Necessarily Transient Quantum Refrigerator

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Outline

- Introduction to quantum refrigerator and its working principle
- A thermalization model: Reset model
  - Cooling in Reset model
  - Necessarily transient cooling in Reset model
- Harmonic oscillator bath model of thermalization
- Info-theoretic aspects of necessarily transient cooling
- Remarks

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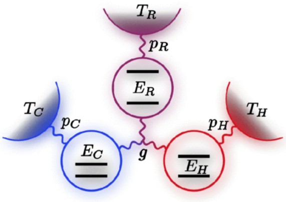
Introduction to quantum refrigerator and working principle

- Quantum thermal machine. Working substance is quantum object.
- Small self-contained quantum refrigerator. Each subsystem has a few quantum levels.

Introduction to quantum refrigerator and working principle



At $t = 0$,

$T_C \leq T_R \leq T_H$ We take, $T_C = T_R = T_r$

$\rho_0 = \rho_0^C \otimes \rho_0^R \otimes \rho_0^H$ $\rho_0^i = r_i |0\rangle \langle 0| + (1 - r_i) |1\rangle \langle 1|$

$r_i = \frac{1}{1 + e^{-E_i/T_i}}, \ i = C, R, H$

$H_{loc} = \frac{1}{2} \sum E_i \sigma_i^z,$

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With time, r_C should increase and r_R should decrease.

Initially, $(1 - r_C)r_R > r_C(1 - r_R)$

Probability of $|10\rangle$ > Probability of $|01\rangle$

- Apply an unitary operation U: $|10\rangle \rightarrow |01\rangle$
  Extra work $(E_R - E_C)$ performed by the external system.

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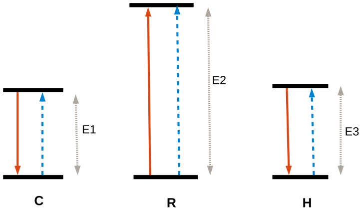

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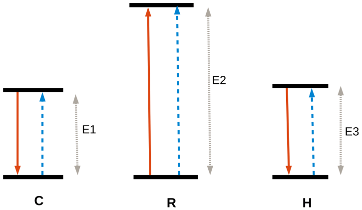

  To cool qubit C, $|101\rangle \longrightarrow |010\rangle$

  Choose $T_H > T_r$,

$$\text{Probability of } |101\rangle > \text{Probability of } |010\rangle$$

Introduction to quantum refrigerator and working principle

Master equation:

$$\frac{\partial \rho(t)}{\partial t} = -\frac{i}{\hbar}[H_{loc} + H_{int}, \rho(t)] + \Phi(\rho(t))$$

$\Phi(\rho)$ depends on nature of reservoir, & interaction between qubits & reservoirs.

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$$T_C(t) = -E_C / \ln\left(\frac{1 - r_C(t)}{r_C(t)}\right)$$

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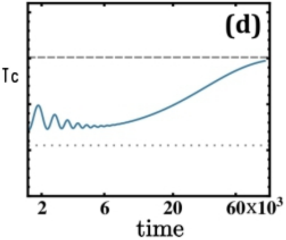

- This minimum temperature T_{min} is roughly independent of the p_i's.

$E_C = 1, E_H = 100$
$T_C = T_R = 1, T_H = 100$
$g = 5 \times 10^{-3}, p_C = p_H = 10^{-5}, p_R = 10^{-3}$

