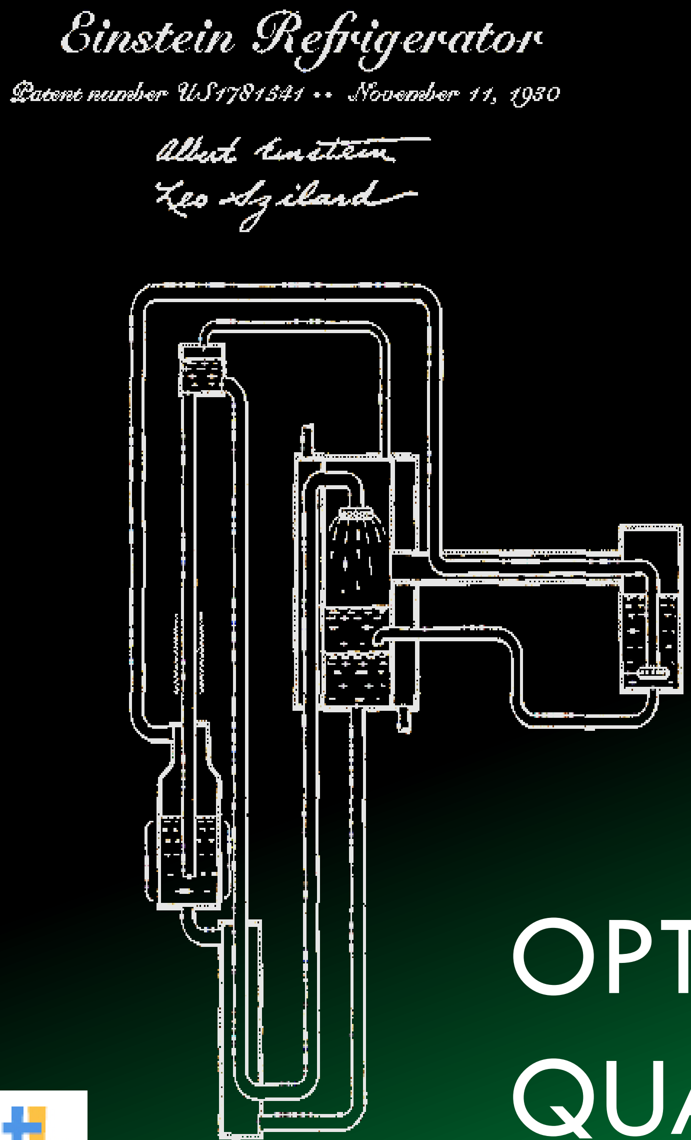

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ULL

OPTIMAL PERFORMANCE OF QUANTUM REFRIGERATORS

2nd Quantum Thermodynamics Conference, Palma, April 2015

L.A. Correa, J.P. Palao, D. Alonso, Gerardo Adesso

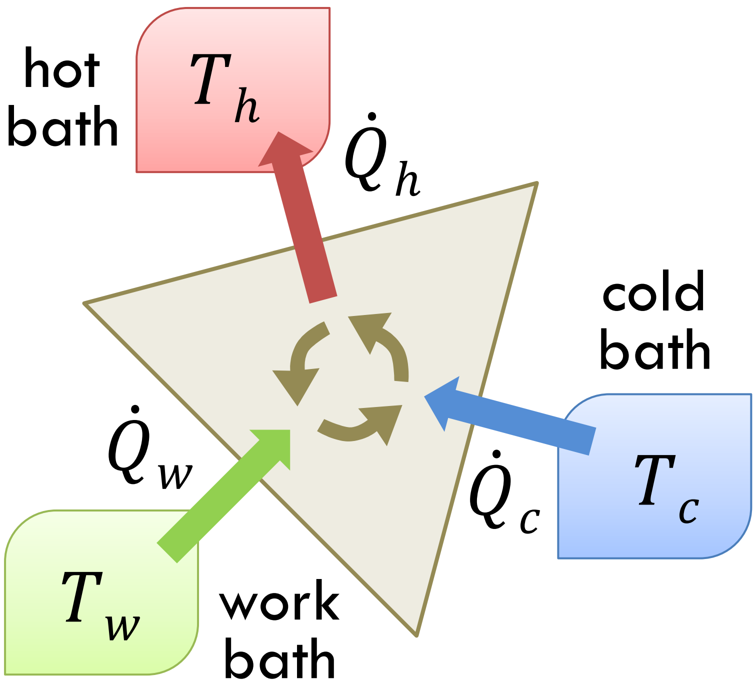
ABSORPTION REFRIGERATORS

"Icyball" (1929)

- Autonomous machines that cool by absorbing heat with no power source
- Used on caravans or in rural areas where main electricity line is missing
- However quite inefficient compared to conventional compression fridges

- *How to understand and possibly improve their optimal performance?*
- *We need to model elementary (quantum) instances of these devices*

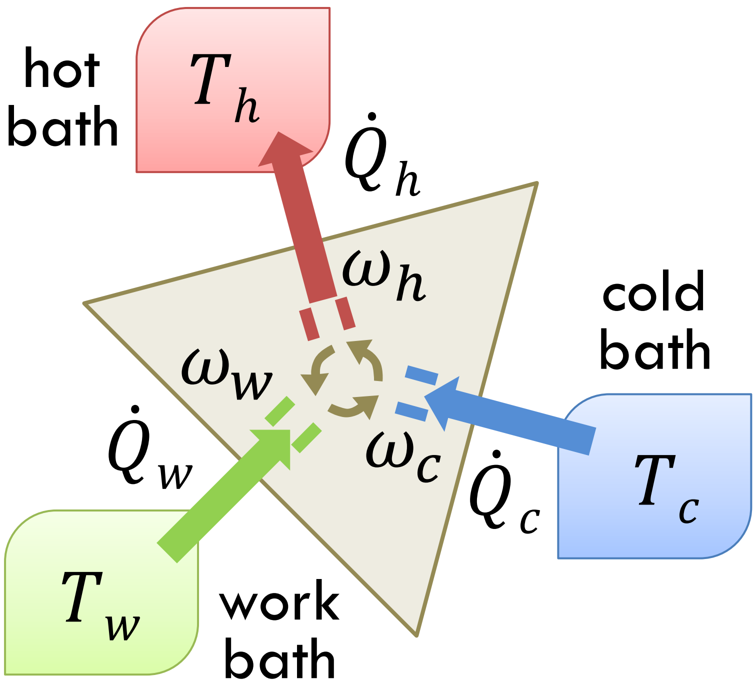
THE TRICYCLE



- Andresen, Salamon & Berry, *J. Chem. Phys.* **66** (1977)

- Prototype of any generic continuous thermal machine
- Includes absorption and power-driven refrigerators ($T_w \to \infty$), heat engines and heat converters
- Three reservoirs: $T_w > T_h > T_c$
- Heat currents: $\dot{Q}_\alpha$ ($\alpha = w, h, c$)
- **Thermodynamics 101**
  1. $\sum_\alpha \dot{Q}_\alpha = 0$ [1st law]
  2. $\sum_\alpha \frac{\dot{Q}_\alpha}{T_\alpha} = -\dot{S} \leq 0$ [2nd law]

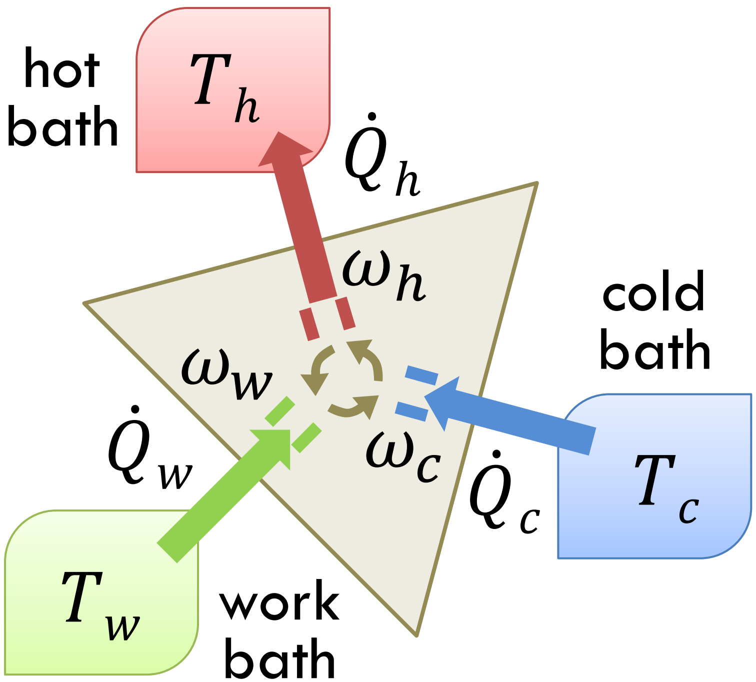
THE QUANTUM TRICYCLE



- Kosloff & Levy, *Annu. Rev. Phys. Chem.* **65** (2014)

- Selective coupling to the baths via filtered frequencies ω_α
- In absence of friction, heat leaks, etc.: single stationary rate J
- Heat currents: $\dot{Q}_\alpha = \pm\,\omega_\alpha\, J$
- **Thermodynamics 101**
  1. $\sum_\alpha \dot{Q}_\alpha = 0$ [1st law]
  2. $\sum_\alpha \frac{\dot{Q}_\alpha}{T_\alpha} = -\dot{S} \leq 0$ [2nd law]
- Resonance: $\omega_w = \omega_h - \omega_c$

