CLASSICAL EMULATION OF QUANTUM-COHERENT THERMAL MACHINES

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UNIVERSITY OF EXETER

Charge and Energy TransferProcesses–
Open Problems in Open Quantum Systems

BIRS, AUGUST 20TH 2019

J. ONAM GONZÁLEZ
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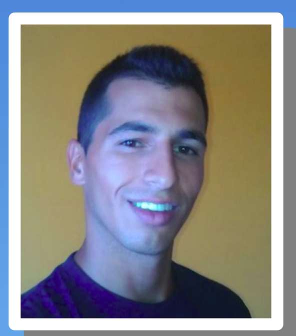
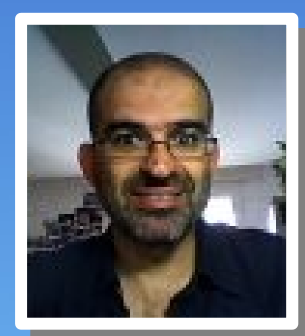
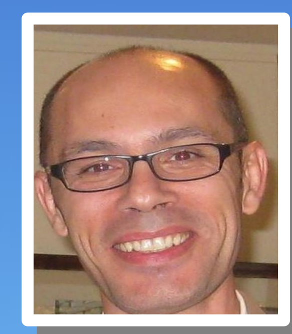






Phys. Rev. E 99, 062102 (2019)

COMPUTING

CRYPTOGRAPHY

METROLOGY

QUANTUM COMPUTING

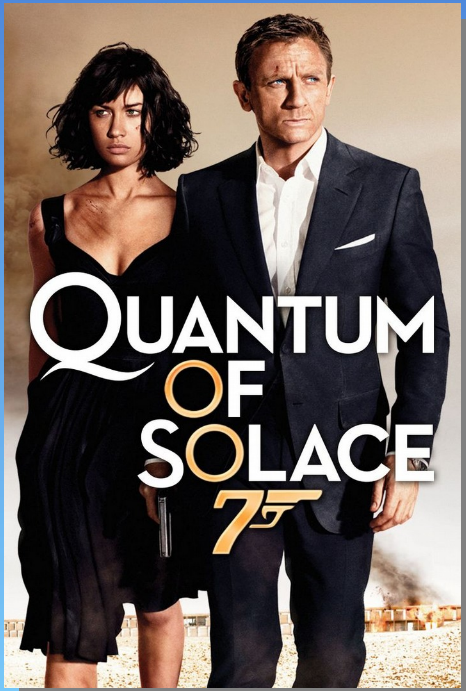
QUANTUM CRYPTOGRAPHY

QUANTUM METROLOGY

QUANTUM COMPUTING

QUANTUM CRYPTOGRAPHY

QUANTUM METROLOGY



QUANTUM COMPUTING

QUANTUM CRYPTOGRAPHY

QUANTUM METROLOGY

QUANTUM THERMODYNAMICS?

QUANTUM THERMODYNAMICS

THREE-LEVEL MASERS AS HEAT ENGINES*

H. E. D. Scovil and E. O. Schulz-DuBois
Bell Telephone Laboratories,
Murray Hill, New Jersey
(Received January 16, 1959)

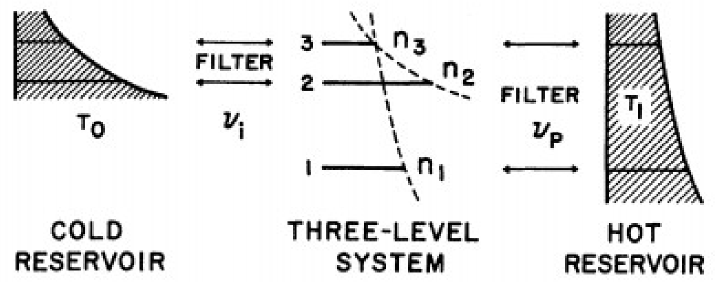


FIG. 1. Three-level system in thermal contact with two heat reservoirs.

J. Phys. A: Math. Gen., Vol. 12, No. 5, 1979.

The quantum open system as a model of the heat engine†

Robert Alicki
Institute of Physics, Gdańsk University, 80-952 Gdańsk, Poland

Received 9 January 1979

WHAT IS QUANTUM THERMODYNAMICS ABOUT?

Describing individual (open) quantum systems in thermodynamic language and take the analogy as far as possible to try to learn about the emergence of thermodynamics from quantum theory.

~~QUANTUM THERMODYNAMICS~~

THERMODYNAMICS IN THE QUANTUM REGIME

Does QUANTUMNESS play any rôle in the thermodynamics of quantum systems ?

...BUT WHICH "QUANTUMNESS"?

ENERGY-LEVEL STRUCTURE

L.A.C. *et al.*, PRE (2014)
Niedenzu *et al.*, PRE (2015)
Silva *et al.*, PRE (2016)
...

QUANTUM RESERVOIR ENGINEERING

Gelbwaser-Klimovsky *et al.*, PRE (2013)
Abah & Lutz, EPL (2014)
L.A.C. *et al.*, Sci. Rep. (2014)
...

QUANTUM CORRELATIONS

L.A.C. *et al.*, PRE (2013)
Brunner *et al.*, PRE (2014)
Brask & Brunner, PRE (2015)
Reid *et al.*, EPL (2017)
...

JOINT PROBABILITY DISTR.

Friedenberger & Lutz, EPL (2017)
Strasberg & García Díaz, PRA (2019)
...

...BUT WHICH "QUANTUMNESS"?

