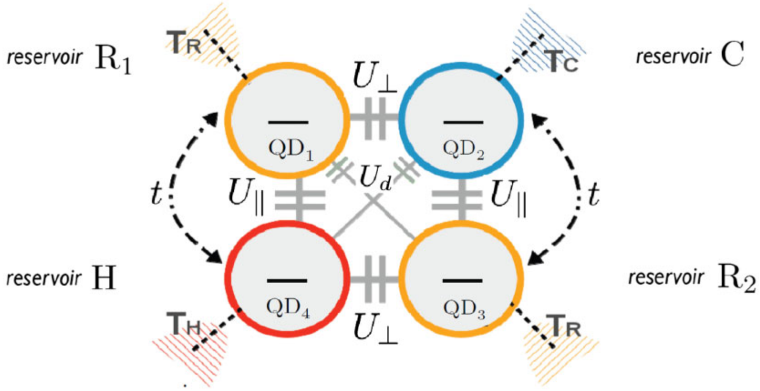
Interaction: $|101\rangle \rightleftharpoons |010\rangle$

Bias → qubit 1 is cooled: $T_1 < T_C$

Linden, Popescu, Skrzypczyk, PRL 2010; Palao et al, PRE 2001

Proposals for implementation

1. Quadri-Dot Fridge



Venturelli, Fazio, Giovanetti, PRL 2013

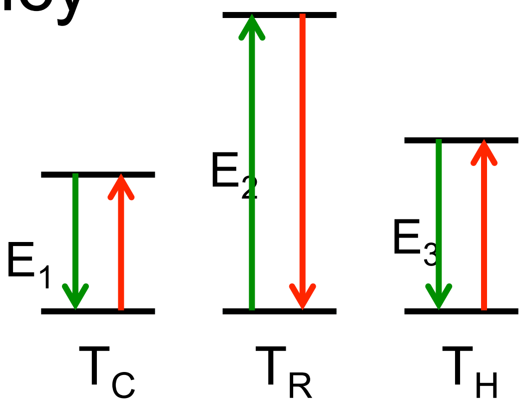
2. Superconducting qubits
   Chen, Li, EPL 2012

3. Optomechanics
   Mari, Eisert, PRL 2012

2-body interactions → Effective 3-body interaction

Cooling & Efficiency

$$|101\rangle \rightleftharpoons |010\rangle$$



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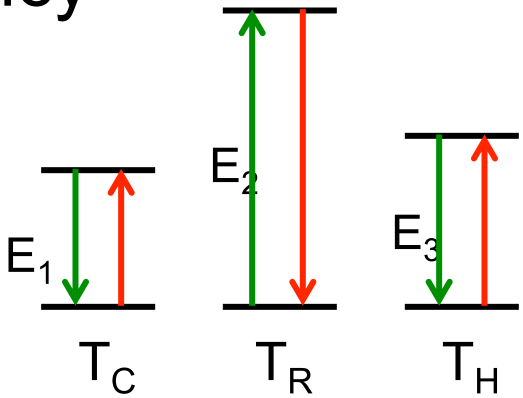

Cooling: when |101> is more populated than |010>

$$e^{-E_1/T_C} e^{-E_3/T_H} > e^{-E_2/T_R} \quad \Rightarrow \quad \frac{E_1}{E_3} < \frac{1 - \frac{T_R}{T_H}}{\frac{T_R}{T_C} - 1}$$

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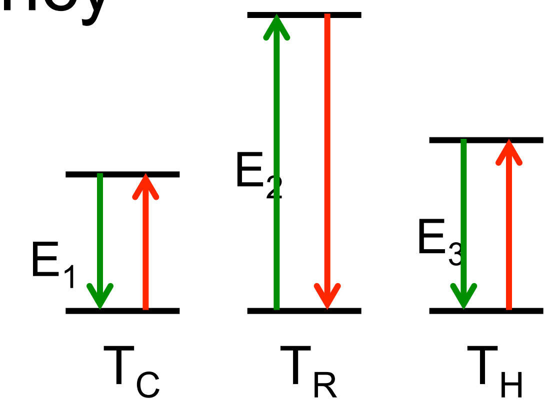