QUANTUM ABSORPTION FRIDGE

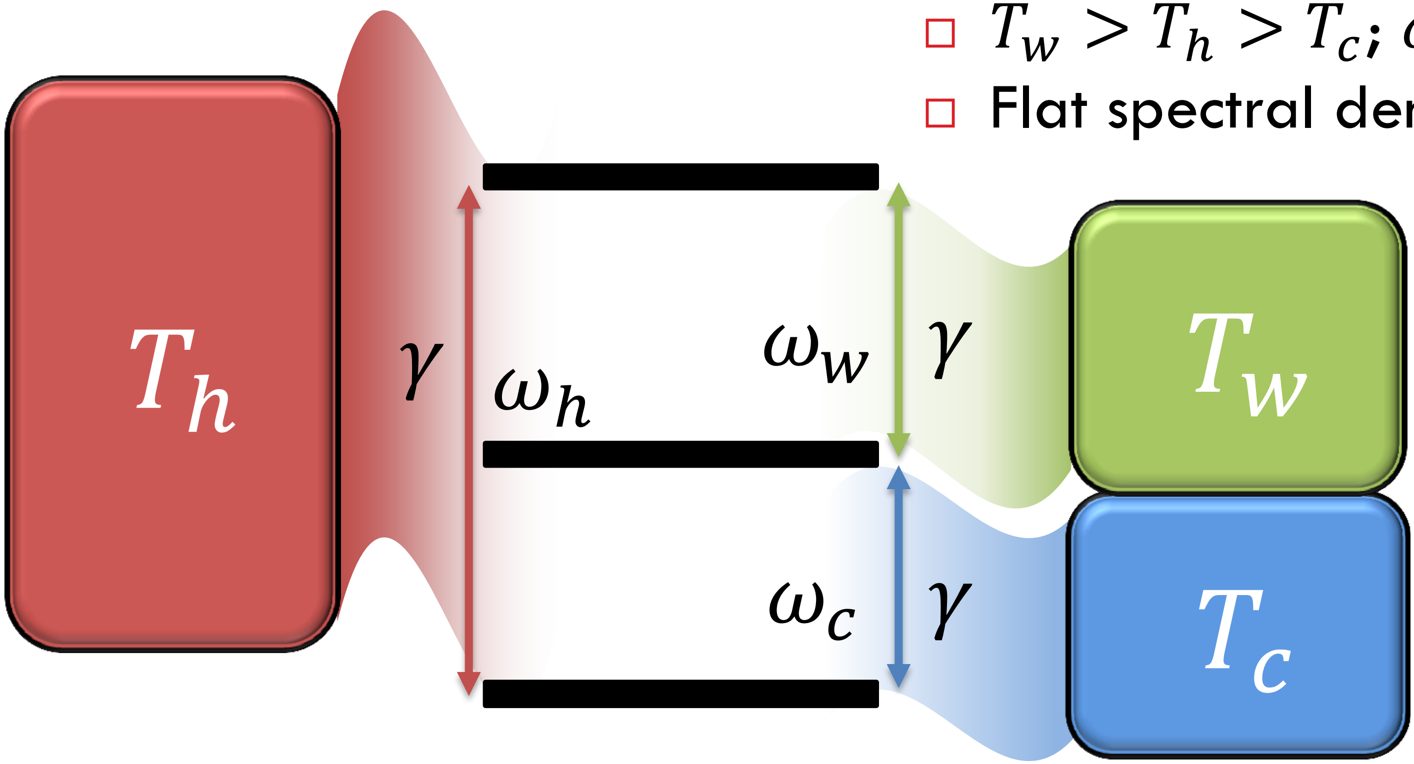


- Kosloff & Levy, *Annu. Rev. Phys. Chem.* **65** (2014)

- $T_w > T_h > T_c$; $\omega_w = \omega_h - \omega_c$
- Cooling window:
  $$\omega_c \leq \omega_c^{\max} = \frac{(T_w - T_h)T_c}{(T_w - T_c)T_h}\omega_h$$
- Cooling power: $\dot{Q}_c$
- Coefficient of performance (COP): $\varepsilon = \frac{\dot{Q}_c}{\dot{Q}_w} \leq \varepsilon_C$
- Carnot COP: $\varepsilon_C = \frac{1 - \frac{T_h}{T_w}}{\frac{T_h}{T_c} - 1}$
- For reversible machines, $\varepsilon \to \varepsilon_C$ at vanishing cooling power

QUANTUM ABSORPTION FRIDGE/1

- **One qutrit** (3-level maser)
- $T_w > T_h > T_c$; $\omega_w = \omega_h - \omega_c$
- Flat spectral densities

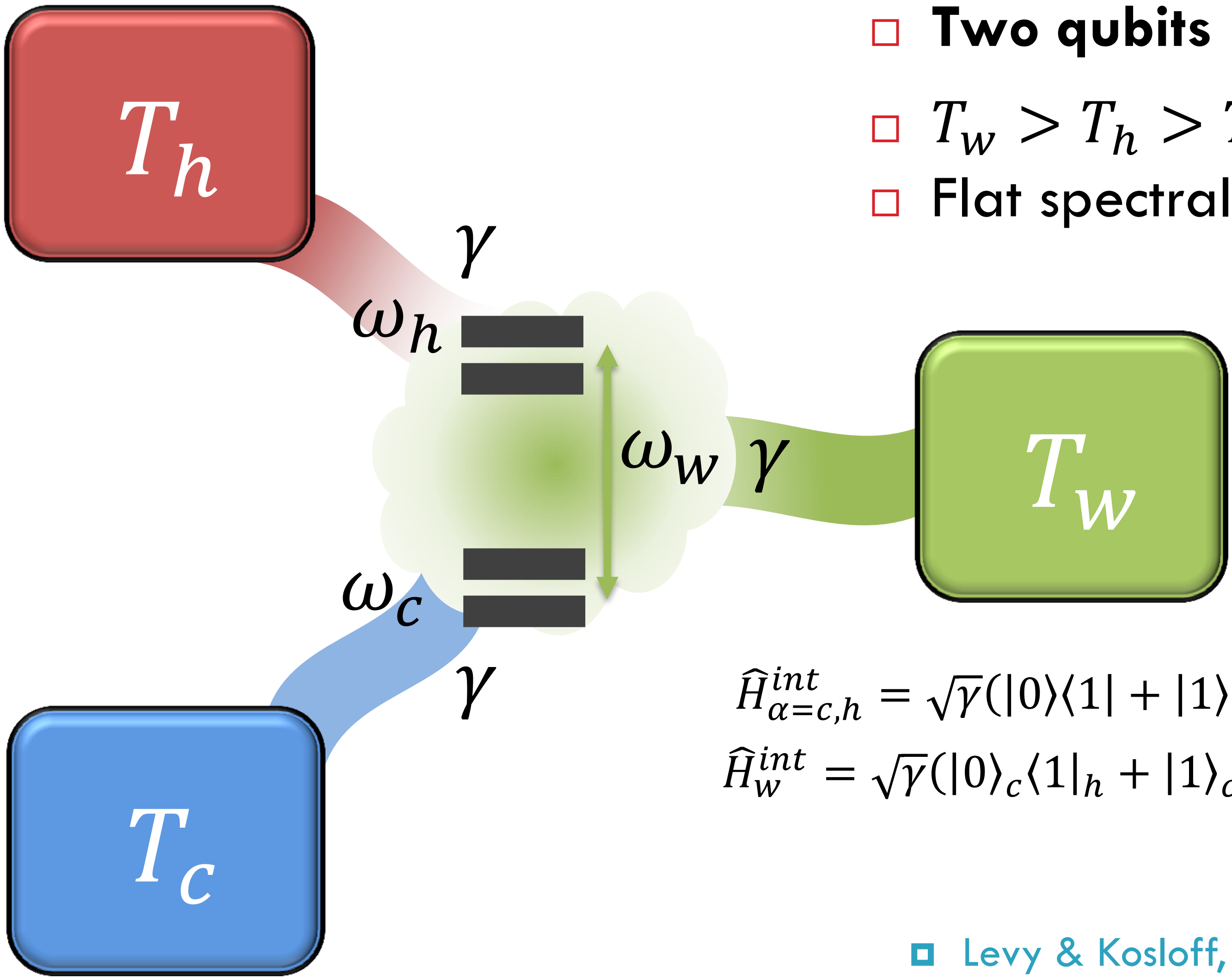


$$\hat{H}_\alpha^{int} = \sqrt{\gamma}(|0\rangle\langle 1| + |1\rangle\langle 0|)_\alpha \otimes \hat{B}_\alpha$$

$$\hat{B}_\alpha = \sum_\mu k_{\alpha,\mu} \sqrt{\omega_\mu}(\hat{b}_{\alpha,\mu} + \hat{b}_{\alpha,\mu}^\dagger)$$

- Geusic, Bios & Scovil, *Phys. Rev. Lett.* **2** (1959)
- Palao, Kosloff & Gordon, *Phys. Rev. E* **64** (2001)

