Title: Activation of Strong Local Passive States with Quantum Energy Teleportation Protocols

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Abstract: "Strong local passivity is a property of multipartite systems from which it is impossible to locally extract energy. Surprisingly, if the system in a strong local passive state displays entanglement, it could be possible to locally activate energy by adding classical communication between different partitions of the system, through so-called 'quantum energy teleportation' protocols.

In this talk, first, I will present how to fully characterize this distinct notion of local passivity by giving necessary and sufficient conditions using optimization techniques from semidefinite programming [1]. Then, I will introduce the minimal theoretical model of energy activation with a fully unitary quantum energy teleportation protocol [2]. Finally, I will present the first experimental observation of the local activation of a strong local passive state on a bipartite quantum system using nuclear magnetic resonance [2].

Refs.
[1] Fundamental limitations to local energy extraction in quantum systems. ÁM Alhambra, G Styliaris, NA Rodriguez-Briones, J Sikora, E Martin-Martinez. Physical review letters 123 19, 190601

[2] Experimental activation of strong local passive states with quantum information. NA Rodríguez-Briones, H Katiyar, R Laflamme, E Martín-Martínez. ArXiv preprint arXiv:2203.16269"

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Activation of strong local passive states with quantum energy teleportation protocols

Nayeli A. Rodríguez-Briones

Hemant Katiyar, Eduardo Martín-Martínez, and Raymond Laflamme

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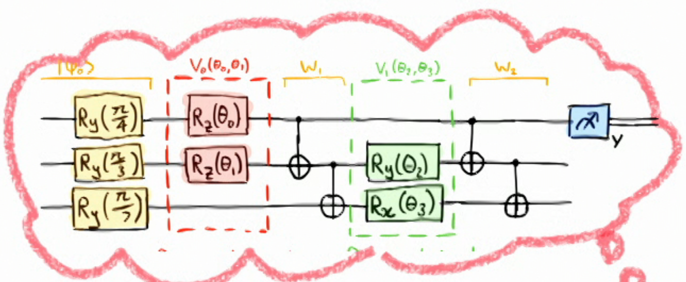
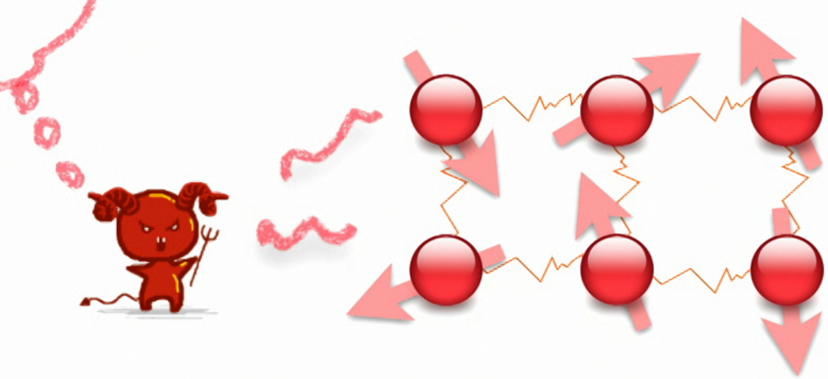
Nov 23, 2022

Introduction

Recently, methods to extract and transfer energy from physical systems at the quantum scale have been developed using tools from quantum information processing



E.g. Algorithmic Cooling protocols



Information processing ⟶ Entropy manipulation

Applications

- Preparation of highly pure quantum states required for quantum technologies (e.g. quantum computers)

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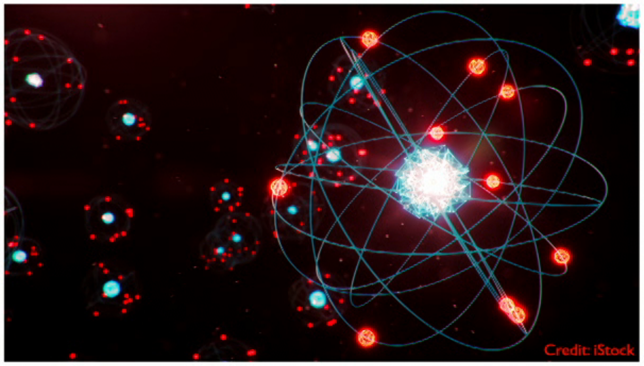
- Providing new insights to elucidate fundamental open questions in physics, such as quantum thermodynamics, quantum gravity, quantum matter, among others



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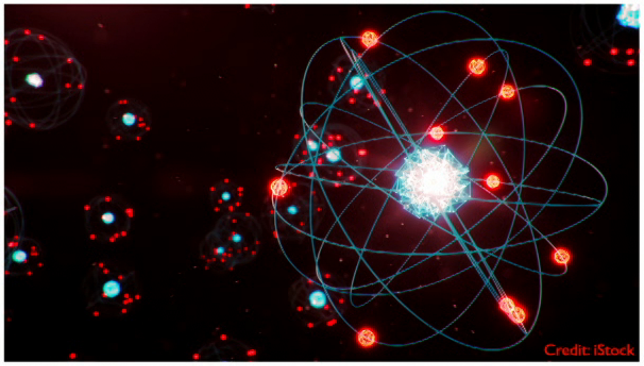
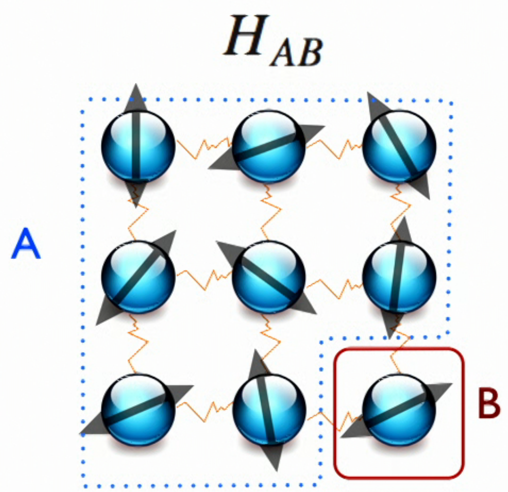


Quantum information theory can help us to understand and generalize thermodynamics to capture quantum phenomena

- Quantum effects on energy and information flows
- Emergent behavior coming from entanglement
- Failure of global thermalization (many-body localization)
- Phase transitions and critical behavior

Motivation



Goal 1:

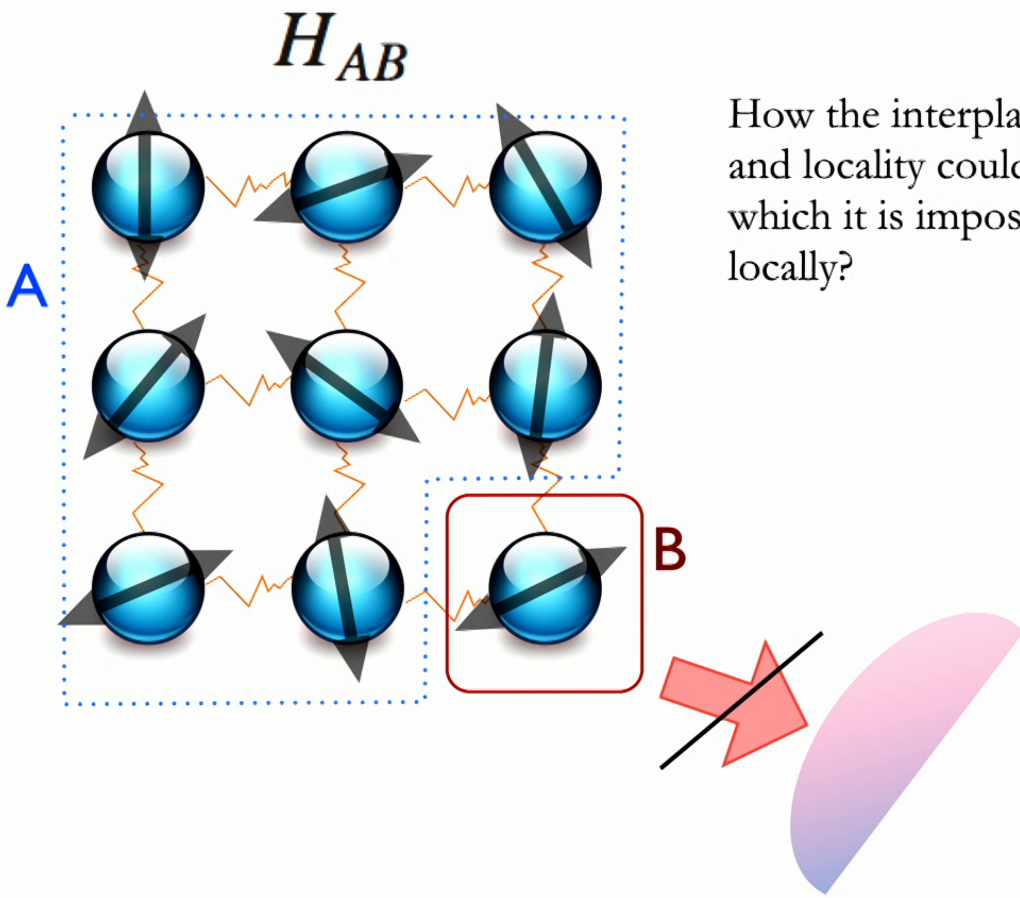
To understand the fundamental limitations of local extraction of energy from quantum systems in the presence of **strong coupling and entanglement**

Goal 2:

To use ideas from quantum field theory, such as quantum energy teleportation protocols to circumvent cooling limitations.

Relevant for cooling and purification of quantum systems subject to many-body interactions

Intuition for local cooling limitations



How the interplay between entanglement and locality could give rise to states from which it is impossible to extract energy locally?

Outline

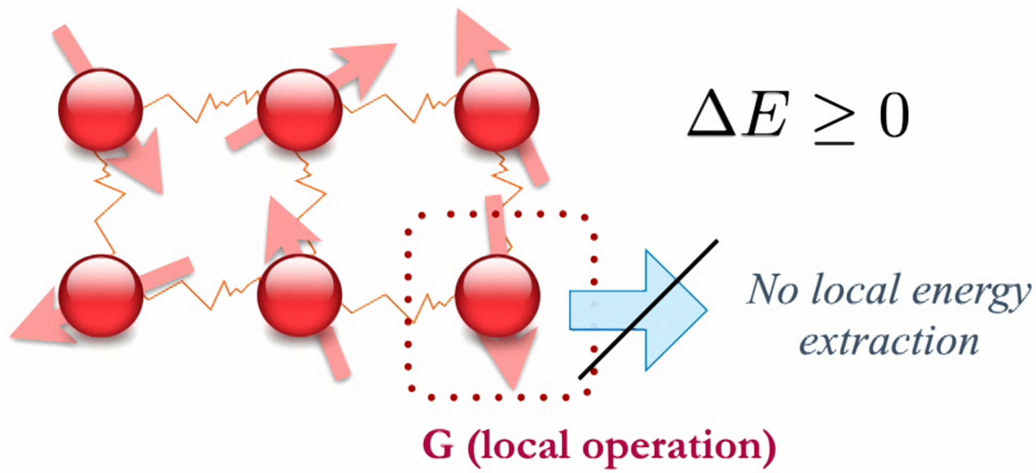
1. What is strong local passivity (SLP)?

2. What are the conditions to have strong local passivity?

3. How can we activate a SLP state?
   - Quantum energy teleportation protocols
   - First experimental demonstration

Strong local passive states

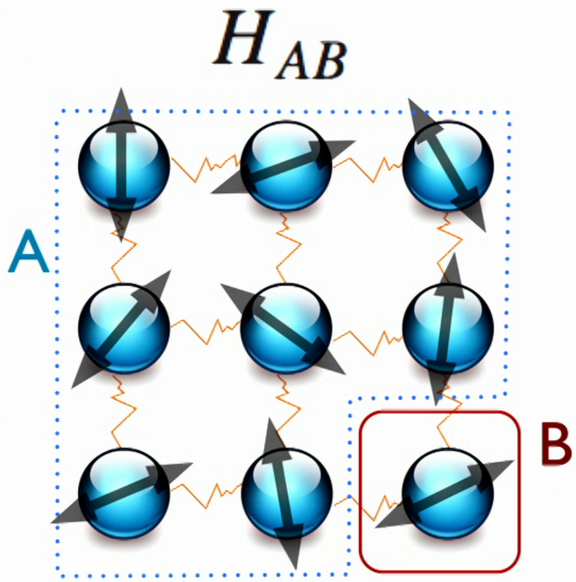
States with subsystem from which no energy can be extracted by local operations



A pair ρ and H has SLP with respect to a subsystem if

$$\forall G, \quad \Delta E(\rho) = \mathrm{Tr}\left[\mathrm{H}\left(\mathrm{I} \otimes \mathrm{G}\right)\rho\right] - \mathrm{Tr}\left[\mathrm{H}\rho\right] \geq 0$$

Theorem. Sufficient conditions for SLP



$$\rho_{AB} = \sum_i p_i |E_i\rangle\langle E_i|$$

If the ground state is max-rank entangled and not degenerate

$\exists\, p_*$ such that if $p_0 \geqslant p_*$

the system state is strong-local passive

Frey, M., Funo, K., & Hotta, M. (2014). Phys Rev E, 90(1), 012127.