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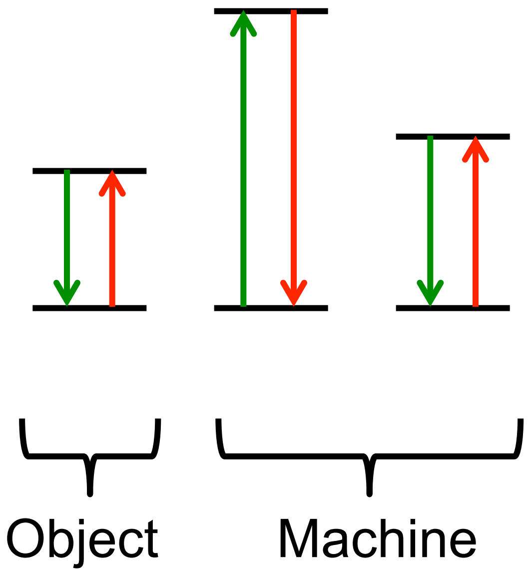
Efficiency → Carnot limit

$$\eta^Q = \frac{Q_C}{Q_H} = \frac{E_1}{E_3} < \frac{1 - \frac{T_R}{T_H}}{\frac{T_R}{T_C} - 1}$$

No trade-off between size and efficiency!

Skrzypczyk, NB, Linden, Popescu, J Phys A 2012

What does the fridge actually do?



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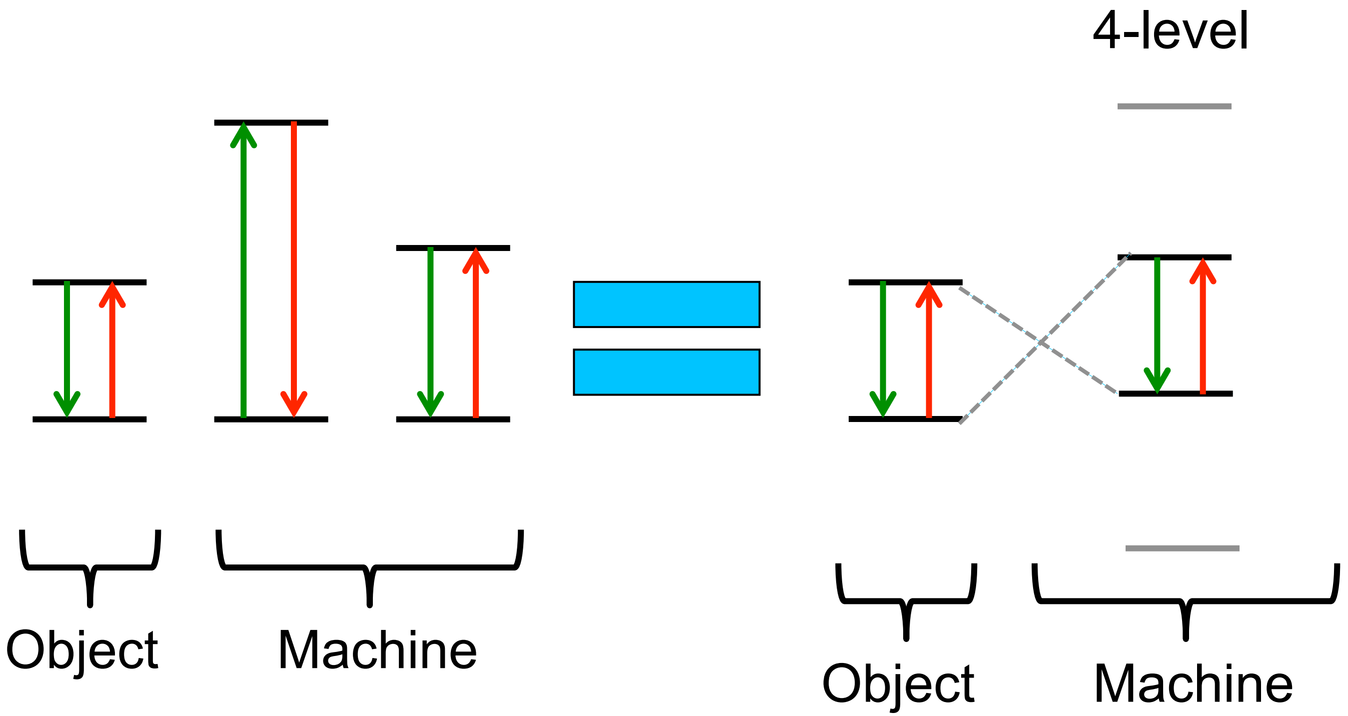