QUANTUM ABSORPTION FRIDGE/2



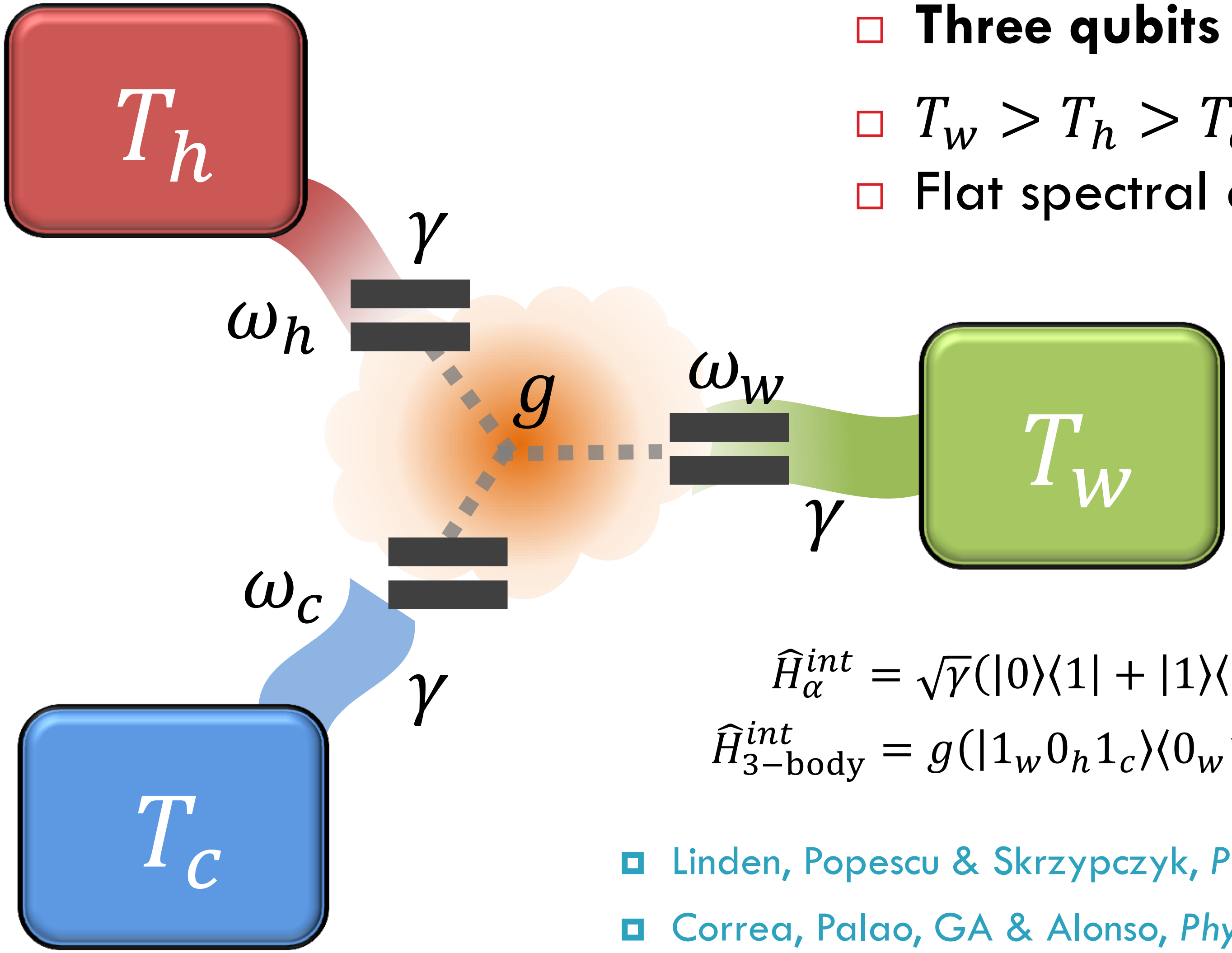
- **Two qubits**
- $T_w > T_h > T_c$; $\omega_w = \omega_h - \omega_c$
- Flat spectral densities

$$\hat{H}^{int}_{\alpha=c,h} = \sqrt{\gamma}(|0\rangle\langle 1| + |1\rangle\langle 0|)_\alpha \otimes \hat{B}_\alpha$$

$$\hat{H}^{int}_{w} = \sqrt{\gamma}(|0\rangle_c\langle 1|_h + |1\rangle_c\langle 0|_h) \otimes \hat{B}_w$$

- Levy & Kosloff, *Phys. Rev. Lett.* **108** (2012)

QUANTUM ABSORPTION FRIDGE/3



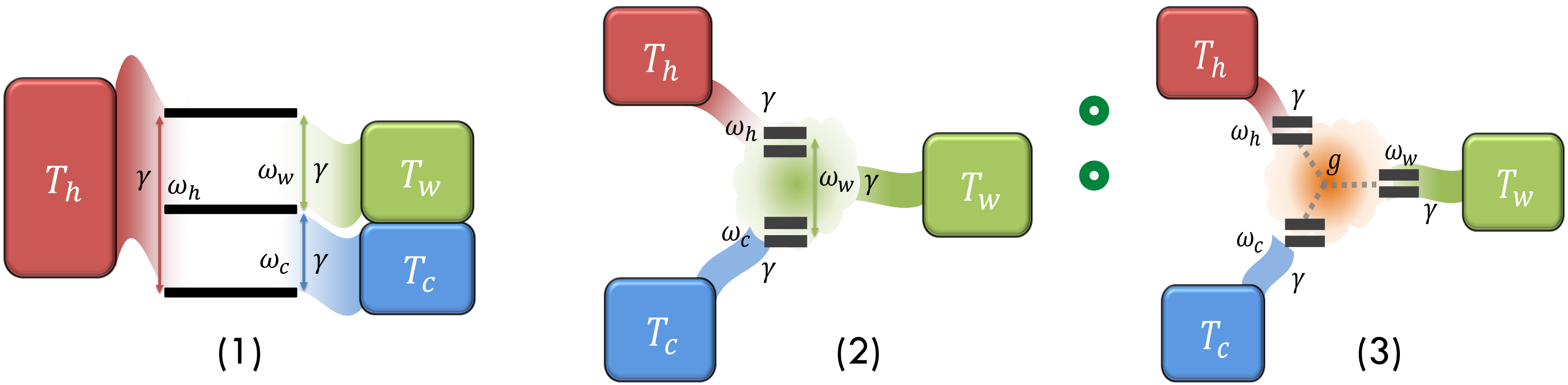
- **Three qubits**
- $T_w > T_h > T_c;\ \omega_w = \omega_h - \omega_c$
- Flat spectral densities

$$\hat{H}_{\alpha}^{int} = \sqrt{\gamma}(|0\rangle\langle 1| + |1\rangle\langle 0|)_{\alpha} \otimes \hat{B}_{\alpha}$$

$$\hat{H}_{3-\text{body}}^{int} = g(|1_w 0_h 1_c\rangle\langle 0_w 1_h 0_c| + h.c.)$$

- Linden, Popescu & Skrzypczyk, *Phys. Rev. Lett.* **105** (2010)
- Correa, Palao, GA & Alonso, *Phys. Rev. E* **87** (2013)

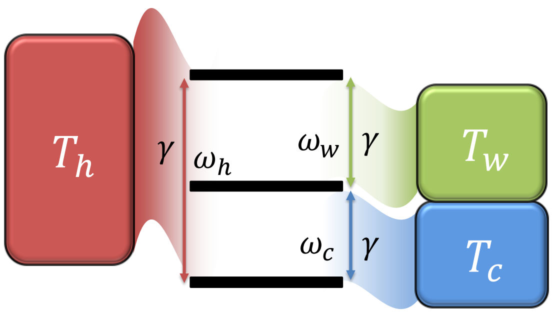
QUANTUM ABSORPTION FRIDGES



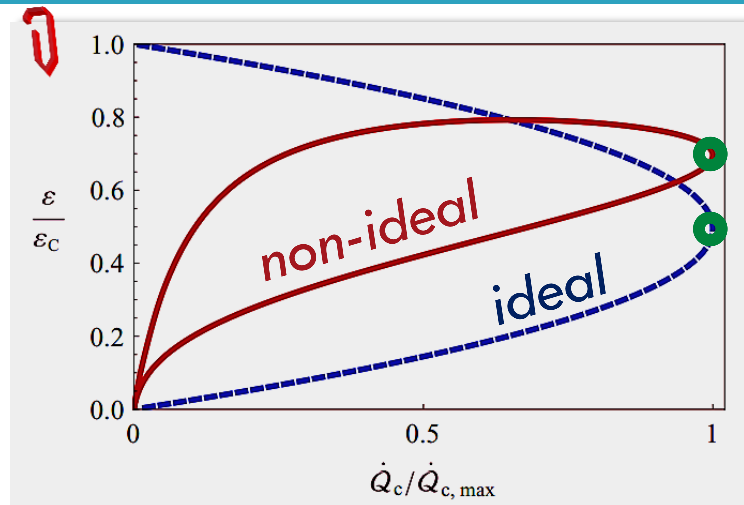
- Models (1) and (2) are ideal reversible devices which can attain the Carnot COP
- Model (3) is non-ideal due to the delocalised dissipation effects

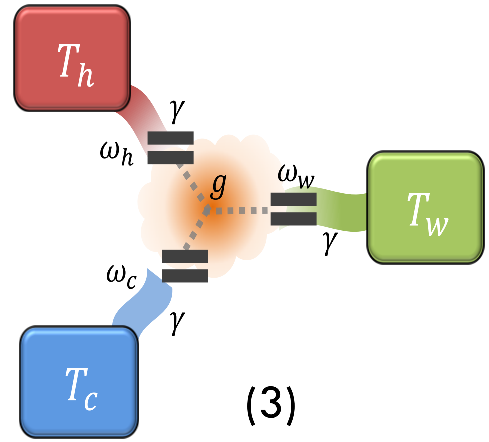
- *Other models:* Mari & Eisert, *Phys. Rev. Lett.* **108** (2012); Boukobza & Ritsch, *Phys. Rev. A* **87** (2013); Gelbwaser-Klimovsky, Alicki & Kurizki, *Phys. Rev. E* **90** (2014); Silva, Skrzypczyk & Brunner, *arXiv* (2015)