QUANTUM COHERENCE

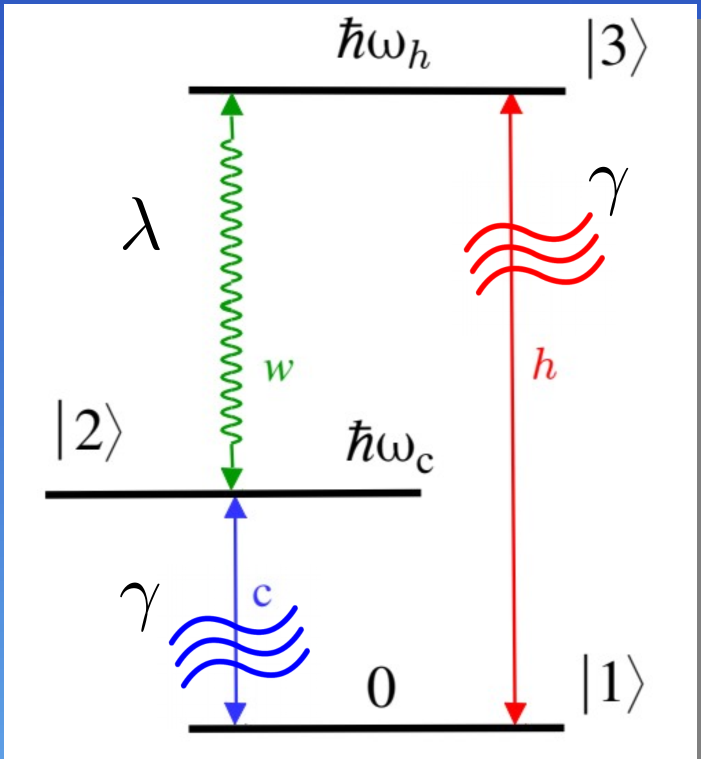
- Scully *et al.*, Science (2003)
- Scully, PRL (2010)
- Anatoly *et al.*, PRA (2011)
- Killoran *et al.*, JCP (2015)
- Mitchison *et al.*, NJP (2015)
- Uzdin *et al.*, PRX (2015)
- Kilgour & Segal, PRE (2018)
- Holubec & Novotny, J. Low. Temp. Phys. (2018)
- Klatzow *et al.*, PRL (2019)
- . . .

Is QUANTUM COHERENCE really necessary?

OUTLINE

1. ~~Motivation~~
2. Two quantum-coherent models
3. How to build a “classical emulator”

POWER-DRIVEN CHILLER

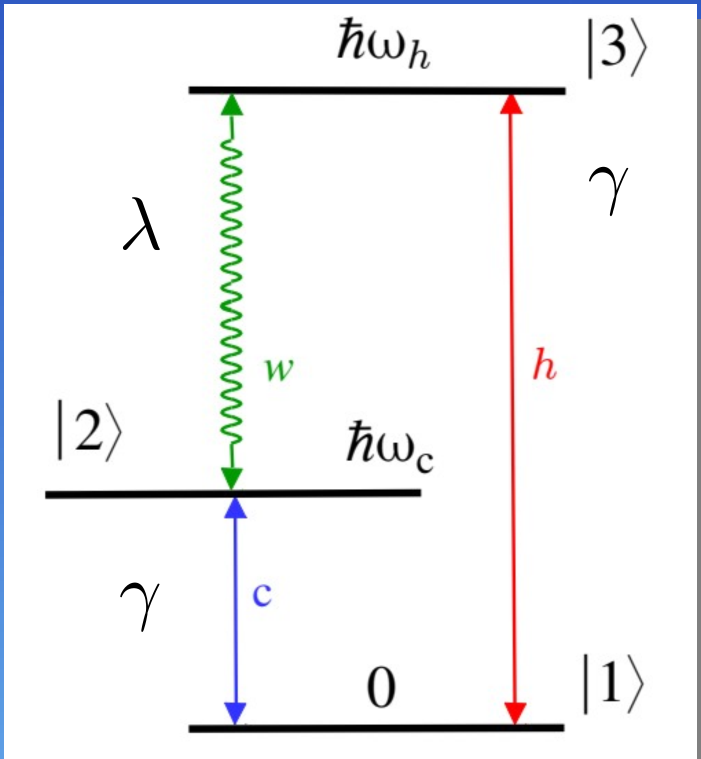


$$\hat{H}_{\rm s}(t) = \hat{H}_0 + \hat{H}_{\rm d}(t)$$

$$\hat{H}_0 = \hbar\omega_c|2\rangle\langle 2| + \hbar\omega_h|3\rangle\langle 3|$$

$$\hat{H}_{\rm d}(t) = 2\hbar\lambda|2\rangle\langle 3|\cos\omega_w t + \text{h.c.}$$

POWER-DRIVEN CHILLER



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$$\hat{H}_{\mathrm{d}}(t) = 2\hbar\lambda|2\rangle\langle 3|\cos\omega_w t + \mathrm{h.c.}$$

$$\tau_{\mathrm{R}} \gg \tau_{\mathrm{B}}$$

$$\tau_{\mathrm{R}} \gg \tau_0$$

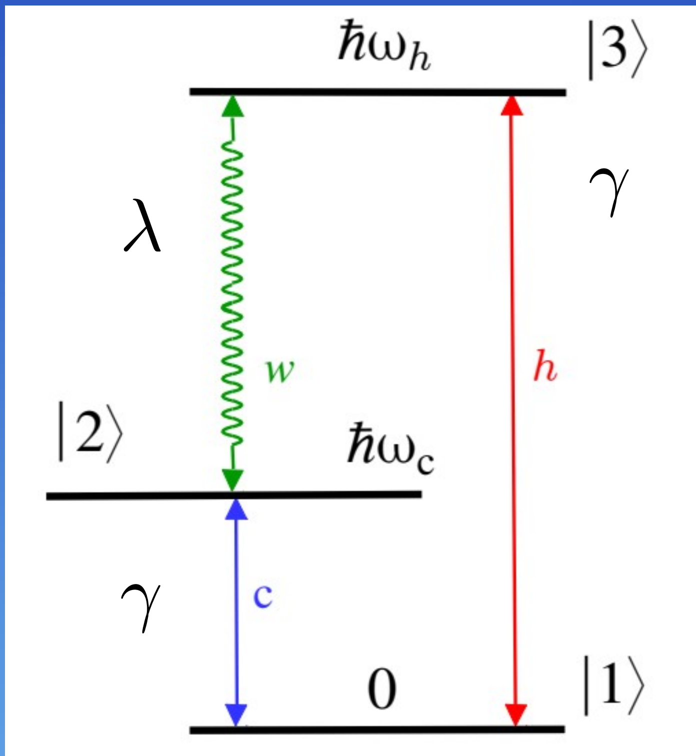
Markov-Floquet master eq.

$$\frac{\mathrm{d}\hat{\varrho}}{\mathrm{d}t} = \sum_\alpha \mathcal{D}_\alpha\,\hat{\varrho} + \mathcal{O}(\gamma^3)$$

Breuer & Petruccione (2002)

Szczygielski, J. Math. Phys. (2014)