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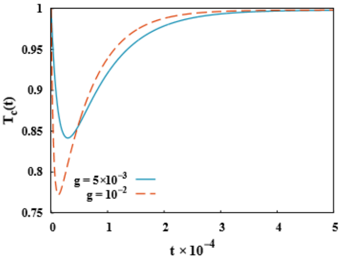
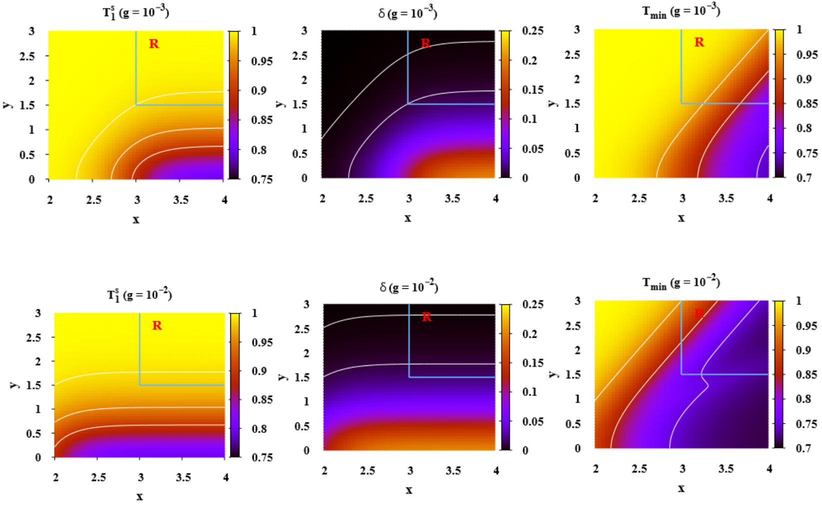


- T_C decreases with time and after attaining a minimum temperature at a very short time, it starts to increase. The steady state temperature $T_C^S \approx T_C$

$$E_C = 1, E_R = 101, E_H = 100$$
$$T_C = T_R = 1, T_H = 100$$
$$x = 3.5, y = 2.5$$

Necessarily transient cooling in Reset model



T_1^S : Steady state temp. of C, $\delta : T_C - T_1^S$

$T_{min} = minT_C$

Necessarily transient cooling in Reset model

Observations

- In a large area of this region, T_1^S is very near or equal to the initial temperature T_1
- So, the steady state cooling δ is negligible in those areas.
- T_{min} has low value in those regions.
- TC without SSC is rich in the first quadrant $\mathbf{R}$ of $x - y$ space.
- With increasing g, area of such region in $\mathbf{R}$ increases.
- With increasing g, T_{min} decreases.

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Bath-qubit interaction:

$$H_{sb} = \sum_{i=1}^{3} A_i \otimes \chi_i$$

$A_i = \sigma_i^x$: Lindblad operator,
$\chi_i = \sum_{i=1}^{3} (\eta_{i,k} b_{i,k} + \eta_{i,k}^{*} b_{i,k}^{\dagger})$: Collective bath co-ordinates

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$$\gamma_i(\omega) = \begin{cases} J_i(\omega)(1 + f(\omega, \beta_i)), & \omega > 0. \\ J_i(|\omega|)f(|\omega|, \beta_i), & \omega < 0. \end{cases} \tag{1}$$

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$\varphi_i^\omega(\rho) = \mathcal{L}_i^\omega \rho \mathcal{L}_i^{\omega\dagger} - \frac{1}{2}\mathcal{L}_i^{\omega\dagger}\mathcal{L}_i^\omega, \rho$

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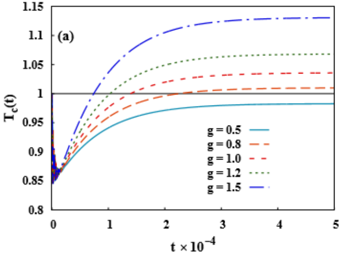

$$E_C = 1, E_R = 2, E_H = 1$$
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$$x = 4, y = 1, g = 10^{-2}$$

- For low values of g, T_C^S is lower than T_C but with increasing g, T_C^S increases and eventually crosses T_C.