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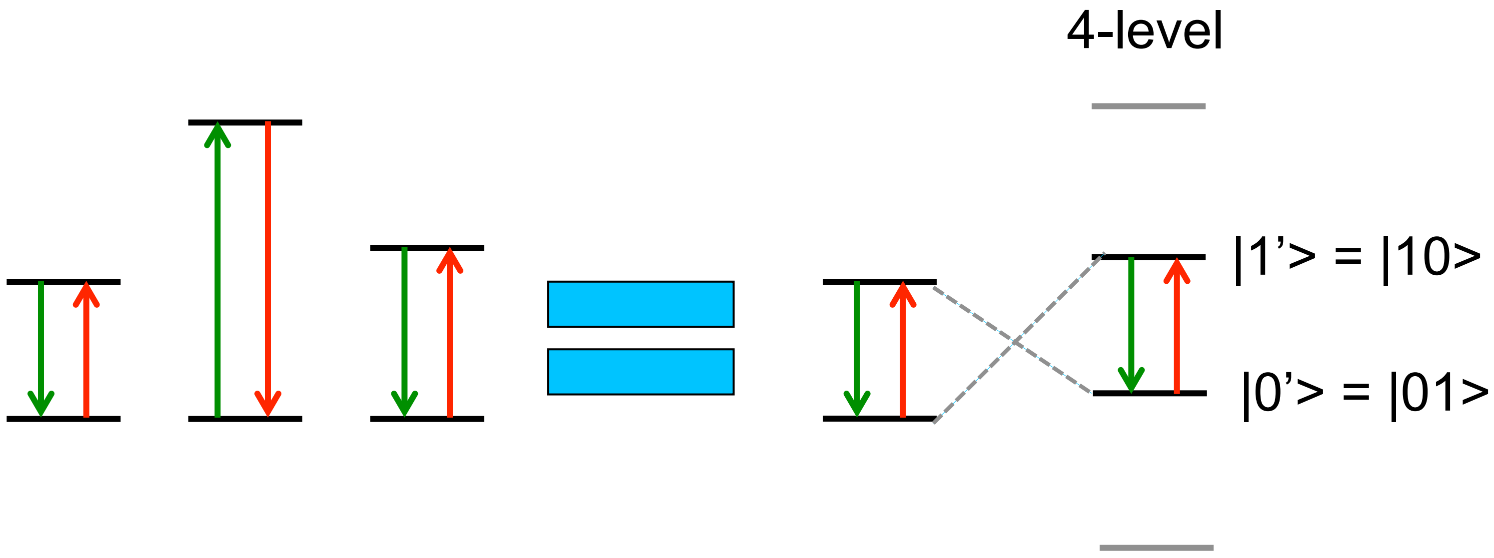

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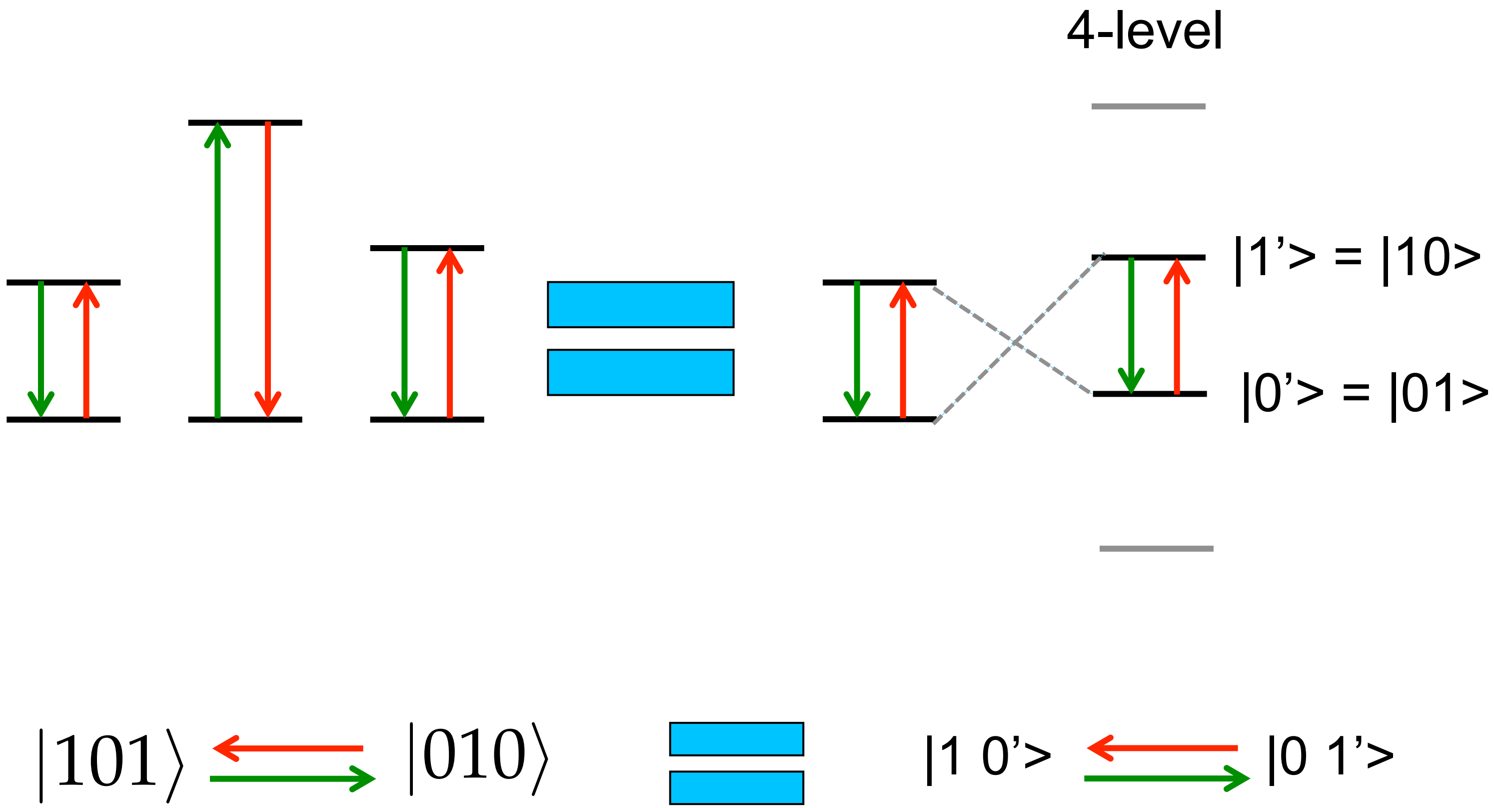