POWER-DRIVEN CHILLER



$$\hat{H}_{\mathrm{s}}(t) = \hat{H}_0 + \hat{H}_{\mathrm{d}}(t)$$

$$\hat{U}_{\mathrm{s}}^{\dagger}\hat{O}\hat{U}_{\mathrm{s}} = e^{\mathrm{i}\hat{H}_0 t/\hbar}\hat{O}e^{-\mathrm{i}\hat{H}_0 t/\hbar} + \mathcal{O}(\lambda)$$

$$\tau_{\mathrm{d}} \gg \tau_{\mathrm{R}} \gg \tau_{\mathrm{B}}$$

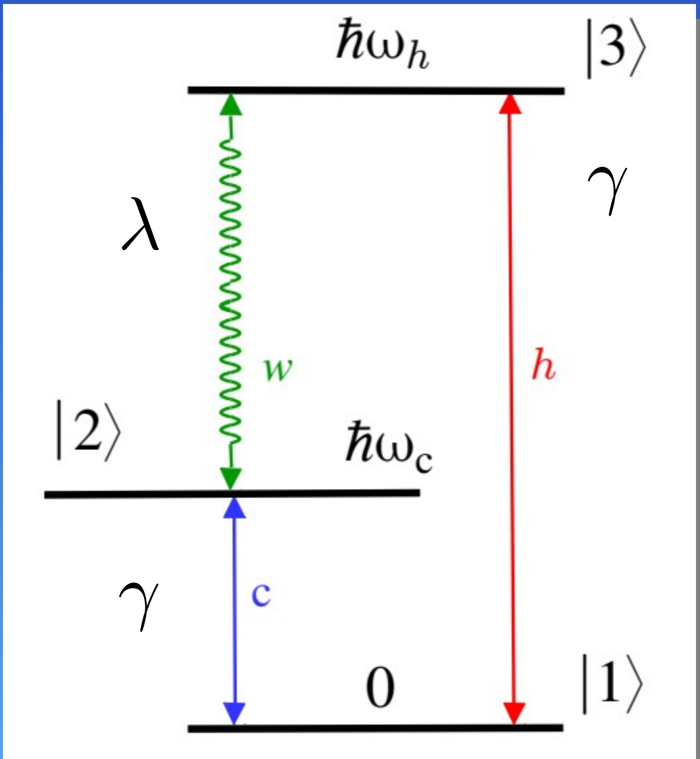
$$\tau_{\mathrm{d}} \gg \tau_{\mathrm{R}} \gg \tau_{0}$$

Local master equation

$$\frac{\mathrm{d}\hat{\varrho}}{\mathrm{d}t} = -i[\hat{H}_0 + \hat{H}_{\mathrm{d}}(t), \hat{\varrho}] + \sum_{\alpha} \mathcal{L}_{\alpha}(\hat{\sigma}_{\alpha})\,\hat{\varrho} + \mathcal{O}(\lambda\gamma^2)$$

González *et al.*, Open Sys. Inf. Dyn. (2017)

POWER-DRIVEN CHILLER



$$\frac{\mathrm{d}\hat{\varrho}_\infty}{\mathrm{d}t} = 0$$

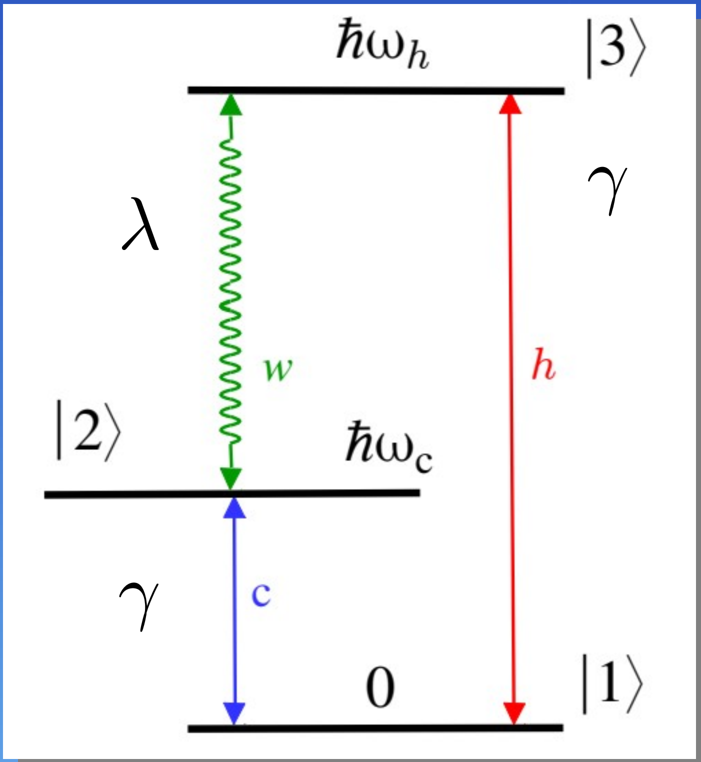
$$\dot{\mathcal{Q}}_\alpha = \mathrm{tr}\,\{\hat{H}_0\,\mathcal{L}_\alpha\,\hat{\varrho}_\infty\} + \mathcal{O}(\lambda\gamma^2)$$

$$\mathcal{P} = -\dot{\mathcal{Q}}_c - \dot{\mathcal{Q}}_h$$

$$\frac{\dot{\mathcal{Q}}_c}{T_c} + \frac{\dot{\mathcal{Q}}_h}{T_h} \leq 0$$

Alicki, J. Phys. A (1979)

POWER-DRIVEN CHILLER



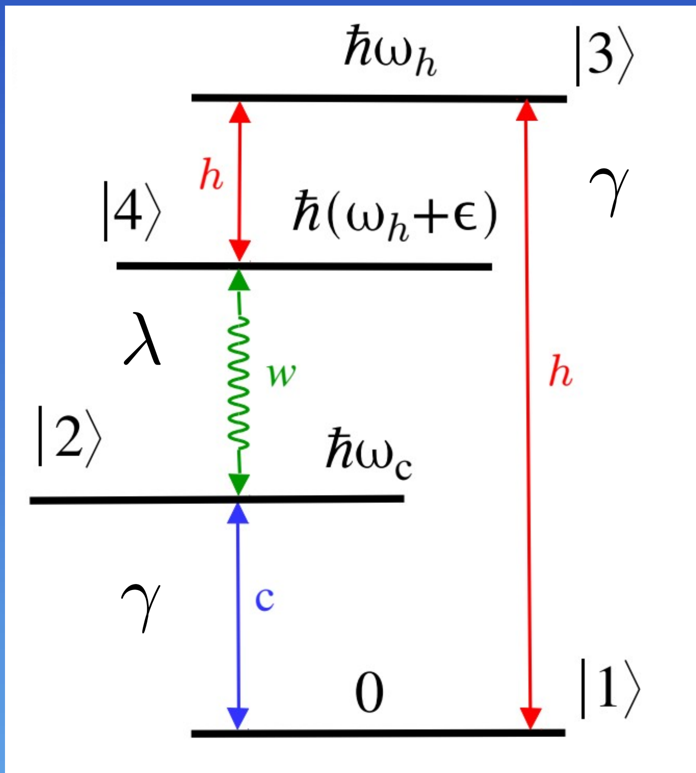
$$\frac{\mathrm{d}\hat{\varrho}_\infty}{\mathrm{d}t} = 0$$