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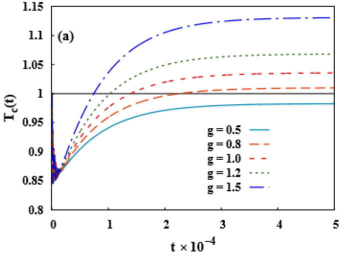

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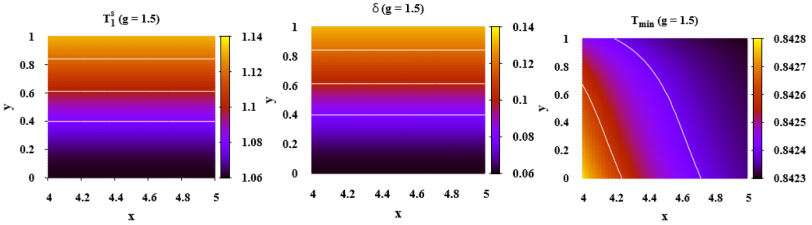
- For low values of g, T_C^S is lower than T_C but with increasing g, T_C^S increases and eventually crosses T_C.
- Minimum temperature however lower than T_C, and obtained at a significantly low time.

Harmonic oscillator bath model of thermalization



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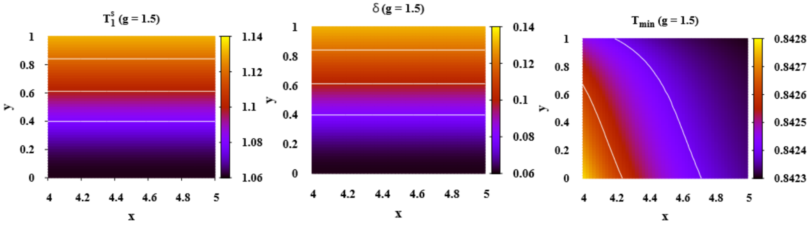

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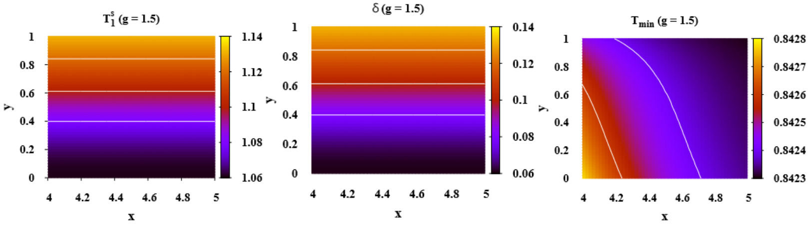

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- *Necessary transient cooling is generic: occurs irrespective of thermalization model.*

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Behavior of logarithmic negativity

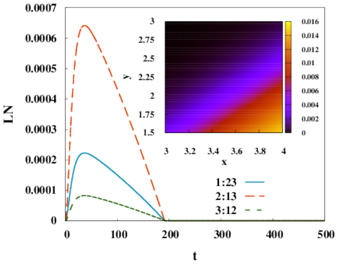

Figure : for Reset model

$$E_C = 1, E_R = 101, E_H = 100$$
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- Throughout the region **R**, LN is considerably low or zero.

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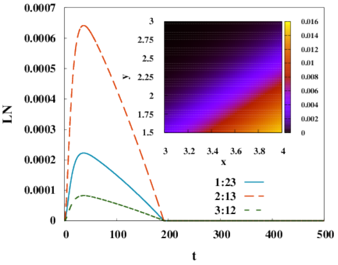

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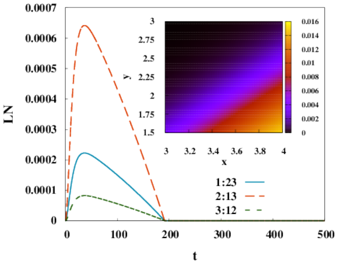

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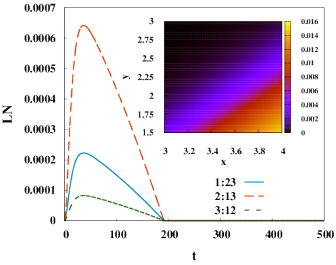

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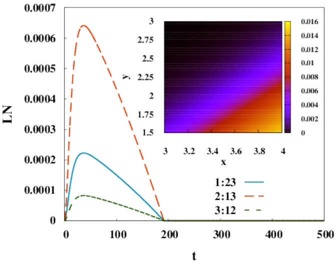