QUANTUM ABSORPTION FRIDGES



(1)



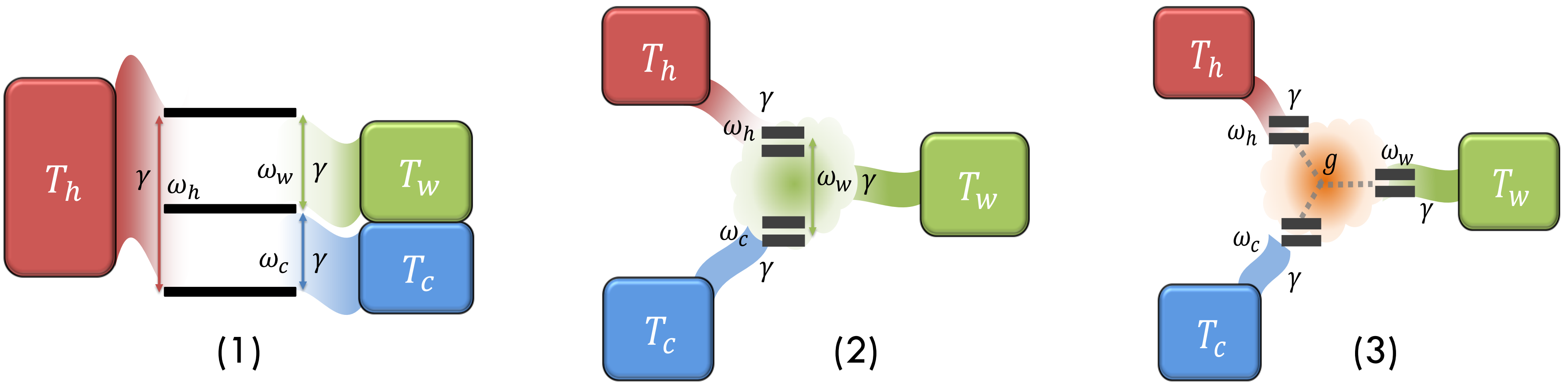


(3)

- Models (1) and (2) are ideal reversible devices which can attain the Carnot COP
- Model (3) is non-ideal due to the delocalised dissipation effects

- *We can focus on the optimisation of a more sensible figure of merit: COP ε_* at maximum cooling power*

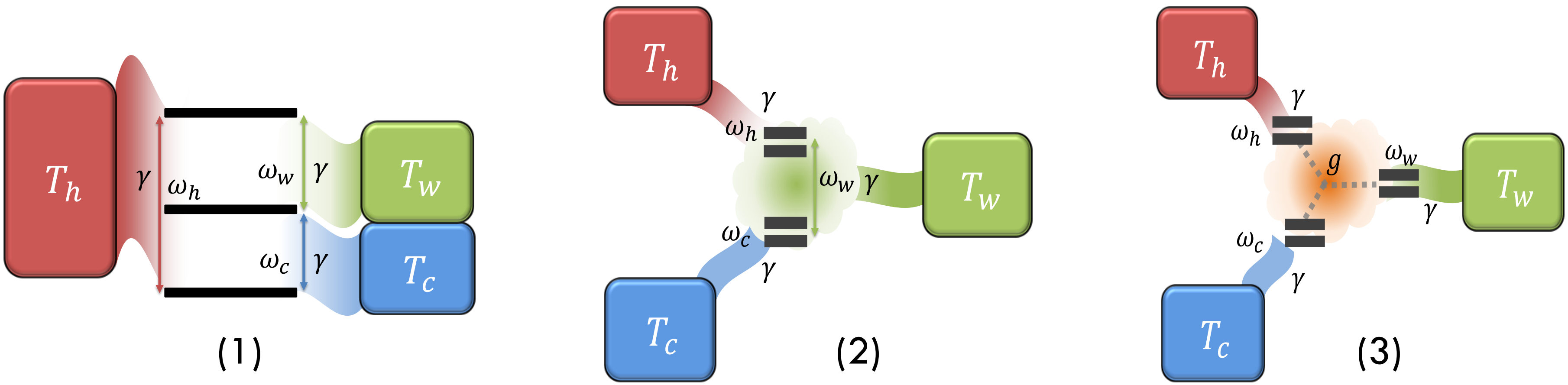
COP AT MAXIMUM POWER



- Weak coupling to the baths: $\gamma \ll \{k_B T_\alpha, \hbar\omega_\alpha, g\}$
- Born, Markov, and rotating wave approximations
- Master equation: $\dot{\rho}(t) = (\mathcal{L}_w + \mathcal{L}_h + \mathcal{L}_c)\rho(t)$
- Lindblad dissipators: $\mathcal{L}_\alpha = \sum_\omega (\propto \omega^{d_\alpha}) \ldots$

  - Correa et al, *Phys. Rev. E* **87** (2013); *Sci Rep* **4** (2014)

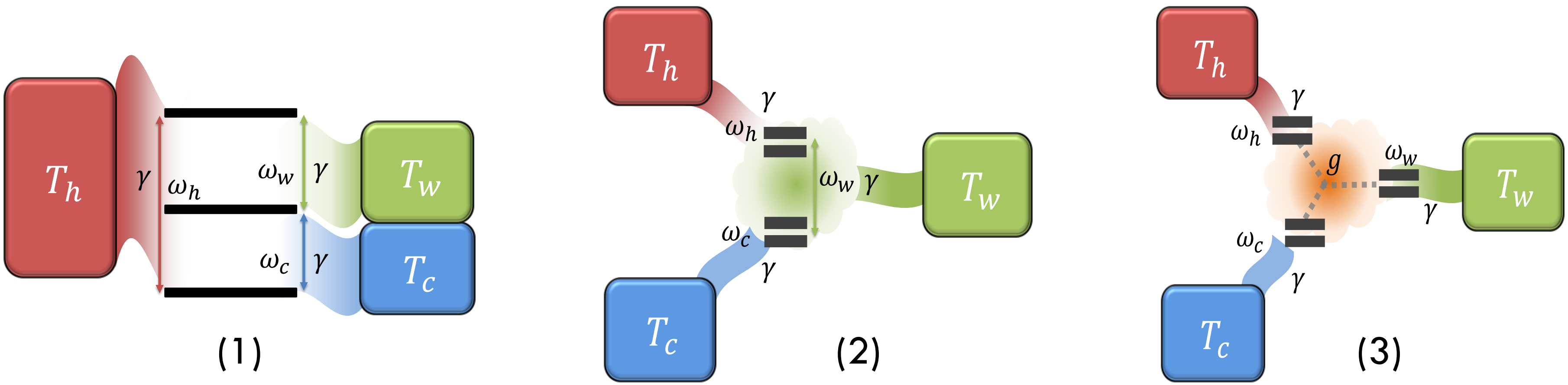
COP AT MAXIMUM POWER



$$\varepsilon_* \leq \frac{d_c}{d_c + 1} \varepsilon_C$$

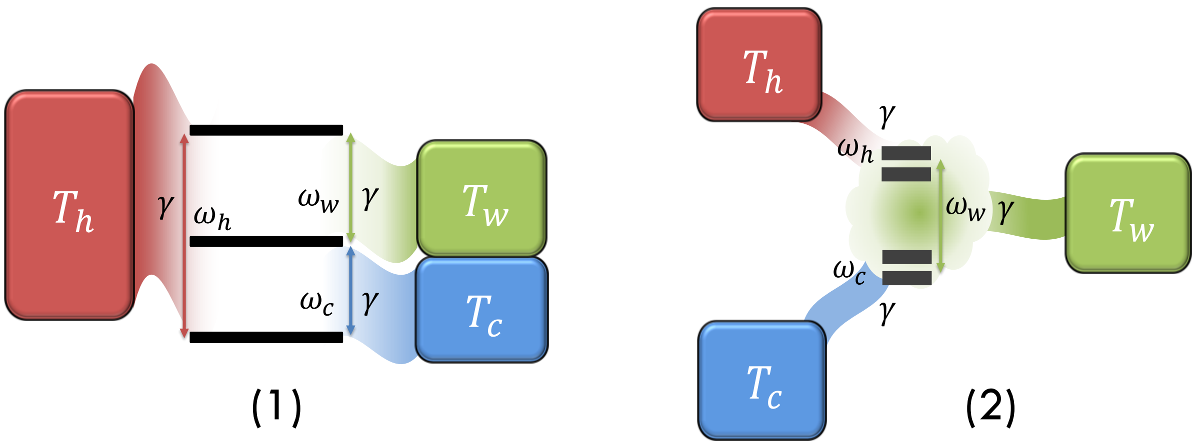
- Correa, Palao, Alonso & GA *Sci Rep* **4** (2014)