$$\left.\begin{aligned} \dot{\mathcal{Q}}_\alpha &= \hbar\omega_\alpha J \\ \mathcal{P} &= \hbar\omega_w J \end{aligned}\right\} \quad \varepsilon = \frac{\omega_c}{\omega_w}$$

$$J = 2\lambda \mathrm{Im}\,\langle 2|\hat{\varrho}_\infty|3\rangle$$

* The device is ENDOREVERSIBLE
* The energy-converstion rate is PROPORTIONAL to the steady-state coherence

HYBRID CHILLER

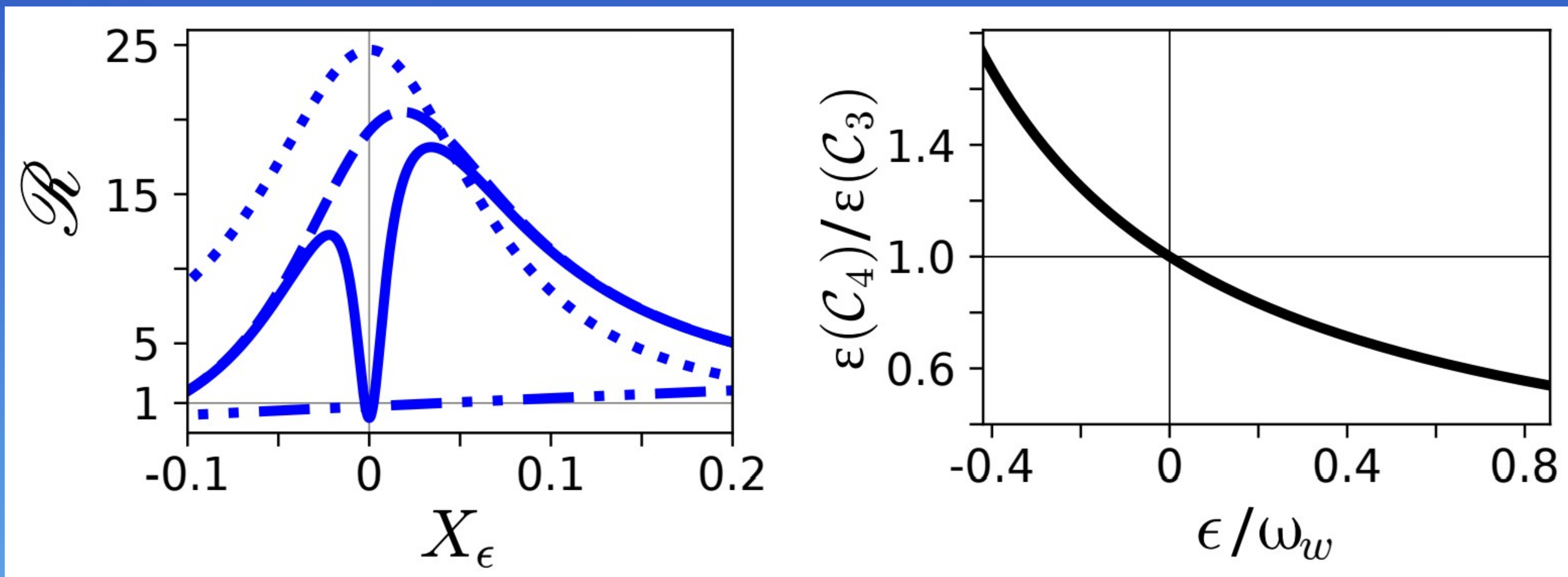


$$\frac{\mathrm{d}\hat{\varrho}'_\infty}{\mathrm{d}t} = 0$$

$$\left.\begin{aligned} \dot{\mathcal{Q}}'_\alpha &= \hbar\omega_\alpha J' \\ \mathcal{P}' &= \hbar(\omega_w + \epsilon) J' \end{aligned}\right\} \varepsilon' = \frac{\omega_c}{\omega_w + \epsilon}$$

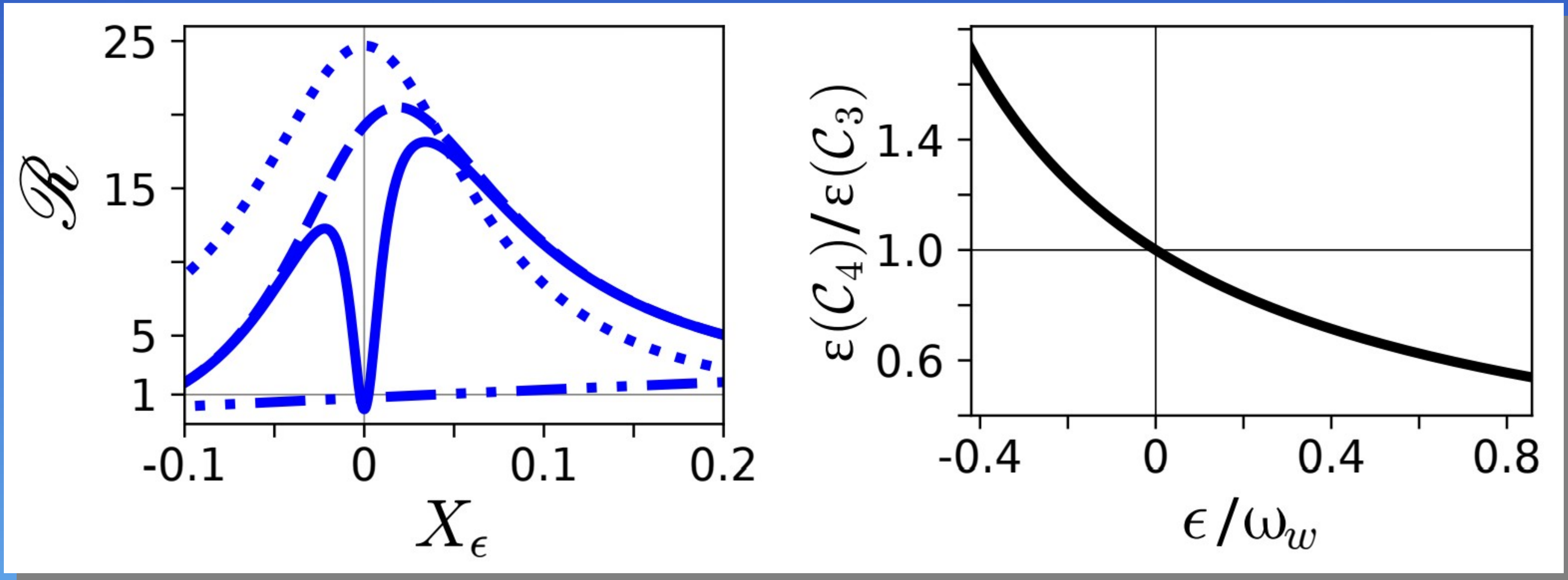
$$J' = 2\lambda \mathrm{Im}\, \langle 2|\hat{\varrho}'_\infty|4\rangle$$