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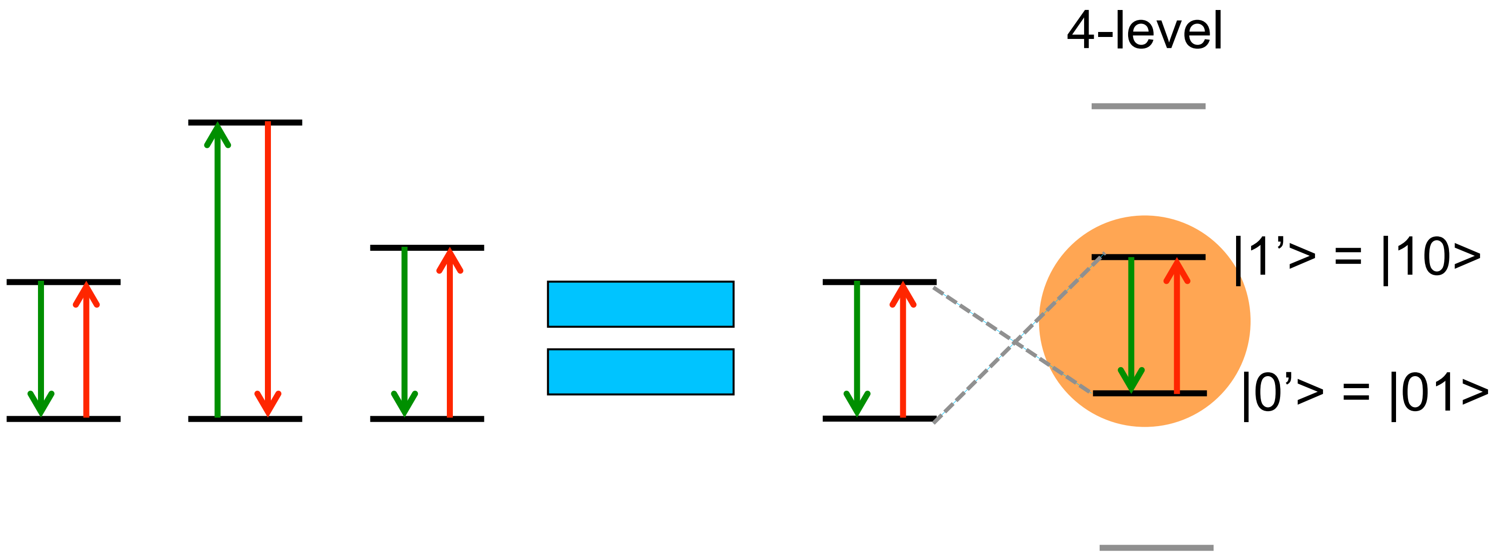