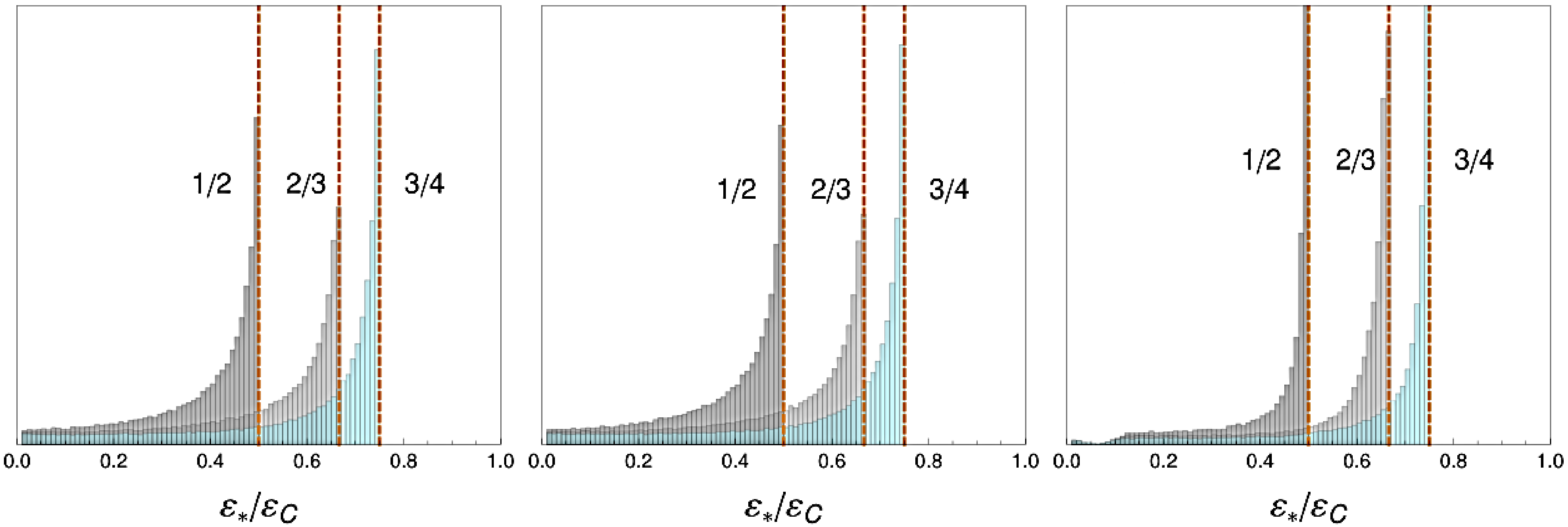
PERFORMANCE BOUND: $\varepsilon_* \leq \frac{d_C}{d_C+1}\varepsilon_C$



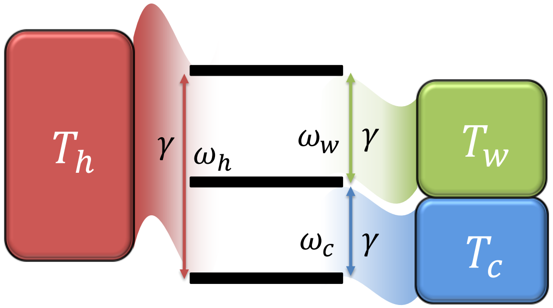
- Rigorously proven for models (1) and (2)
- Valid for any multistage refrigerator built upon (1)
- Verified numerically for model (3) as well
- Tight: saturated for $T_c \ll T_h$, $\omega_w \ll T_{w,h}$ (i.e. $\varepsilon_C \to 0$)
  - Correa et al, *Phys. Rev. E* **87** (2013); *Sci Rep* **4** (2014)

PERFORMANCE BOUND: $\varepsilon_* \leq \frac{d_c}{d_c+1}\varepsilon_C$

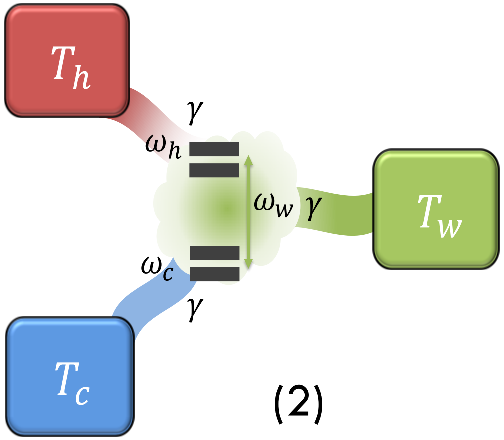




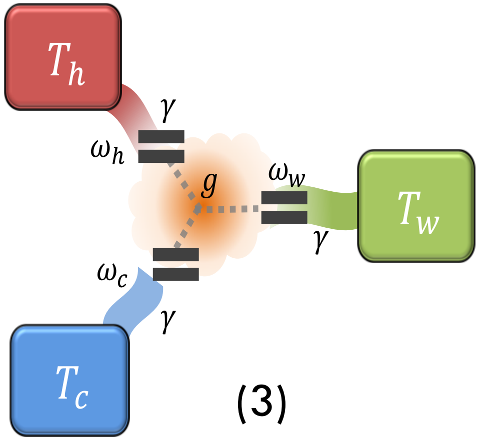
PERFORMANCE BOUND: $\varepsilon_* \leq \frac{d_c}{d_c+1}\varepsilon_C$



(1)



(2)

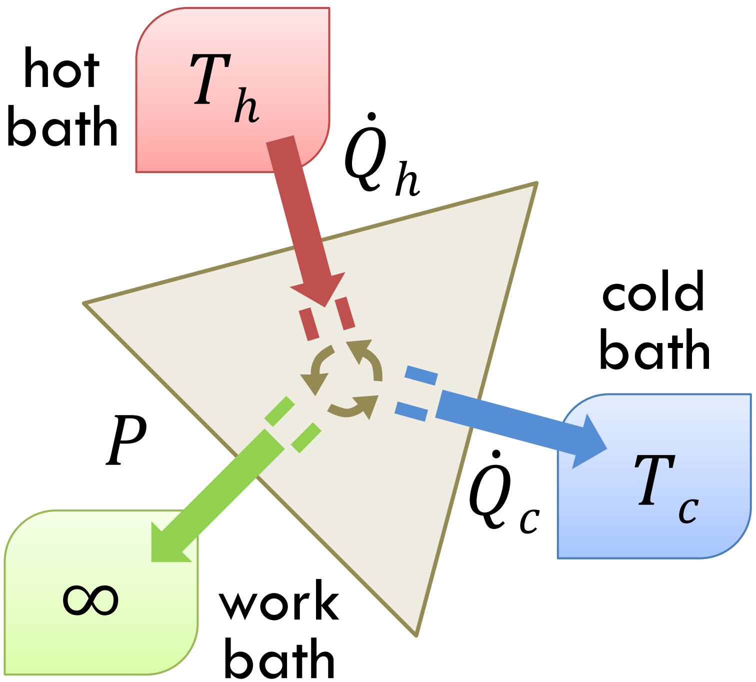


(3)

- The bound is clearly **model-independent** and holds for all known embodiments of quantum absorption fridges

IS IT UNIVERSAL ?

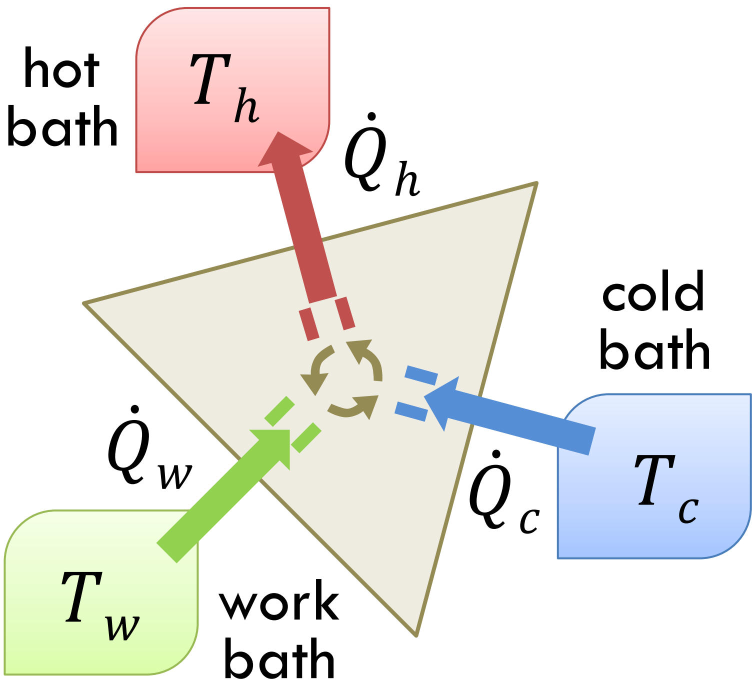
UNIVERSALITY: HEAT ENGINES



- Kosloff & Levy, *Annu. Rev. Phys. Chem.* **65** (2014)

- Carnot efficiency: $\eta_C = 1 - T_c/T_h$
- **Endoreversible regime**: the main source of irreversibility is the imperfect thermal contact
- Effective temperature $T_h' \leq T_h$
- Efficiency at max power for endo-reversible engines: $\eta_* = 1 - \sqrt{T_c/T_h}$
  - Yvon '55, Novikov '57; Curzon-Ahlborn '75
- When $\eta_C \to 0$: $\eta_* \approx \frac{1}{2}\eta_C + \frac{1}{8}\eta_C^2 + \cdots$
  - Van der Broeck, *Phys. Rev. Lett.* **95** (2005); Esposito et al, *Phys. Rev. Lett.* **102** (2009)

UNIVERSALITY: REFRIGERATORS?