Corollary: For thermal states

If the ground state is entangled max-rank with respect to A and B and not degenerate.

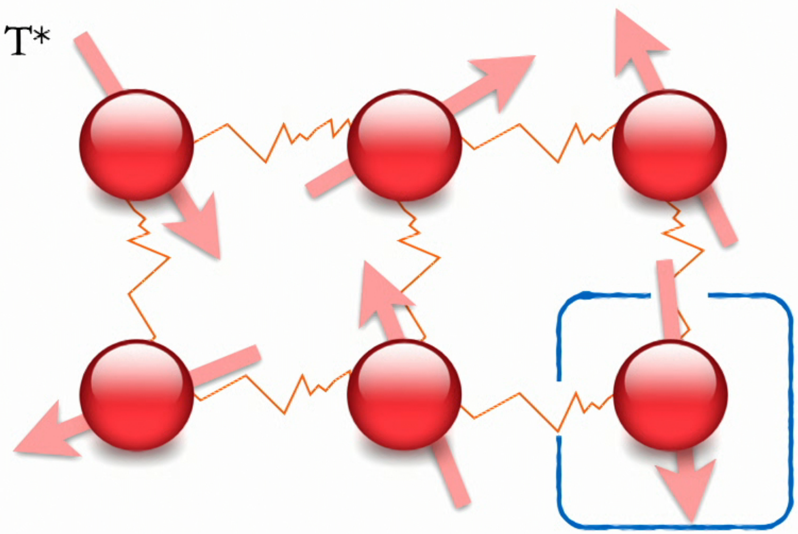
$$\exists\, T_* > 0, \text{ such that if } \quad T \leq T_*,$$

the system state is strong-local passive

Frey, M., Funo, K., & Hotta, M. (2014). Phys Rev E, 90(1), 012127.

Corollary: For thermal states

Hot system at
temperature T < T*



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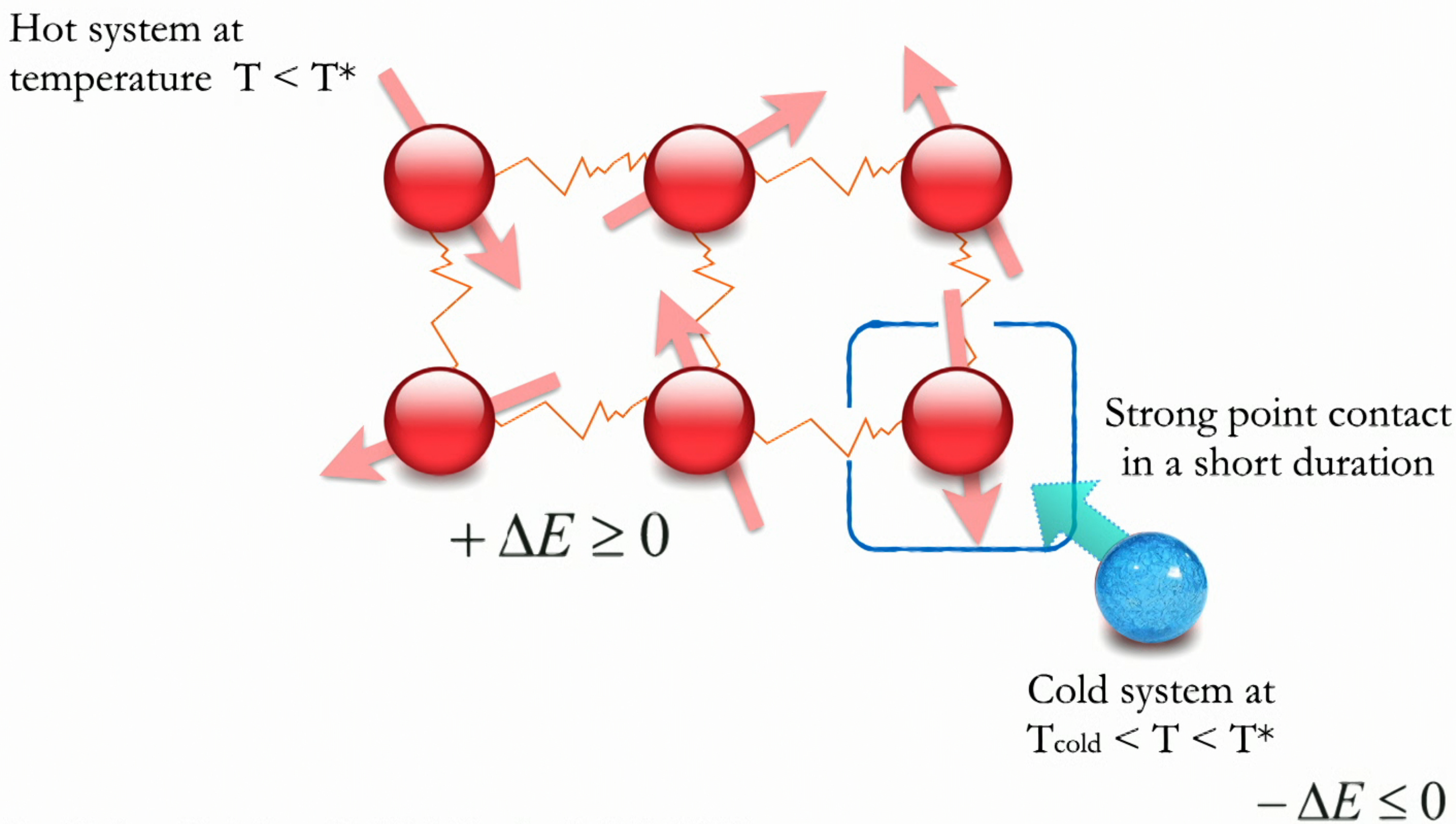
Corollary: For thermal states