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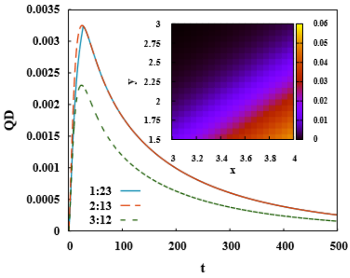
In the realistic model, no bi-partition entanglement arises for any set of (x, y) for all $t > 0$

Information theoretic aspects of Necessarily transient cooling

Behavior of Quantum Discord



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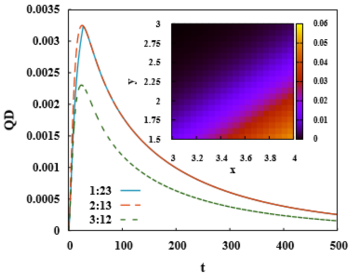

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Information theoretic aspects of Necessarily transient cooling

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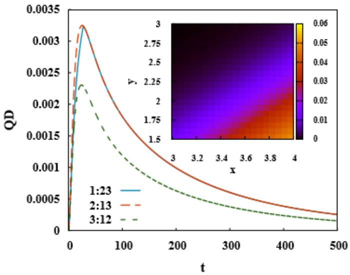

Figure : for Reset model

$$E_C = 1, E_R = 101, E_H = 100$$
$$T_C = T_R = 1, T_H = 100$$
$$x = 3.5, y = 2.5, g = 10^{-2}$$

- In contrast to LN, QD decreases slowly with time.
- The maximum value QD^m is higher in the region where T_{min} is lower.
- Unlike LN^m, the ordering between $\mathrm{QD}^m_{1:23}$, $\mathrm{QD}^m_{3:12}$ and $\mathrm{QD}^m_{2:13}$ remains unchanged throughout $\mathbf{R}$.

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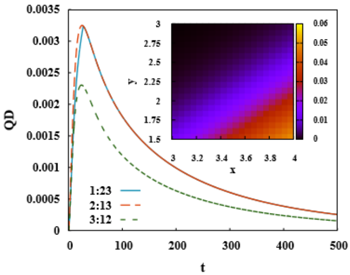

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- For fixed bi-partition, value of QD^m is higher than the corresponding value of LN^m.

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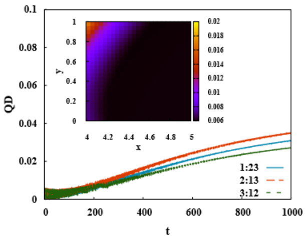

Figure : for the realistic model

$$E_C = 1, E_R = 101, E_H = 100$$
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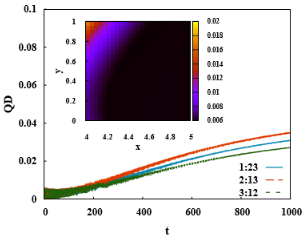

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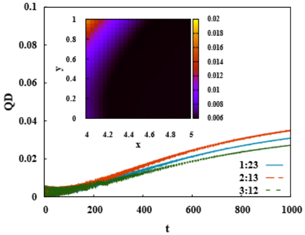

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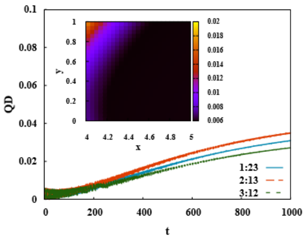

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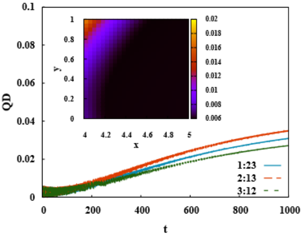

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- Higher values of QD is observed in low x and high y regions.
- With increasing g, the higher values of QD are found in high x and low y regions.
- Unlike LN, QD negligible or zero in regions where T_{min} has low value.

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- Canonical form of interaction parameters facilitates analysis of necessarily transient cooling.
- Phenomenon generic and independent of specific thermalization model.
- In case of the realistic model, transient cooling is even more pertinent as steady state heating occurs.
- Lowest attainable temperature freezes (remains unchanged) wrt system parameters in realistic model.

Thank You !