POWER-DRIVEN vs. HYBRID



$$\mathscr{R} = \frac{\dot{\mathcal{Q}}'_c}{\dot{\mathcal{Q}}_c}$$

POWER-DRIVEN vs. HYBRID



$$\mathscr{R} = \frac{\dot{\mathcal{Q}}'_c}{\dot{\mathcal{Q}}_c} = \frac{\mathcal{C}_{l_1}(\hat{\varrho}'_\infty)}{\mathcal{C}_{l_1}(\hat{\varrho}_\infty)} > 1$$

OUTLINE

1. ~~Motivation~~
2. ~~Two quantum-coherent models~~
3. How to build a “classical emulator”

3-STATE EMULATOR

Local master equation in the (bare) energy basis

$$\frac{\mathrm{d}\varrho_{11}}{\mathrm{d}t} = \Gamma^h_{\omega_h}\varrho_{33} - (\Gamma^h_{-\omega_h} + \Gamma^c_{-\omega_c})\varrho_{11} + \Gamma^c_{\omega_c}\varrho_{22}$$

$$\frac{\mathrm{d}\varrho_{22}}{\mathrm{d}t} = \Gamma^c_{-\omega_c}\varrho_{11} - \Gamma^c_{\omega_c}\varrho_{22} - 2\lambda \mathrm{Im}\,\varrho_{23}$$

$$\frac{\mathrm{d}\varrho_{33}}{\mathrm{d}t} = \Gamma^h_{-\omega_h}\varrho_{11} - \Gamma^c_{\omega_c}\varrho_{33} + 2\lambda \mathrm{Im}\,\varrho_{23}$$

$$\frac{\mathrm{d}\varrho_{23}}{\mathrm{d}t} = -\frac{1}{2}(\Gamma^c_{\omega_c} + \Gamma^h_{\omega_h})\varrho_{23} - \mathrm{i}(\varrho_{33} - \varrho_{22})$$

$$\Gamma^\alpha_{-\omega_\alpha} = e^{-\frac{\hbar\omega_\alpha}{k_B T_\alpha}}\Gamma^\alpha_{\omega_\alpha}$$

3-STATE EMULATOR

Stationary solution

$$0 = \Gamma^{h}_{\omega_h}\varrho_{33} - (\Gamma^{h}_{-\omega_h} + \Gamma^{c}_{-\omega_c})\varrho_{11} + \Gamma^{c}_{\omega_c}\varrho_{22}$$

$$0 = \Gamma^{c}_{-\omega_c}\varrho_{11} - \Gamma^{c}_{\omega_c}\varrho_{22} - 2\lambda \mathrm{Im}\,\varrho_{23}$$

$$0 = \Gamma^{h}_{-\omega_h}\varrho_{11} - \Gamma^{c}_{\omega_c}\varrho_{33} + 2\lambda \mathrm{Im}\,\varrho_{23}$$

$$0 = -\frac{1}{2}(\Gamma^{c}_{\omega_c} + \Gamma^{h}_{\omega_h})\varrho_{23} - \mathrm{i}(\varrho_{33} - \varrho_{22})$$

$$\varrho_{23} = 2\mathrm{i}\lambda \frac{\varrho_{22} - \varrho_{33}}{\Gamma^{\mathrm{c}}_{\omega_\mathrm{c}} + \Gamma^{\mathrm{h}}_{\omega_\mathrm{h}}}$$

3-STATE EMULATOR

Stationary populations

$$0 = \Gamma^h_{\omega_h}\varrho_{33} - (\Gamma^h_{-\omega_h} + \Gamma^c_{-\omega_c})\varrho_{11} + \Gamma^c_{\omega_c}\varrho_{22}$$

$$0 = \Gamma^c_{-\omega_c}\varrho_{11} - \Gamma^c_{\omega_c}\varrho_{22} - 4\lambda^2\frac{\varrho_{22} - \varrho_{33}}{\Gamma^c_{\omega_c} + \Gamma^h_{\omega_h}}$$

$$0 = \Gamma^h_{-\omega_h}\varrho_{11} - \Gamma^c_{\omega_c}\varrho_{33} + 4\lambda^2\frac{\varrho_{22} - \varrho_{33}}{\Gamma^c_{\omega_c} + \Gamma^h_{\omega_h}}$$

3-STATE EMULATOR

Classical emulator

$$\frac{\mathrm{d}\varrho_{11}}{\mathrm{d}t} = \Gamma^{h}_{\omega_h}\varrho_{33} - (\Gamma^{h}_{-\omega_h} + \Gamma^{c}_{-\omega_c})\varrho_{11} + \Gamma^{c}_{\omega_c}\varrho_{22}$$