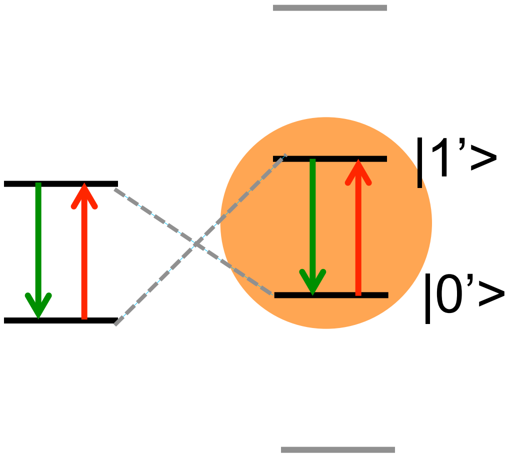
$$|101\rangle \rightleftharpoons |010\rangle \quad = \quad |1\ 0'\rangle \rightleftharpoons |0\ 1'\rangle$$

Machine places object in thermal contact with a **virtual qubit**

Virtual temperature

Temperature of virtual qubit

$$T_V = \frac{E_1}{\frac{E_2}{T_R} - \frac{E_3}{T_H}}$$



NB, Linden, Popescu, Skrzypczyk, PRE 2013

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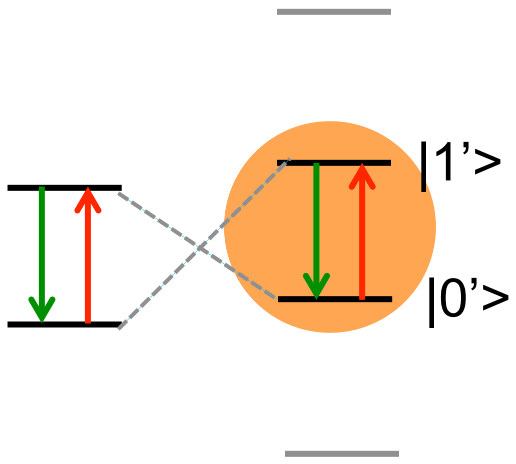

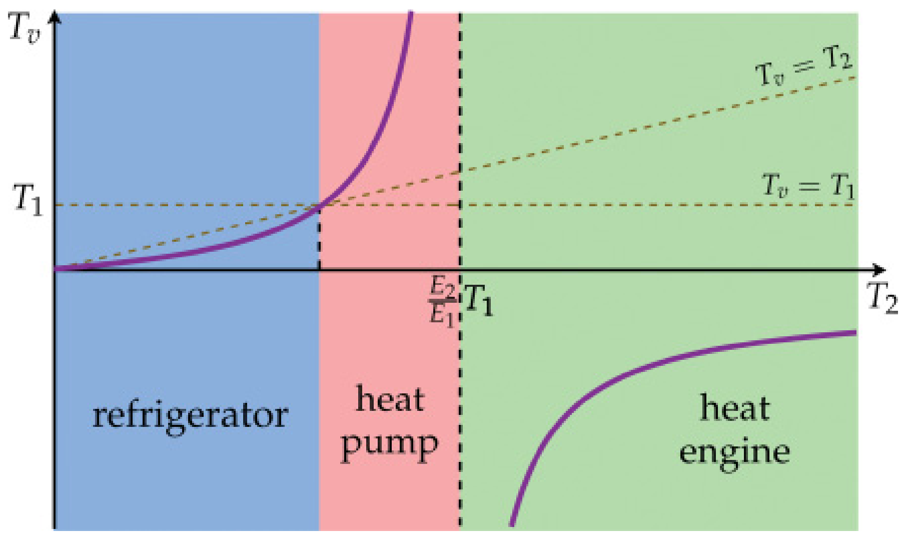

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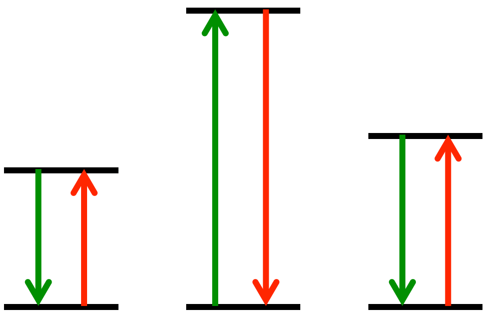
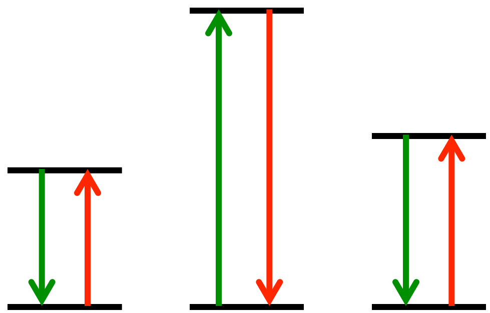
Quantum effects?