- Kosloff & Levy, *Annu. Rev. Phys. Chem.* **65** (2014)

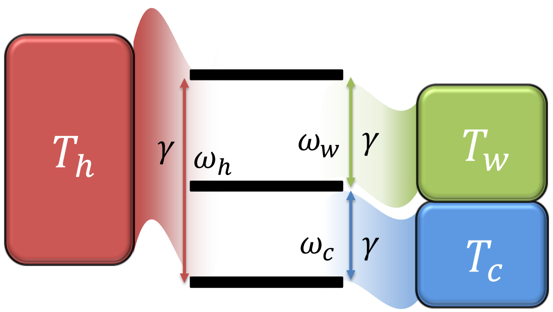
- **Endoreversible regime**: the main source of irreversibility is the imperfect thermal contact ($T'_\alpha \neq T_\alpha$)
- In the limit $T_c \ll T_h$, $\omega_w \ll T_{w,h} \ldots$
- COP at maximum power for all endoreversible refrigerators:

$$\varepsilon_* = \frac{\Lambda\, \varepsilon_C}{(1-\Lambda)\varepsilon_C + 1}$$

  - Correa et al, *Phys. Rev. E* **90** (2014)

- But: Λ depends on the bath details!
- *The COP bound **cannot** be universal*

ENDOREVERSIBLE FRIDGE: EXAMPLE



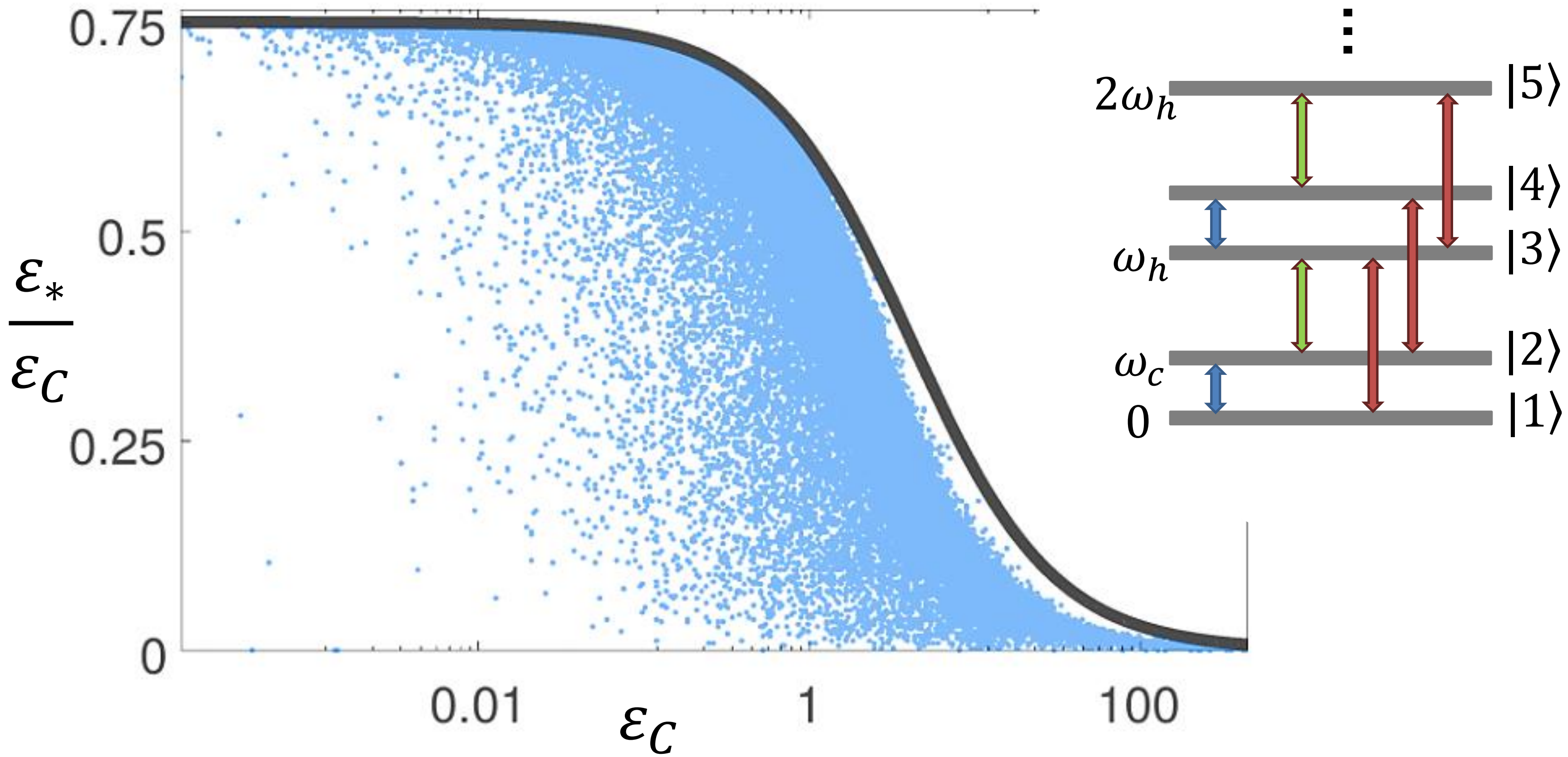
(1)

- Model (1): Qutrit; d_α-dimensional baths with flat spectral densities
- We find: $\Lambda = d_c/(d_c + 1)$
- *Sharper performance bound* (although strictly valid only at endoreversibility)

$$\varepsilon_* \leq \frac{d_c}{d_c + 1 + \varepsilon_C}\varepsilon_C$$

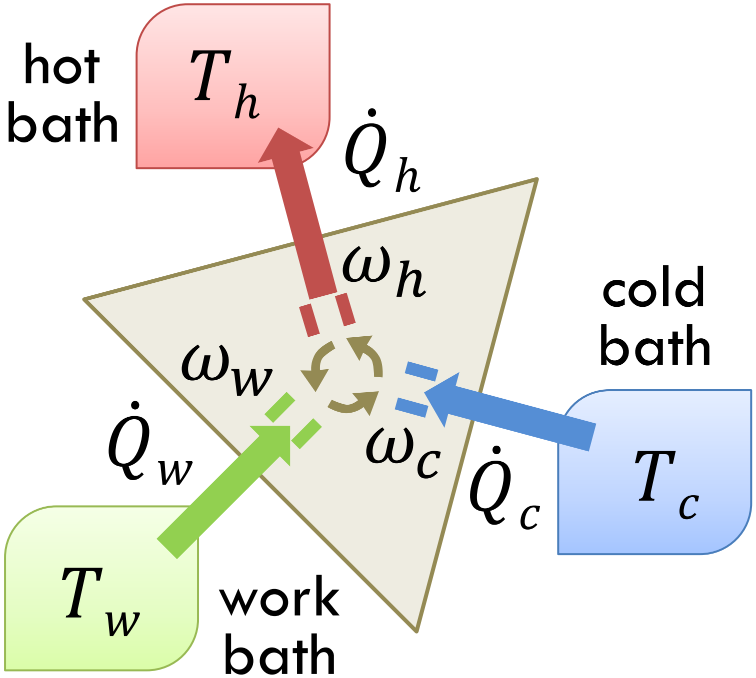
- Correa, Palao, GA & Alonso, *Phys. Rev. E* **90** (2014)

TESTING THE BOUND: $\varepsilon_* \leq \frac{d_c}{d_c+1+\varepsilon_C}\varepsilon_C$



- *N*-stage quantum absorption refrigerators with three-dimensional unstructured baths ($d_\alpha = 3$)
- Correa et al, *Phys. Rev. E* **90** (2014)

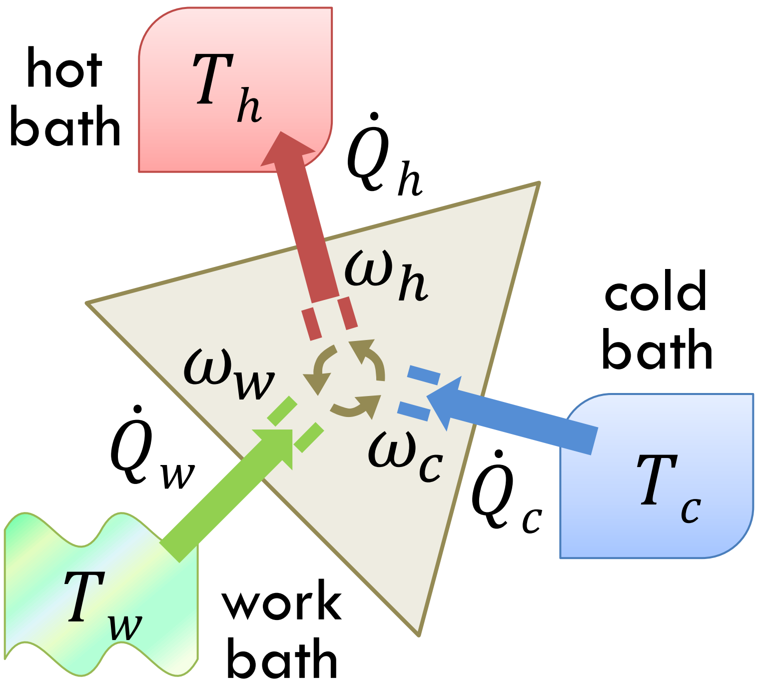
ABSORPTION REFRIGERATORS



- *How to understand and possibly* ***improve*** *their optimal performance?*

CAN QUANTUMNESS HELP ?