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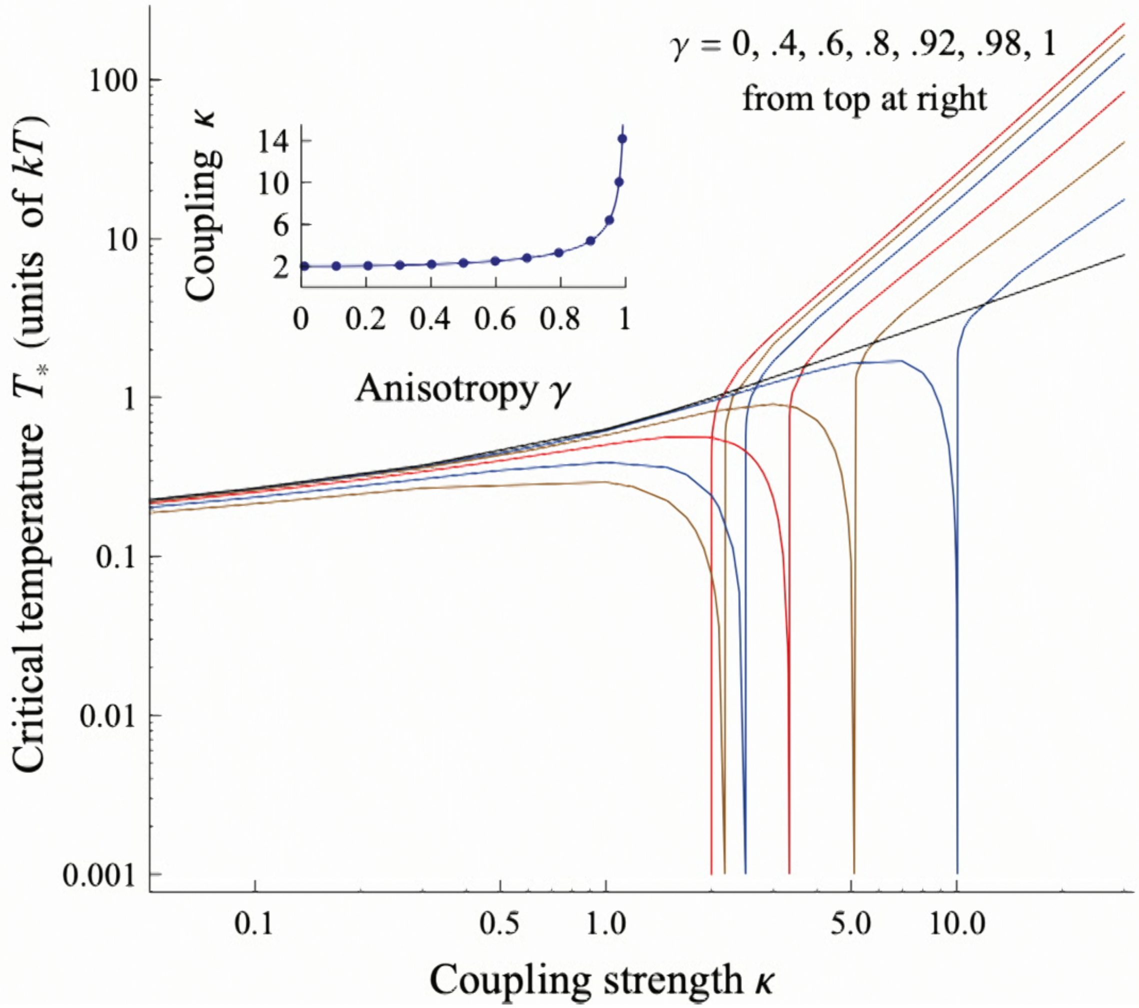
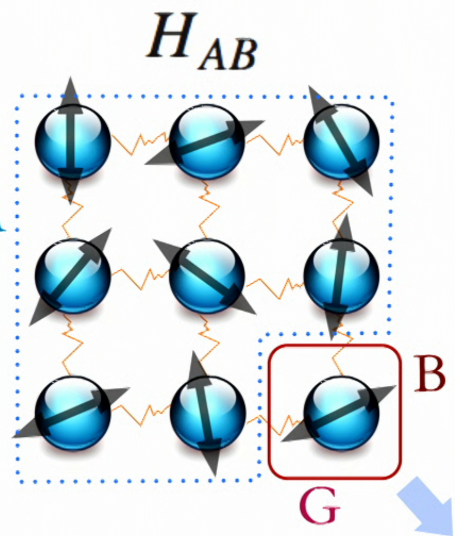
Example

$$H = \sigma_Z^A + \sigma_Z^B + \kappa\left(\frac{1+\gamma}{2}\sigma_X^A\sigma_X^B + \frac{1-\gamma}{2}\sigma_Y^A\sigma_Y^B\right)$$



How can we fully characterize this new notion of strong-local passivity?



Maximum extractable energy under general local operations on B:

$$\Delta E_{A(B)_{max}} := \mathrm{Tr}\left[H_{\mathrm{AB}}\rho_{\mathrm{AB}}\right] - \min_{\mathrm{G}} \mathrm{Tr}\left[H_{\mathrm{AB}}(I_{\mathrm{A}} \otimes \mathrm{G})\rho_{\mathrm{AB}}\right]$$

$$\Delta E_{A(B)_{max}} = \Delta E^{I_{\mathrm{B}}}_{A(B)_{max}} = 0$$

A Alhambra, G Styliaris, NA Rodriguez Briones, J Sikora, Martín-Martínez. Phys Rev Lett. 123 (19), 190601

The problem of finding the conditions for the CP-local passivity becomes an optimization problem over all G, such that for the pair $\{\rho_{AB}, H_{AB}\}$ satisfies

$$\Delta E_{A(B)_{max}} = \Delta E^{I_B}_{A(B)_{max}} = 0$$

Semi-definite programming

$$\alpha = \inf\{\mathrm{Tr}(CX) : \Phi(X) = B, X \geq 0\}$$

Allowing us to obtain a theorem with the necessary and sufficient conditions

A Alhambra, G Styliaris, NA Rodriguez Briones, J Sikora, Martín-Martínez. Phys Rev Lett. 123 (19), 190601