Are there regimes in which the 3-qubits get entangled?

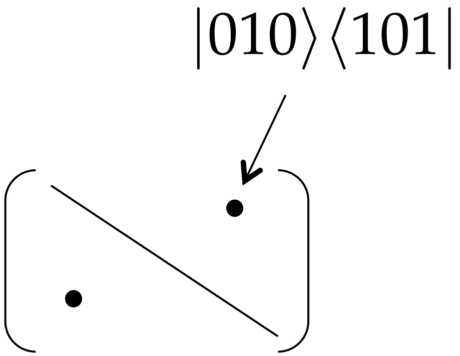
If yes, is this entanglement useful?

Entanglement?



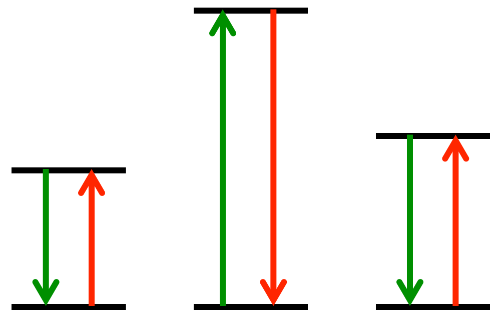
Steady state

$$\rho_S = \tau_1\tau_2\tau_3 + \gamma\sigma =$$



bias population |010> vs |101>

Entanglement?



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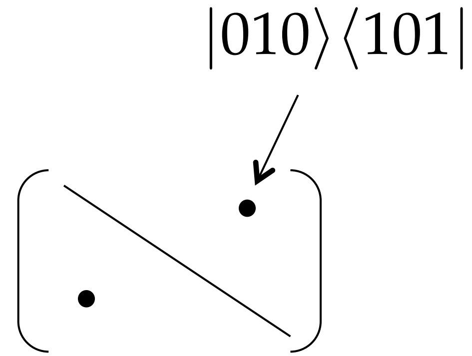

bias population |010> vs |101>

Carnot point $\gamma = 0,$ ➡ $\rho_S = \tau_1 \tau_2 \tau_3$ **separable**

Entanglement is detrimental for efficiency

Entanglement?

Moving away from Carnot point, entanglement can be found

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$$\rho_S = w|GHZ\rangle\langle GHZ| + (1-w)\sigma_{diag}$$

where $|GHZ\rangle = (|010\rangle + i|101\rangle)/\sqrt{2}$

Tools: entanglement witnesses

Guhne, Seevinck NJP 2010, Huber et al. PRL 2010

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Does this entanglement play any role?

Can entanglement enhance cooling?

Consider: (i) object (qubit 1) to be cooled (fix E, T_C)

(ii) resources: hot bath T_H and cold bath T_R

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Case B: **separability** is enforced   Lowest temp = T_S^*