QUANTUM-ENHANCED FRIDGES



- Huang, Wang & Yi, *Phys. Rev. E* **86** (2012); Abah & Lutz, *Europhys. Lett.* **106** (2014); Roßnagel et al, *Phys. Rev. Lett.* **112** (2014); Alicki, *arXiv:*1401.7865 (2014)

- Work bath: *squeezed thermal* (with squeezing degree *r*)
- **Squeezing the 2nd law**

$$\frac{\dot{Q}_c}{T_c}+\frac{\dot{Q}_h}{T_h}+\frac{\dot{Q}_w}{\tilde{T}_w(r)}\leq 0\,,\ \ \tilde{T}_w(r)>T_w$$

- Modified master equation:

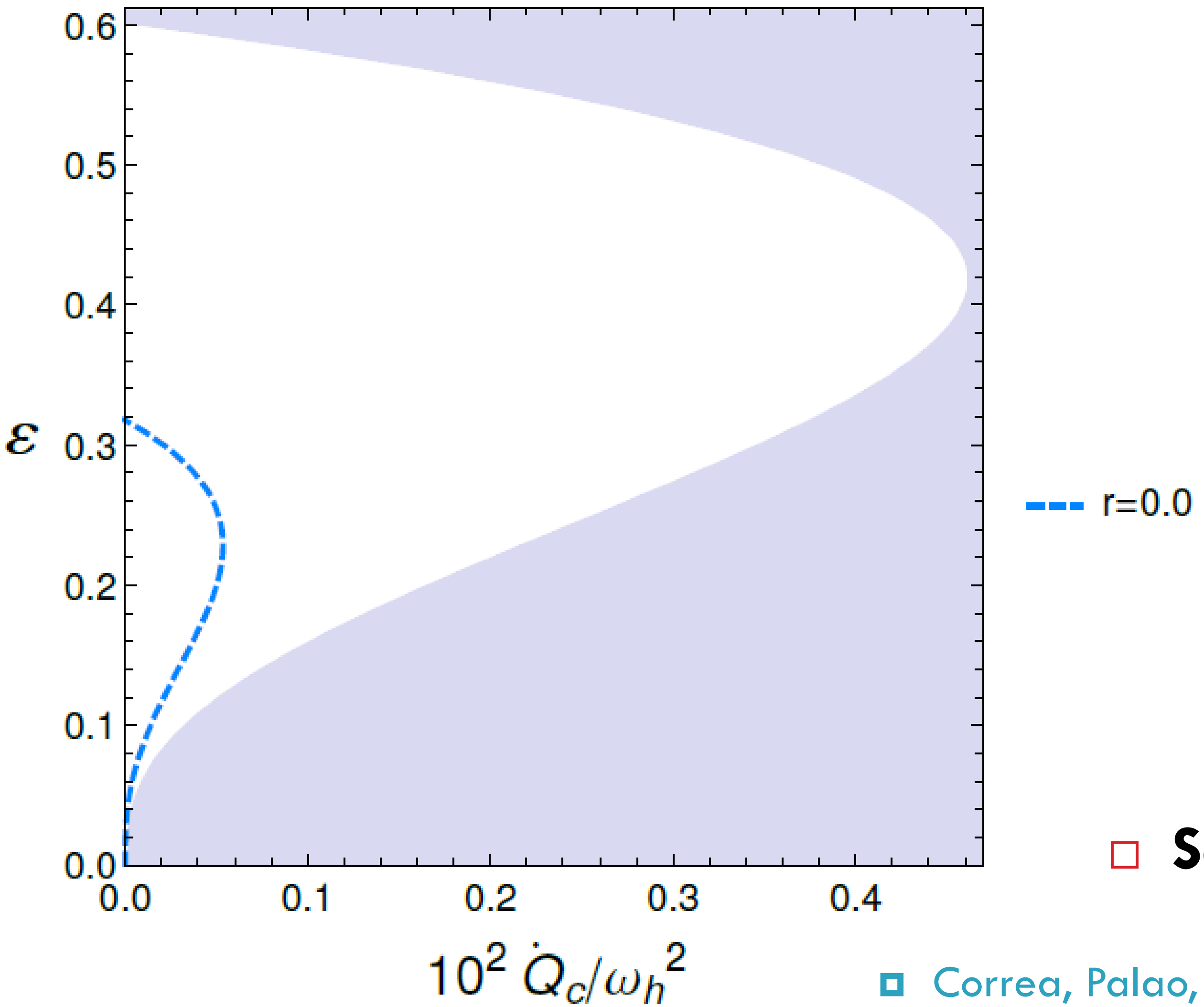
$$\dot{\rho}(t)=\left(\mathcal{L}_w^{(r)}+\mathcal{L}_h+\mathcal{L}_c\right)\rho(t)$$

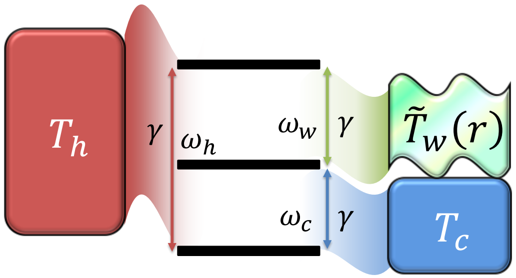
- The Carnot COP increases with *r*:

$$\varepsilon_C(r)=\frac{1-\frac{T_h}{\tilde{T}_{w(r)}}}{\frac{T_h}{T_c}-1}>\varepsilon_C(0)$$

- Correa, Palao, Alonso & GA *Sci Rep* **4** (2014)

QUANTUM-ENHANCED FRIDGES

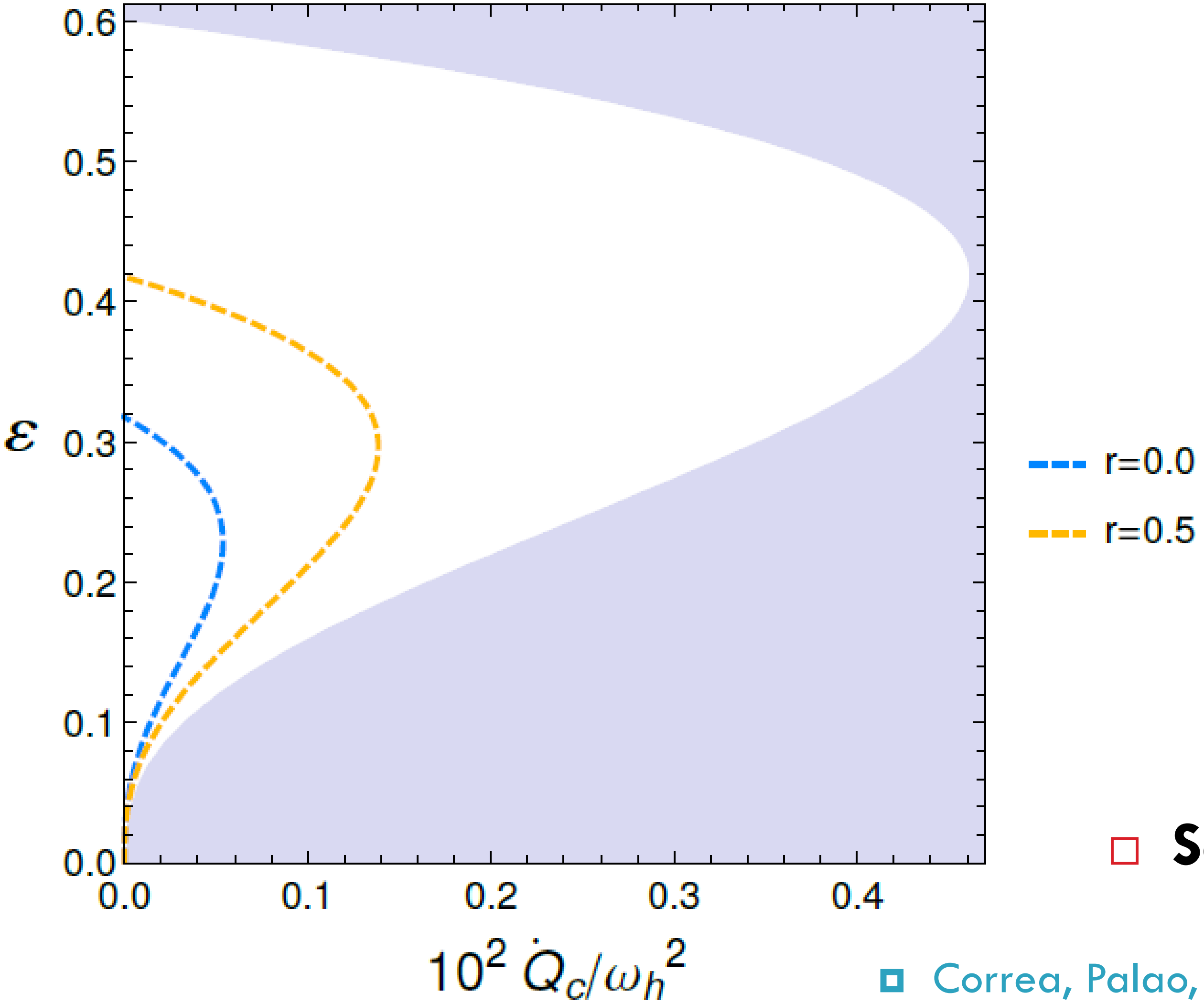


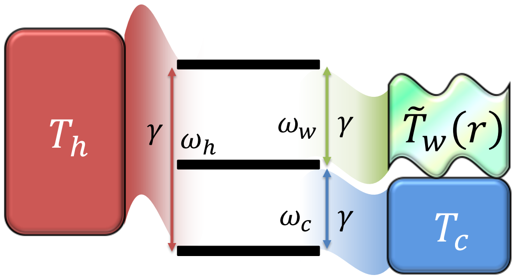


- **Squeezing the 2nd law**

- Correa, Palao, Alonso & GA *Sci Rep* **4** (2014)