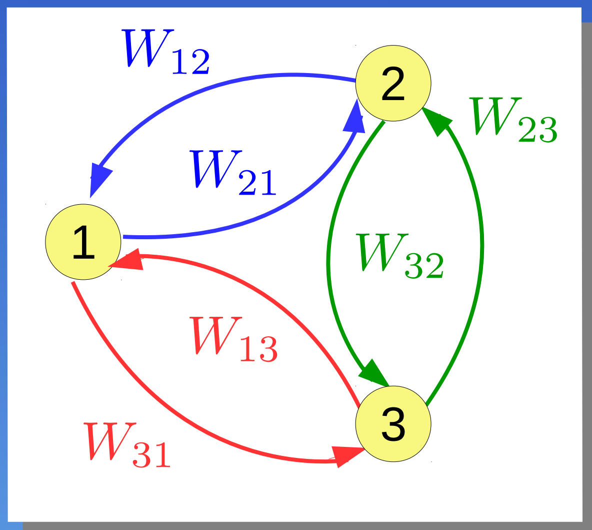
$$\frac{\mathrm{d}\varrho_{22}}{\mathrm{d}t} = \Gamma^{c}_{-\omega_c}\varrho_{11} - \Gamma^{c}_{\omega_c}\varrho_{22} - 4\lambda^2\frac{\varrho_{22}-\varrho_{33}}{\Gamma^{c}_{\omega_c} + \Gamma^{h}_{\omega_h}}$$

$$\frac{\mathrm{d}\varrho_{33}}{\mathrm{d}t} = \Gamma^{h}_{-\omega_h}\varrho_{11} - \Gamma^{c}_{\omega_c}\varrho_{33} + 4\lambda^2\frac{\varrho_{22}-\varrho_{33}}{\Gamma^{c}_{\omega_c} + \Gamma^{h}_{\omega_h}}$$

$$\frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t} = \boldsymbol{W}\boldsymbol{p}$$

THERMODYNAMIC EQUIVALENCE

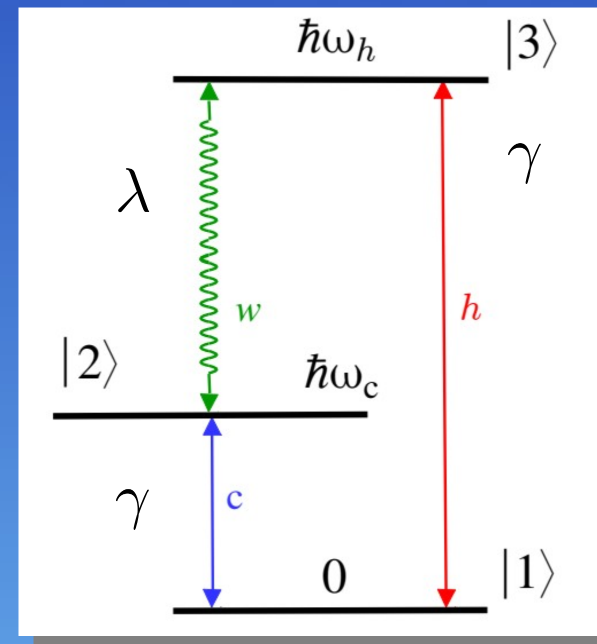
Classical emulator



$$\frac{\mathrm{d}\boldsymbol{p}}{\mathrm{dt}} = \boldsymbol{W}\boldsymbol{p}$$

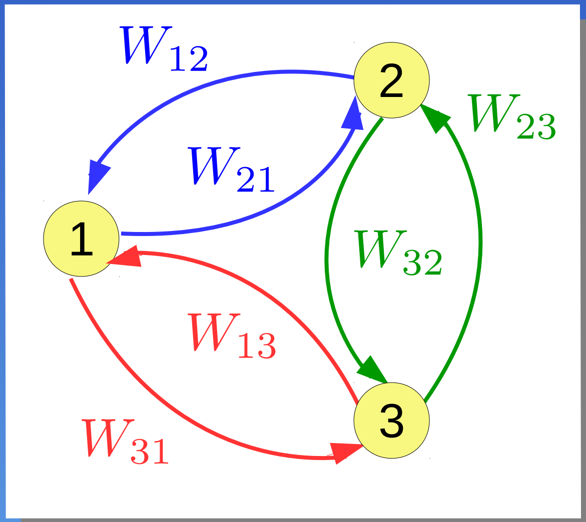
?
=

Coherent chiller



THERMODYNAMIC EQUIVALENCE

Classical emulator



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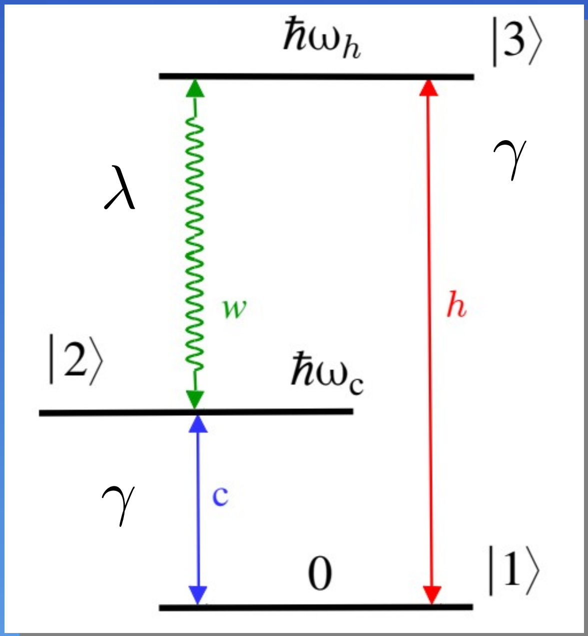
Coherent chiller