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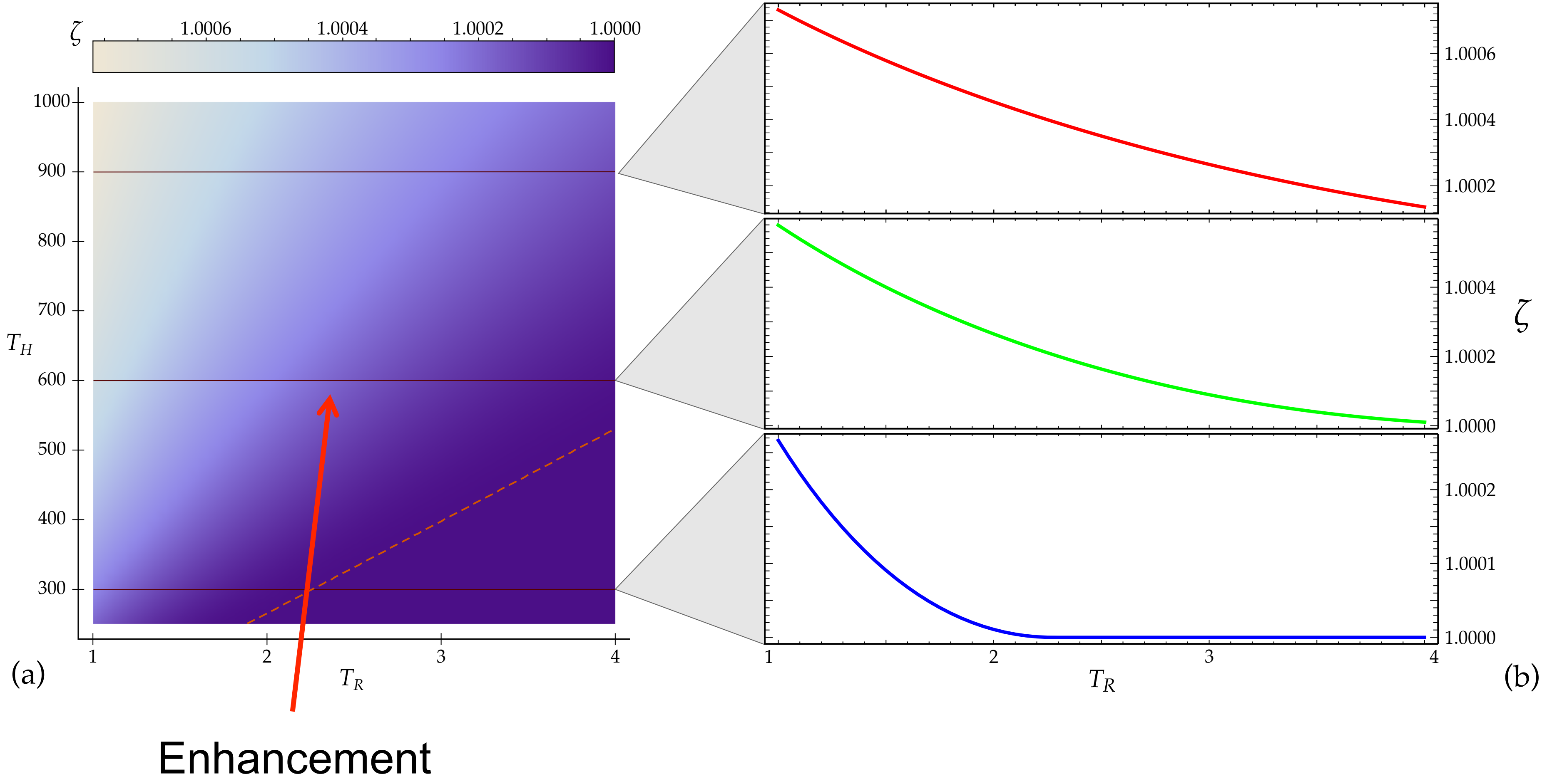
Relative cooling enhancement $$\zeta = \frac{T_C - T_S}{T_C - T_S^*}$$