QUANTUM-ENHANCED FRIDGES

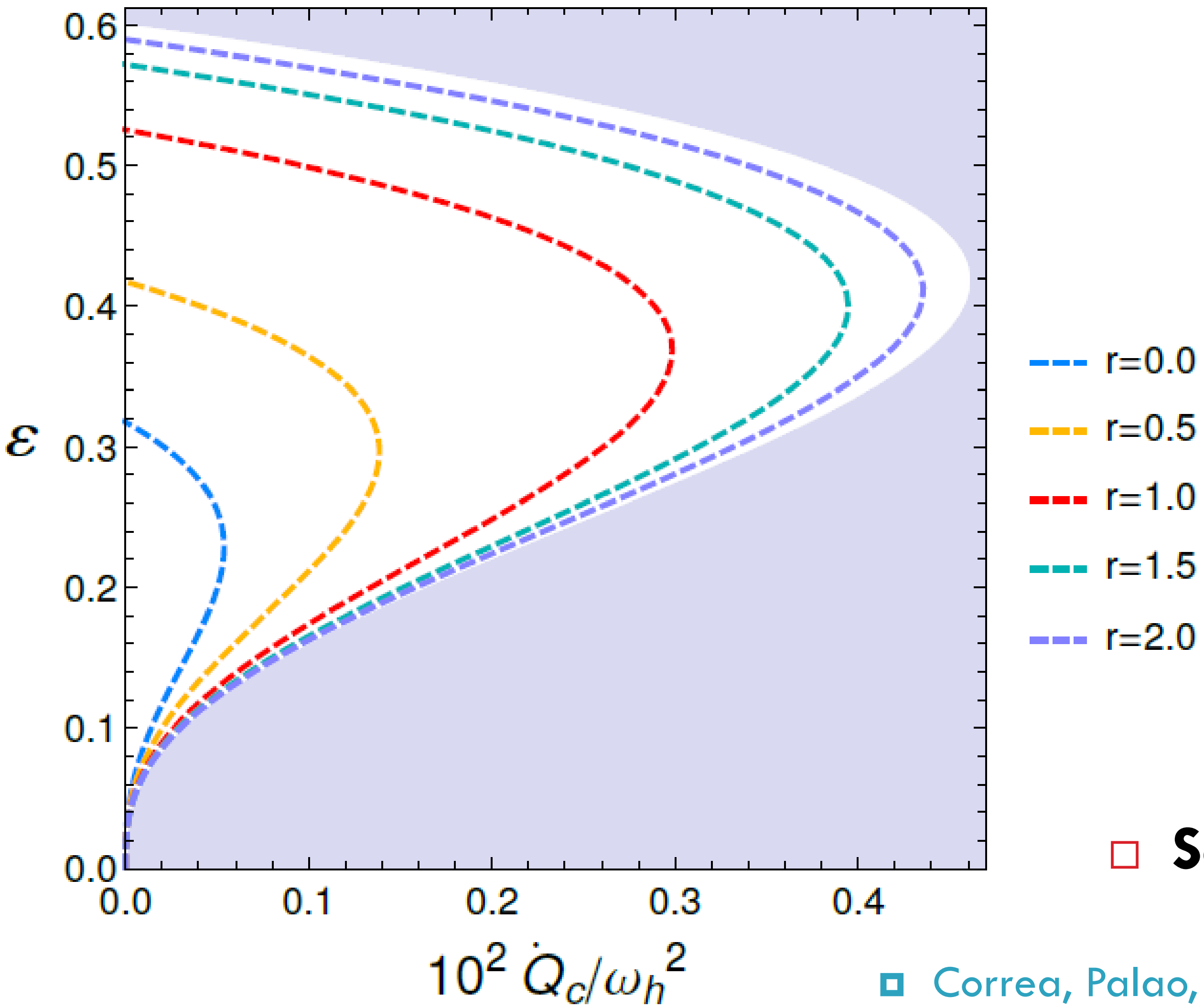


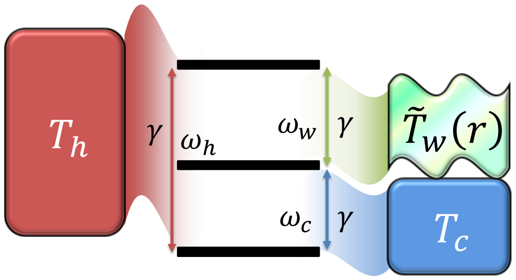


- **Squeezing the 2nd law**

- Correa, Palao, Alonso & GA *Sci Rep* **4** (2014)

QUANTUM-ENHANCED FRIDGES





- **Squeezing the 2nd law**

- Correa, Palao, Alonso & GA *Sci Rep* **4** (2014)

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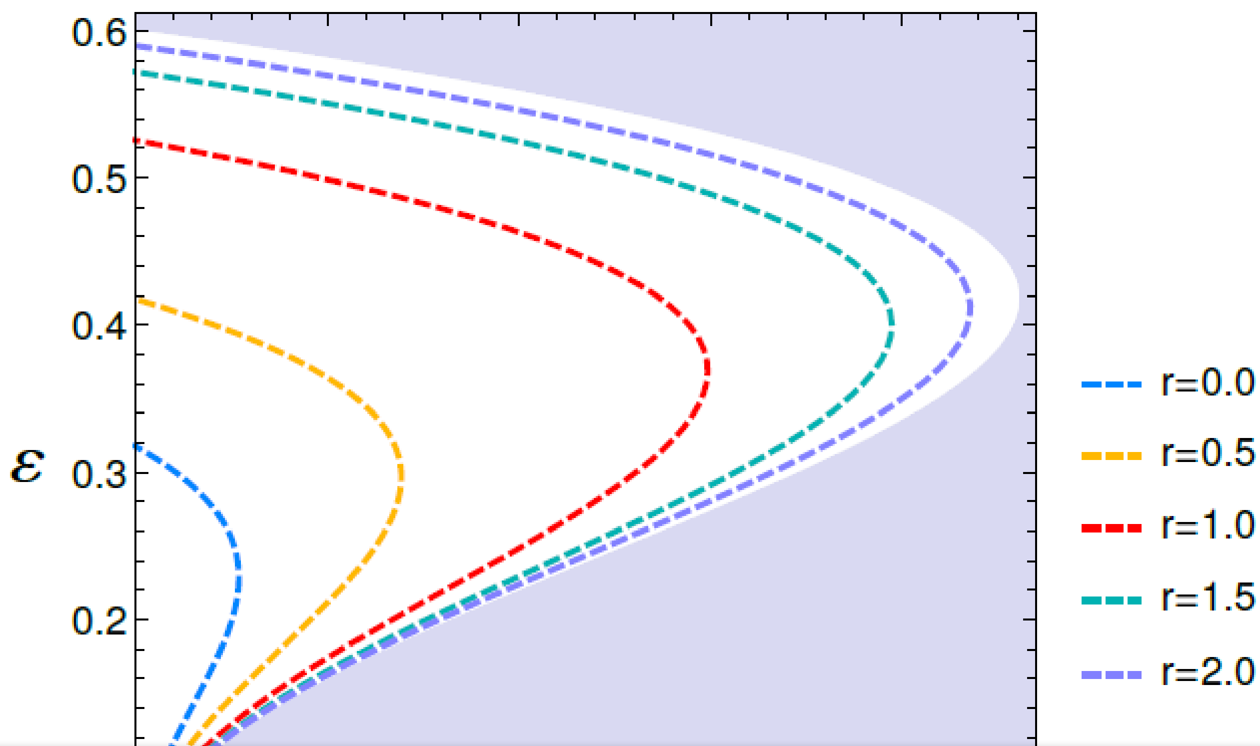

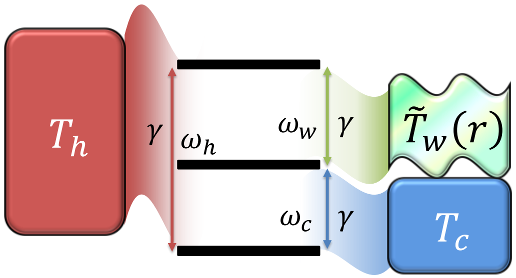

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Home » Physics » Quantum Physics » February 5, 2014

Quantum engineering pushes refrigerator beyond classical efficiency limits

Feb 05, 2014 by Lisa Zyga report

SUMMARY

- *Overview of quantum refrigerators and their generic modelling using the framework of quantum tricycles*
- *Tight bound $\varepsilon_*/\varepsilon_C \leq d_c/(d_c + 1)$ on the coefficient of performance at maximum cooling power for all known models of quantum absorption refrigerators*
- *Analogue of Curzon-Ahlborn bound – although not universal – for endoreversible quantum refrigerators*
- *Quantum fluctuations in the work bath (e.g. squeezing) can push the performance beyond classical limitations*

WHAT IS GENUINELY QUANTUM IN QUANTUM THERMODYNAMICS ?

2nd Quantum Thermodynamics Conference, Palma, April 2015

L.A. Correa, J.P. Palao, D. Alonso, Gerardo Adesso

Quantum Correlations Group
The University of Nottingham

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- L. A. Correa, J. P. Palao, GA & D. Alonso
  Performance bound for quantum absorption refrigerators
  Phys. Rev. E **87**, 042131 (2013)
- L. A. Correa, J. P. Palao, D. Alonso & GA
  Quantum-enhanced absorption refrigerators
  Sci. Rep. **4**, 3949 (2014)
- L. A. Correa, J. P. Palao, GA & D. Alonso
  Optimal performance of endoreversible quantum refrigerators
  Phys. Rev. E **90**, 062124 (2014)

THANK YOU