Necessary and sufficient conditions

Theorem

The pair $\{\rho_{AB}, H_{AB}\}$ is CP-local passive with respect to B iff

$$\mathrm{Tr}_{A'}[d_A|\Phi\rangle\langle\Phi|C_{AA'}] \text{ is Hermitian, and}$$

$$C_{AA'} - \mathrm{Tr}_{A'}[d_A|\Phi\rangle\langle\Phi|C_{AA'}] \otimes \mathbf{I}_{A'} \geq 0$$

$\mathcal{H}_{A'}$ being a copy of $\mathcal{H}_A$

Where $C_{AA'} \equiv \mathrm{Tr}_B[\rho_{AB}^{\Gamma_A} H_{A'B}] \in \mathcal{H}_A \otimes \mathcal{H}_{A'}$

$\rho_{AB}^{\Gamma_A}$ is the partial transpose on A, and

$d_A|\Phi\rangle\langle\Phi|$ is the (maximally entangled) Choi-Jamiołkowski operator of the identity channel

A Alhambra, G Styliaris, NA Rodriguez Briones, J Sikora, Martín-Martínez. Phys Rev Lett. 123 (19), 190601

Bad news for local cooling of interacting systems?

Bad news for local cooling of interacting systems?

- Cool down the system:

Ground state is entangled ⟶ Subsystems are mixed

- Break entanglement through interaction with environment:

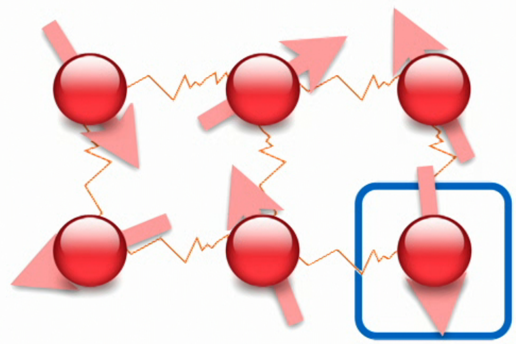
System in a Gibbs state ⟶ Subsystems are mixed

- Apply local operations on the subsystem:

Strong local passivity ⟶ Subsystem's energy increases

How do we cool down a part of an interacting system?

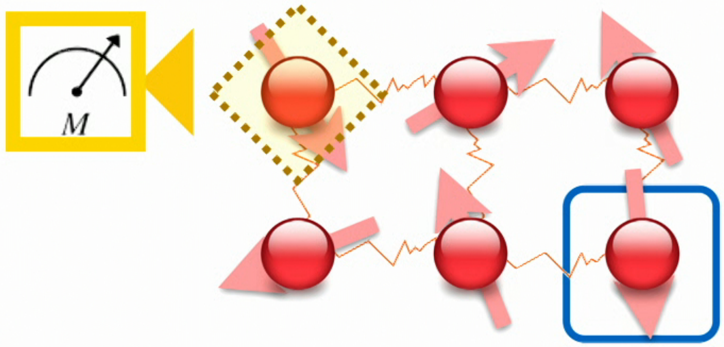
Breaking Strong-Local Passivity with Quantum Energy Teleportation



M. Hotta, Physics Letters A 374, 3416 (2010)

Breaking Strong-Local Passivity with Quantum Energy Teleportation

1) Local measurement



- **Step I.** Local measurement of a distant subsystem, with measurement operators that commute with the interaction Hamiltonian

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Breaking Strong-Local Passivity with Quantum Energy Teleportation

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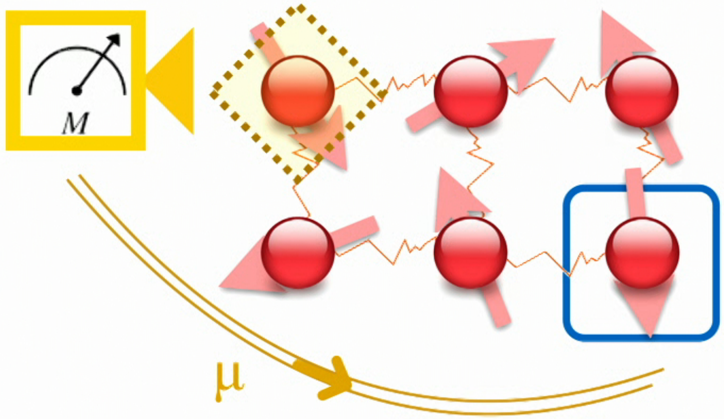

2) Communicating outcome μ

- **Step I.** Local measurement of a distant subsystem, with measurement operators that commute with the interaction Hamiltonian
- **Step II.** Communicate the outcome μ to subsystem A

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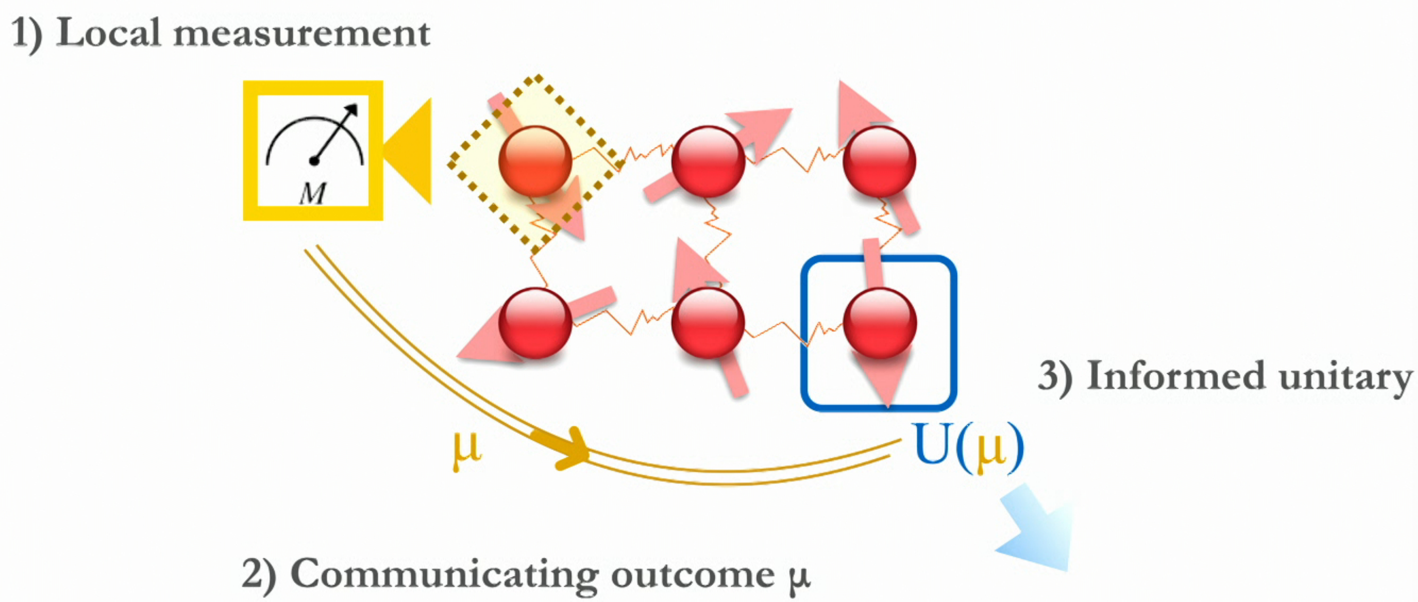
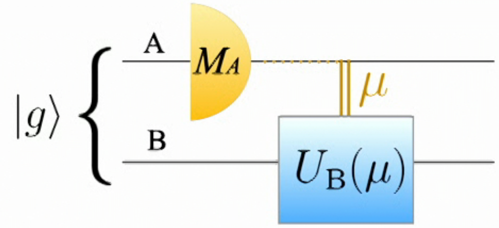
Breaking Strong-Local Passivity with Quantum Energy Teleportation