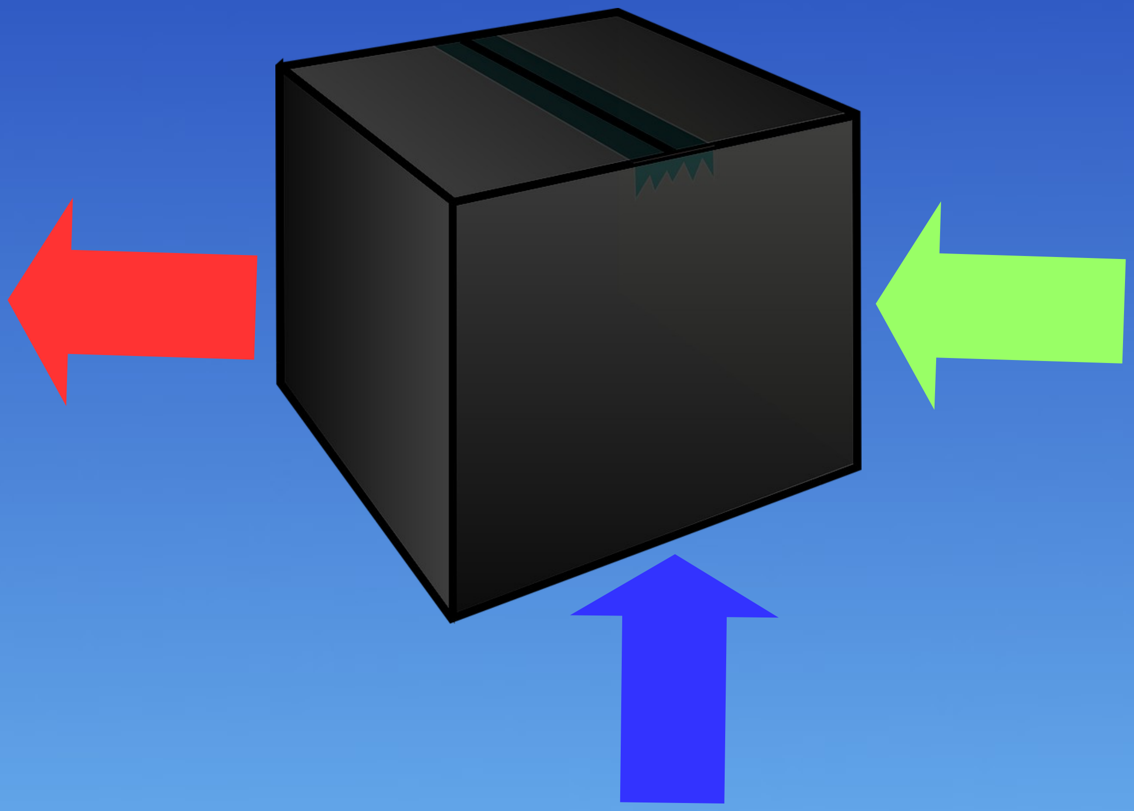


$$\dot{\mathcal{Q}}_\alpha(\mathcal{G}_3) = \dot{\mathcal{Q}}_\alpha$$

Hill, J. Theoret. Biol. (1966)
Schnackenberg, RMP (1976)

González *et al.*, Entropy (2016)
González *et al.*, NJP (2017)

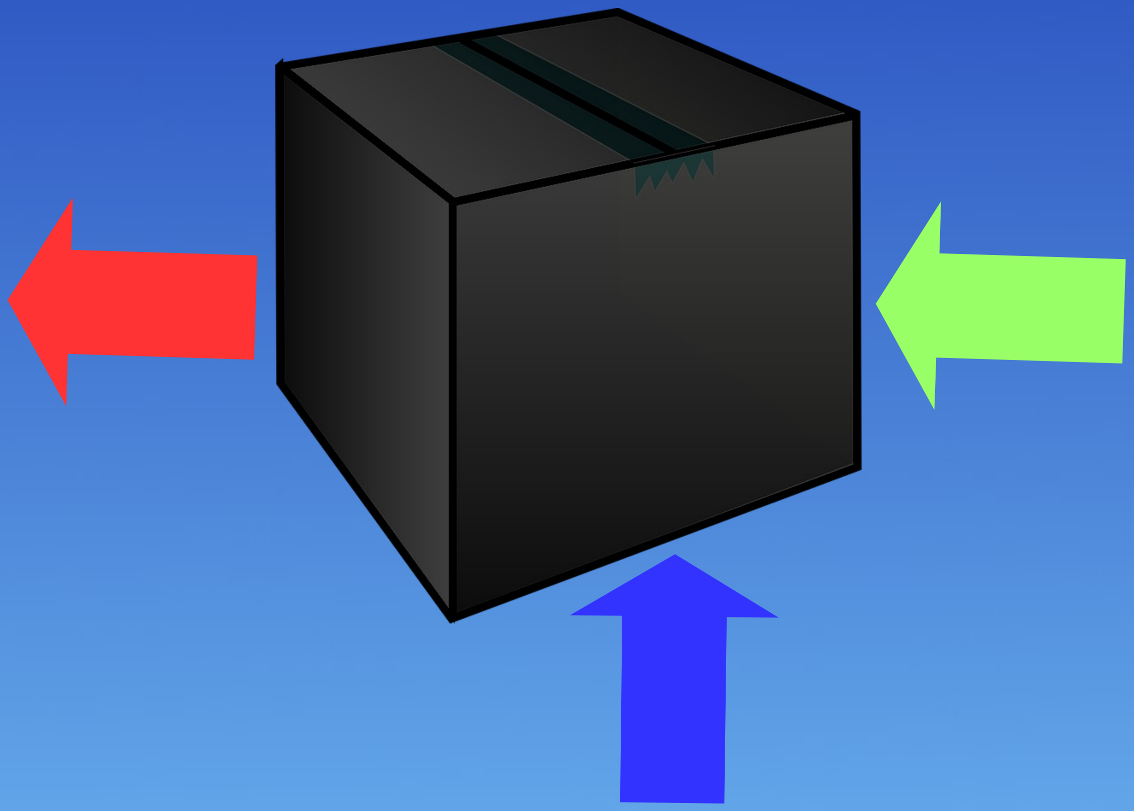
COHERENT OR INCOHERENT?



Cyclic weakly-driven (coherent) heat devices can all be emulated classically.

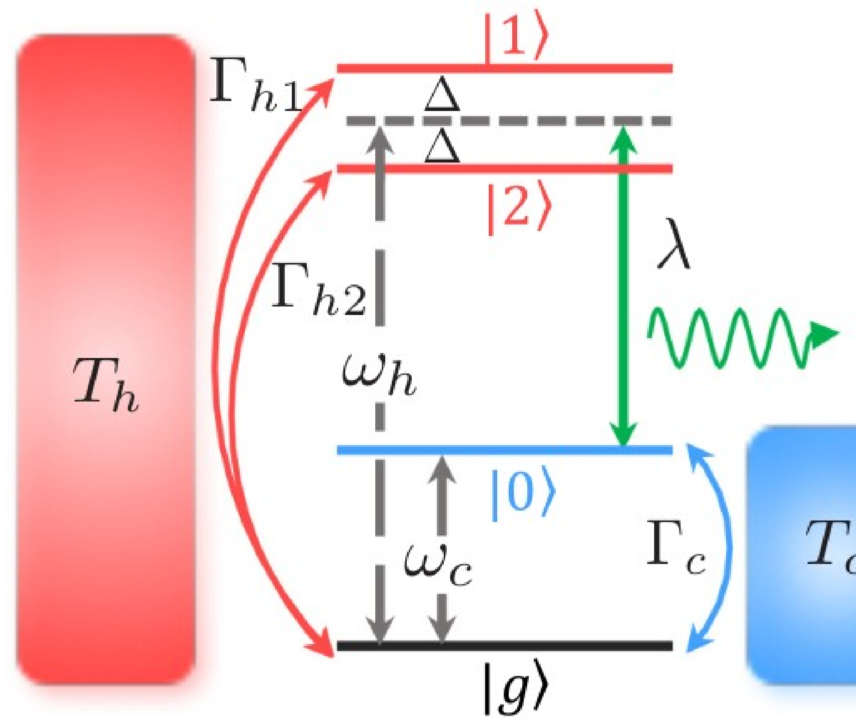
Quantum coherence is NOT NECESSARY to explain their thermodynamic behaviour.