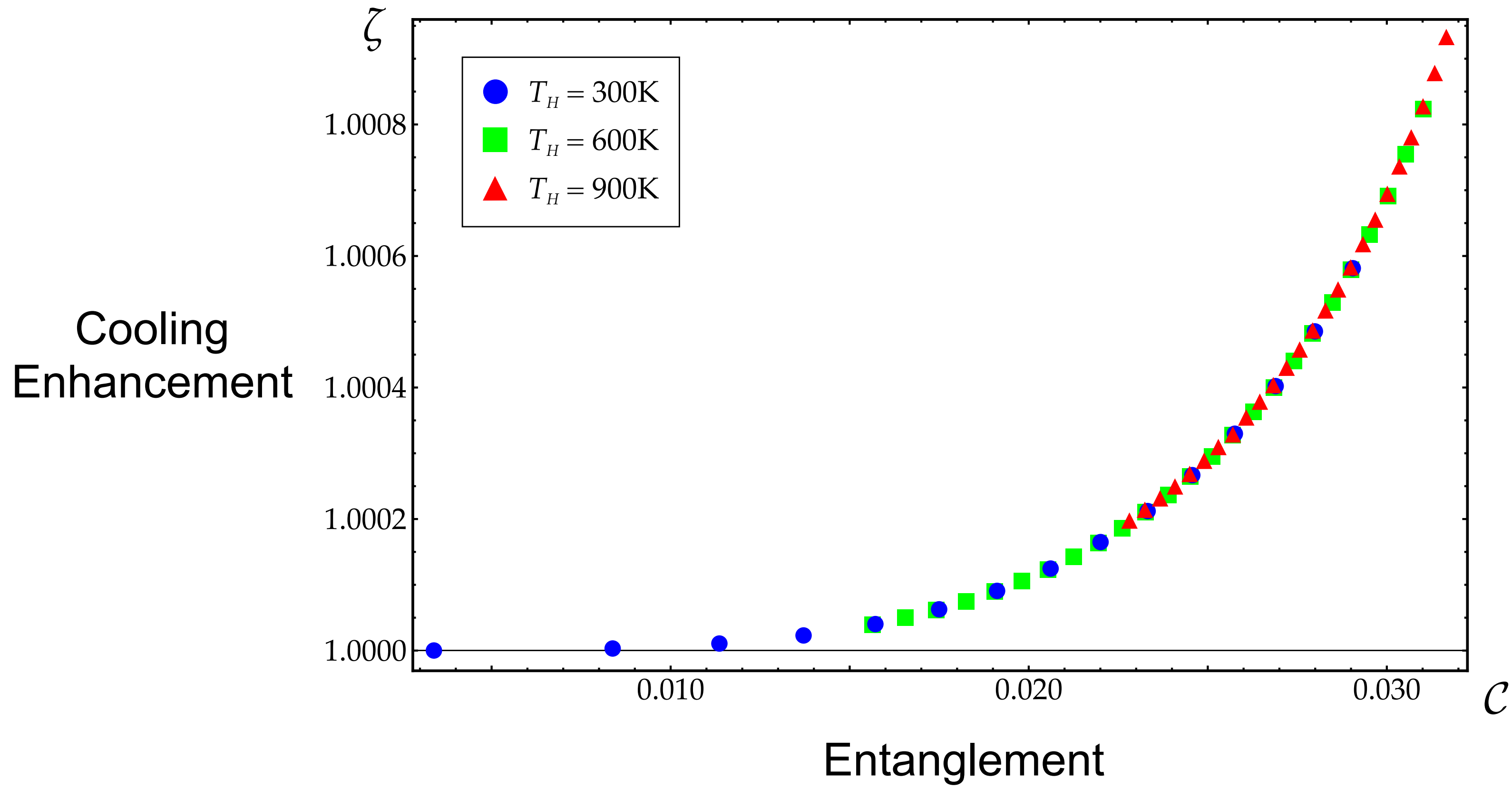
→ If $\zeta > 1$ entanglement helps!

Entanglement helps



NB, Huber, Linden, Popescu, Silva, Skrzypczyk, PRE 2014

Functional relationship?



Amount of entanglement determines cooling enhancement

NB, Huber, Linden, Popescu, Silva, Skrzypczyk, PRE 2014

Remarks

1. Which qubits get entangled?

Energy IN / Energy OUT

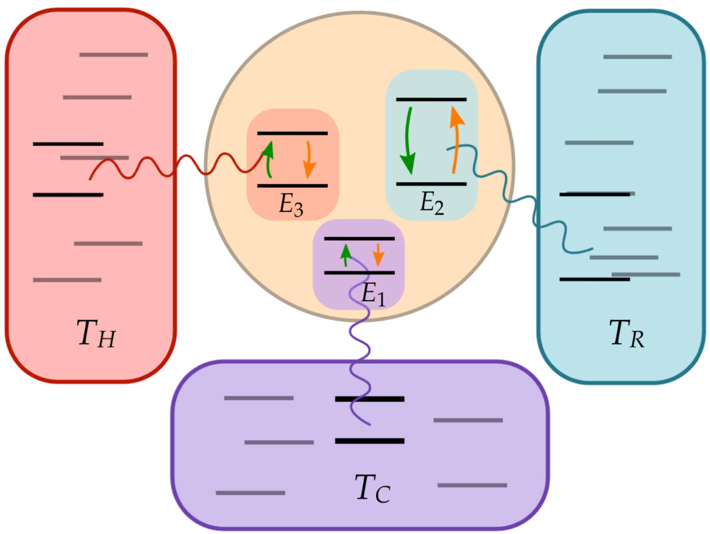
Entanglement enhances transport

2. Steady state entanglement in open quantum system

Open questions

- Beyond weak coupling regime
- Other models
- Macroscopic fridges
- Heat engines
- Other quantum effects. Bath?

THE MODEL



FREE HAMILTONIAN

$$H_0 = E_1\Pi_1 + E_2\Pi_2 + E_3\Pi_3$$

WITH $E_2 = E_1 + E_3$

INTERACTION

$$H_{int} = g\left(|010\rangle\langle 101| + |101\rangle\langle 010|\right)$$

THERMALISATION

p_i → RESET QUBIT TO THERMAL STATE τ_i

$$\tau_i = r_i|0\rangle_i\langle 0| + (1-r_i)|1\rangle_i\langle 1| \qquad r_i = 1/(1+e^{-E_i/T_i})$$

WEAK COUPLING REGIME $p_i \approx g \ll E_i$