- **Step I.** Local measurement of a distant subsystem, with measurement operators that commute with the interaction Hamiltonian
- **Step II.** Communicate the outcome μ to subsystem A
- **Step III.** Informed unitary depending on outcome μ to extract energy locally

M. Hotta, Physics Letters A 374, 3416 (2010)

Minimal QET protocol



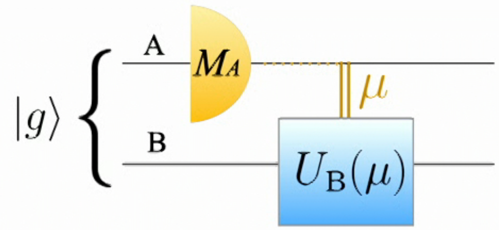
I)

$$H = H_A + H_B + V$$

$$H = \sigma_Z^A + \sigma_Z^B + \kappa\left(\frac{1+\gamma}{2}\sigma_X^A\sigma_X^B + \frac{1-\gamma}{2}\sigma_Y^A\sigma_Y^B\right)$$

γ=1 $\qquad |g\rangle = \left(F_+ |00\rangle_{AB} - F_- |11\rangle_{AB}\right)/\sqrt{2}$

Minimal QET protocol



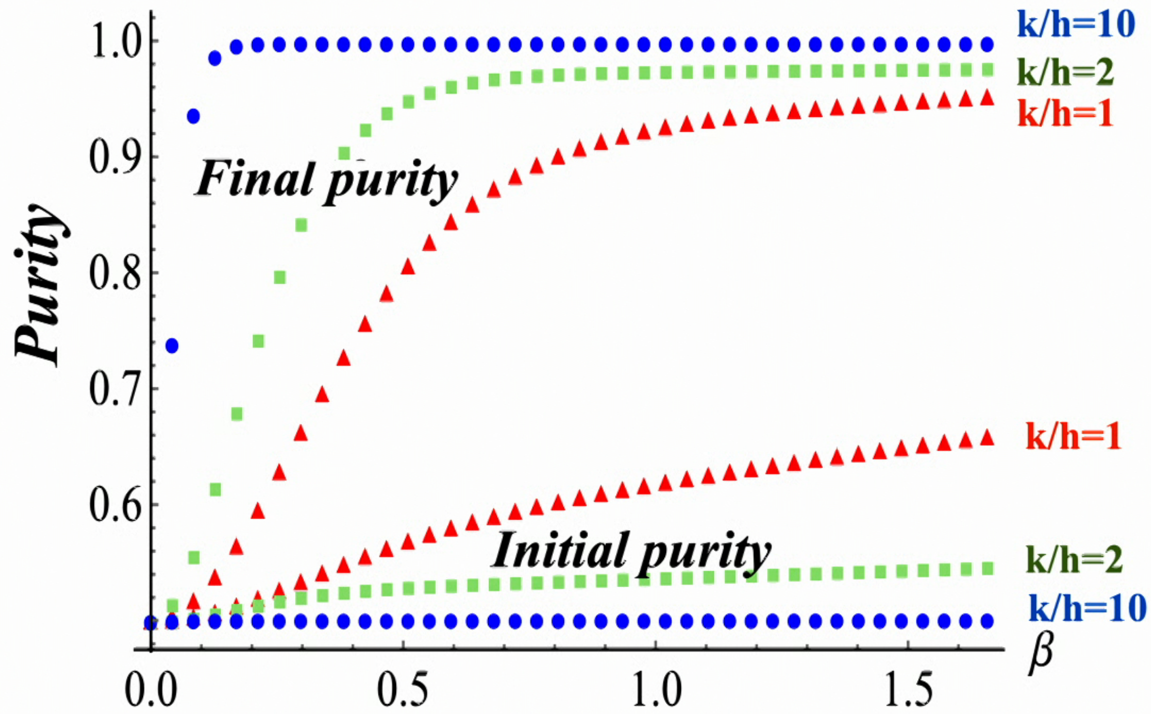
I)

$[M_A, V] = 0$

E_A

Purifying with the minimal QET

$$H = \sigma_Z^A + \sigma_Z^B + \kappa\left(\frac{1+\gamma}{2}\sigma_X^A\sigma_X^B + \frac{1-\gamma}{2}\sigma_Y^A\sigma_Y^B\right)$$