TRULY QUANTUM?



Are there coherent models that CANNOT be emulated classically ?

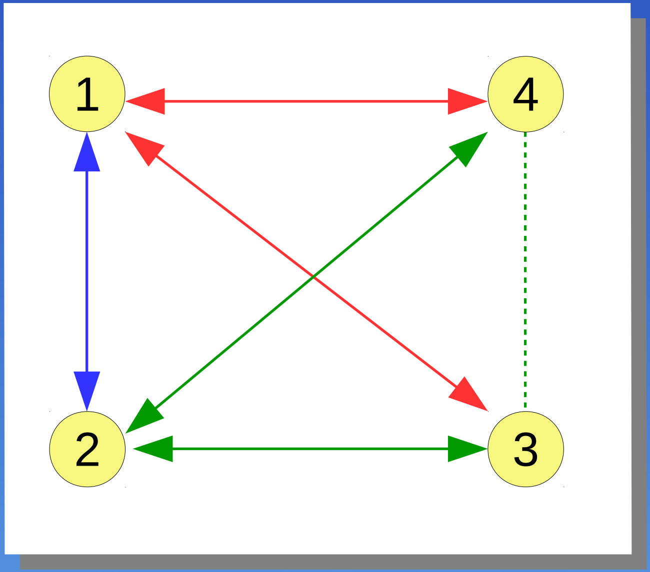
TRULY QUANTUM



$$\hat{U}_0^\dagger \hat{H}_d(t)\hat{U}_0 = \hbar\lambda(|1\rangle\langle 0| + |2\rangle\langle 0| + \text{h.c.})$$

Dorfman, *et al.* PRE (2018)

TRULY QUANTUM



$$\frac{\mathrm{d}\boldsymbol{p}}{\mathrm{dt}} = \boldsymbol{W}\boldsymbol{p}$$

Not always positive!

$$\{W_{34}, W_{43}\}$$

$$\dot{\mathcal{Q}}_\alpha = \sum_k \dot{\mathcal{Q}}_\alpha(\mathcal{C}_j) = \dot{\mathcal{Q}}_\alpha^{\mathrm{class}} + \dot{\mathcal{Q}}_\alpha^{\mathrm{quant}}$$

Quantum is NOT better?!

$$\dot{\mathcal{Q}}_c^{\mathrm{quant}} < 0$$

Dorfman, *et al.* PRE (2018)

OUTLINE

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2. ~~Two quantum-coherent models~~
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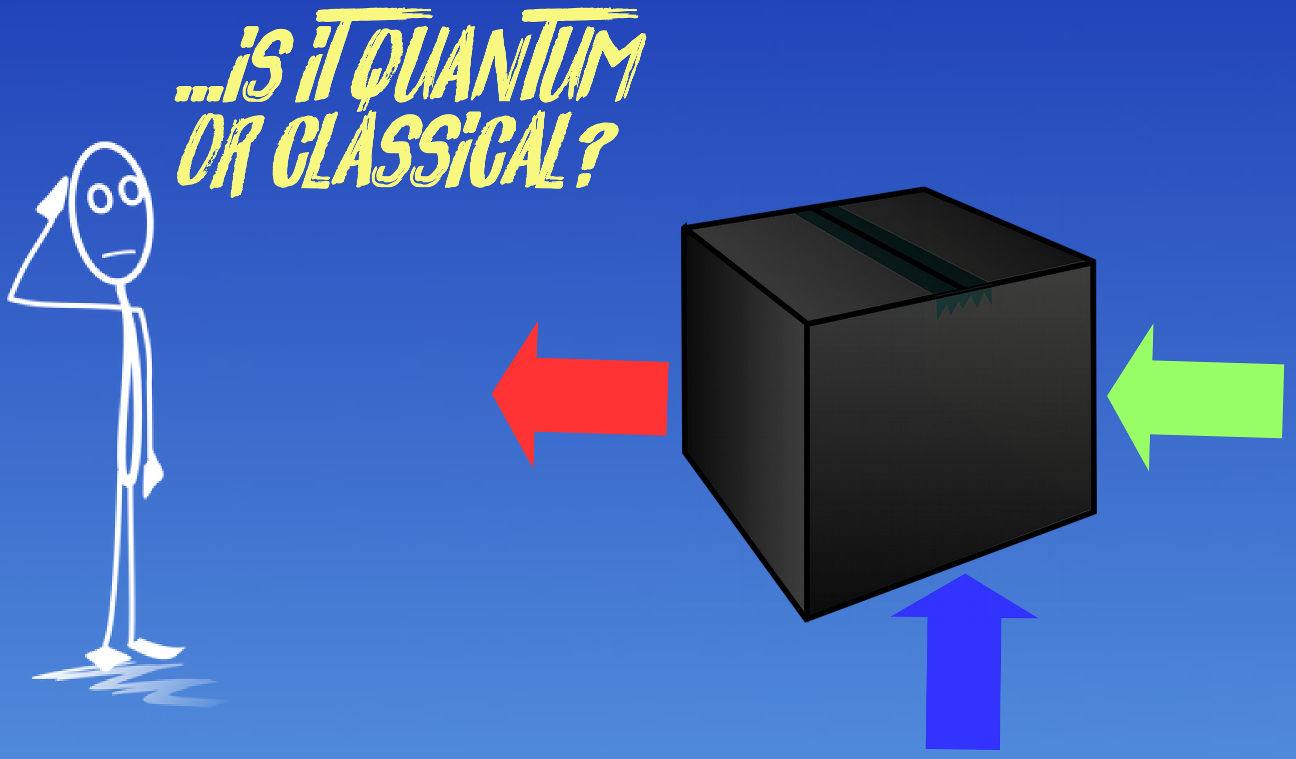

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Thanks for your attention!