γ=1

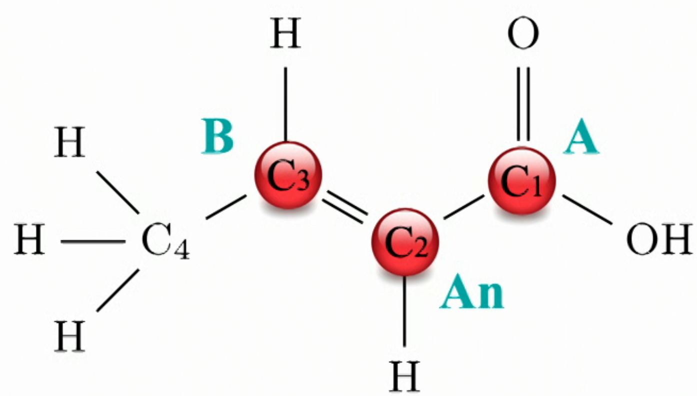
N. Rodríguez-Briones, E.Martín-Martínez, A. Kempf, R. Laflamme Phys. Rev. Lett. 119 (5), 050502

First QET experimental implementation

Transcrotonic acid

$$H = \sigma_Z^A + \sigma_Z^B + \kappa\left(\frac{1+\gamma}{2}\sigma_X^A\sigma_X^B + \frac{1-\gamma}{2}\sigma_Y^A\sigma_Y^B\right)$$

$\gamma=1$



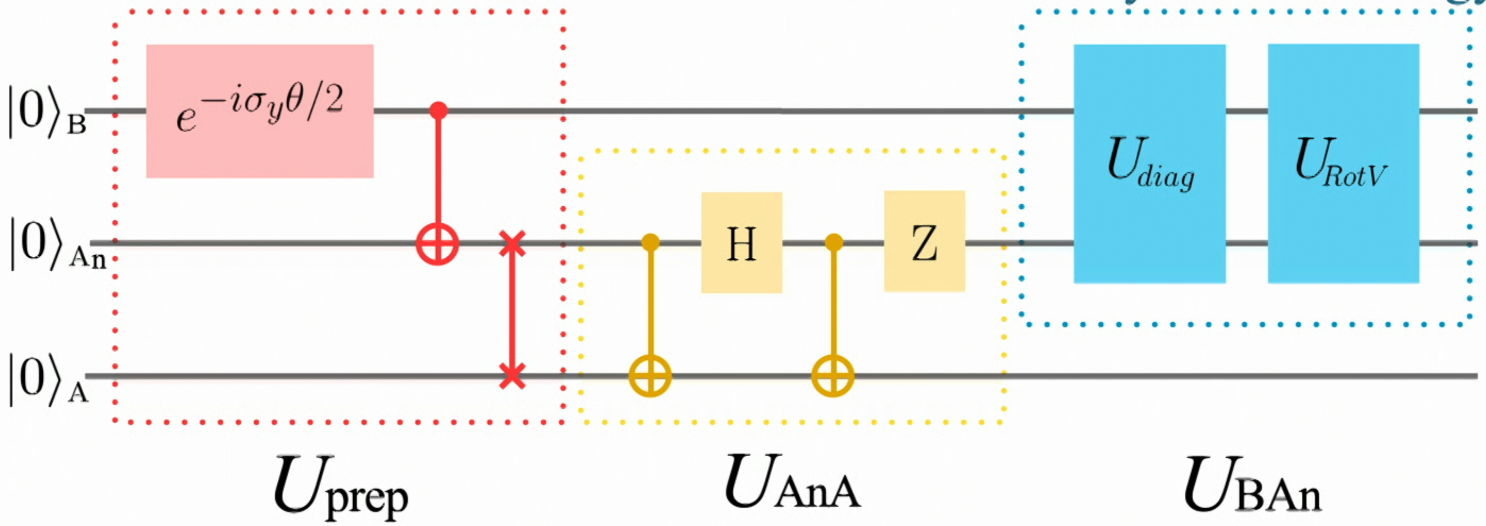
	C_1	C_2	C_3	C_1
C_1	-29343.19			
C_2	72.27	-21591.54		
C_3	1.16	69.68	-25463.29	
C_4	7.04	1.44	41.65	-2991.62

NA Rodriguez-Briones, H Katiyar, R Laflamme, E Martin-Martinez. arXiv preprint arXiv:2203.16269

Fully Unitary QET

0) SLP state preparation

2-3) An transmits information to B and locally extracts energy



1) Auxiliary system An mediates local measurement of A

Energy extracted locally from B: $-\Delta E_{\mathrm{B}} = h_{\mathrm{B}}\langle Z_{\mathrm{B}}\rangle - 2\kappa\langle X_{\mathrm{A}} X_{\mathrm{B}}\rangle + \frac{h_{\mathrm{B}}\left(h_{\mathrm{A}}+h_{\mathrm{B}}\right)-4\kappa^2}{\sqrt{\left(h_{\mathrm{A}}+h_{\mathrm{B}}\right)^2+4\kappa^2}}$

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First QET experimental implementation

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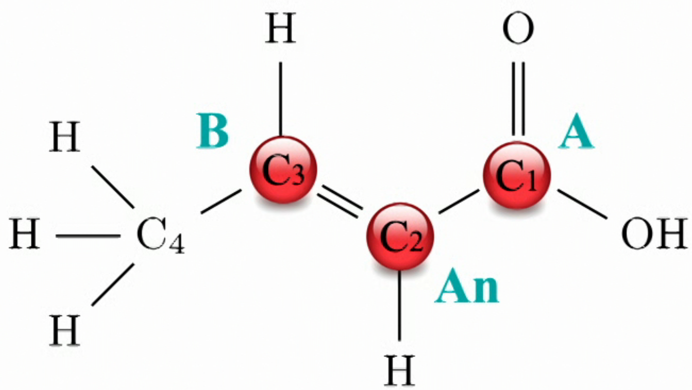
$$H = \sigma_Z^A + \sigma_Z^B + \kappa\left(\frac{1+\gamma}{2}\sigma_X^A\sigma_X^B + \frac{1-\gamma}{2}\sigma_Y^A\sigma_Y^B\right)$$

γ=1



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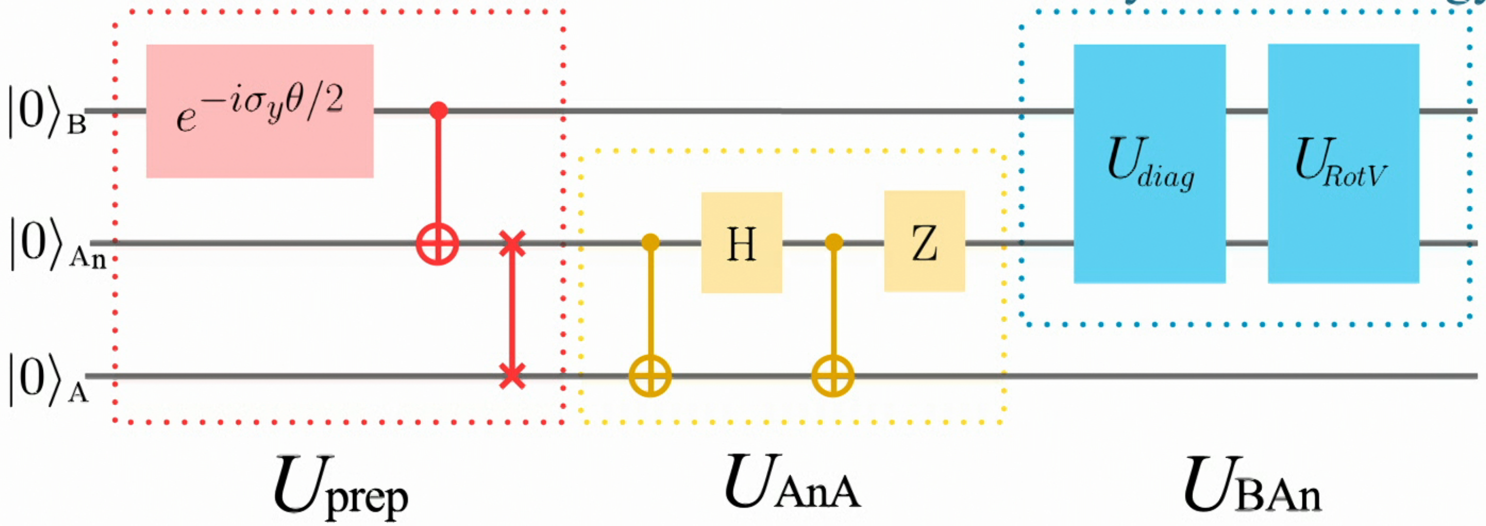

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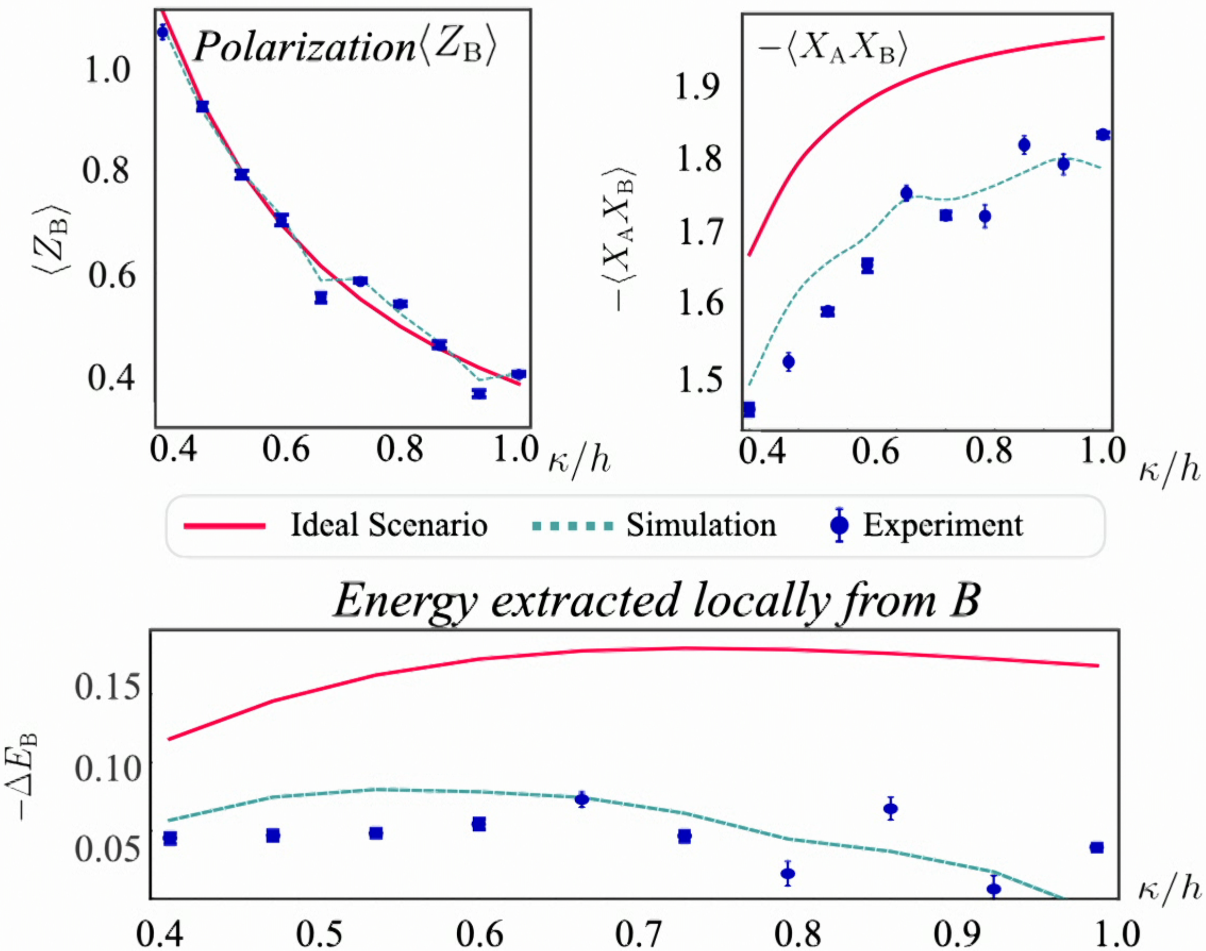
Experimental results



NA Rodríguez-Briones, H Katiyar, R Laflamme, E Martín-Martínez. arXiv preprint arXiv:2203.16269

Conclusions

- We have fully characterized the property of strong-local passivity (giving necessary and sufficient conditions).
- We showed how it is possible to circumvent these local cooling limitations by adding communication between distant subsystems
- We present the first experimental realization of quantum energy teleportation protocol and first observation of local activation of a strong local passive state

NA Rodríguez-Briones, H Katiyar, R Laflamme, E Martín-Martínez. arXiv preprint arXiv:2203.16269 (2022)
A Alhambra, G Styliaris, NA Rodriguez Briones, J Sikora, Martín-Martínez. **Phys Rev Lett.** 123 (19), 190601 (2019)