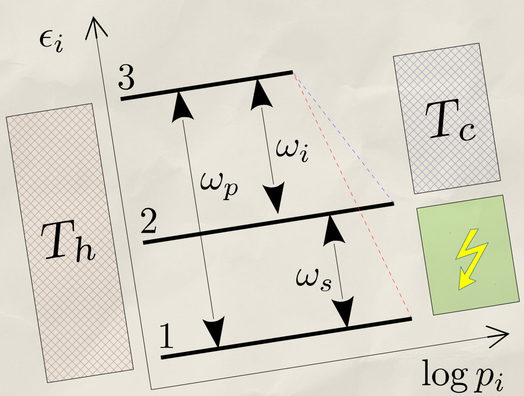
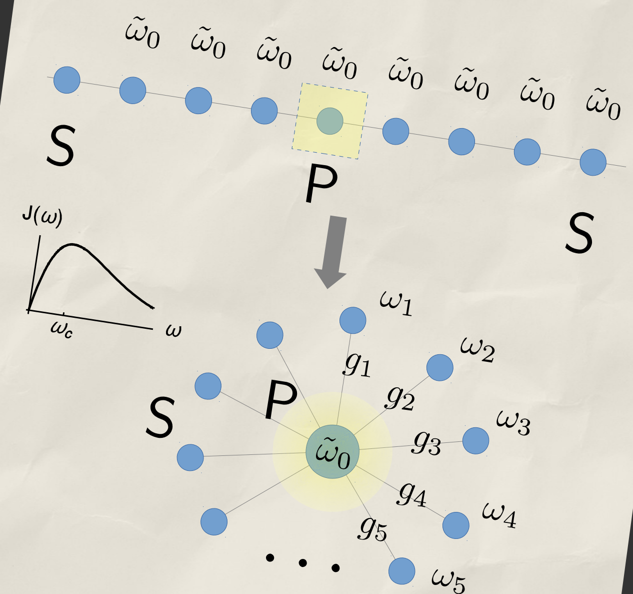
DOUBLE FEATURE!

Quantum thermal engineering



AND

Quantum thermometry

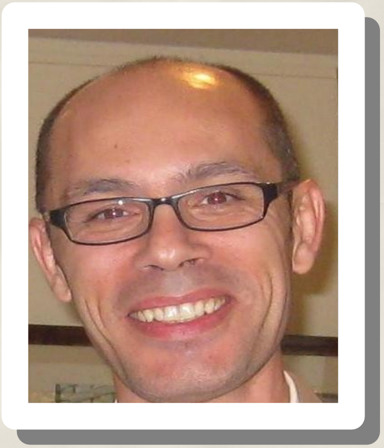


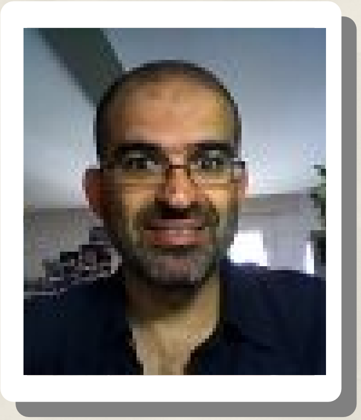
★ ★ ★ ★ ★ ★ ★ KITP USBC 08/06/18 ★ ★ ★ ★ ★ ★ ★

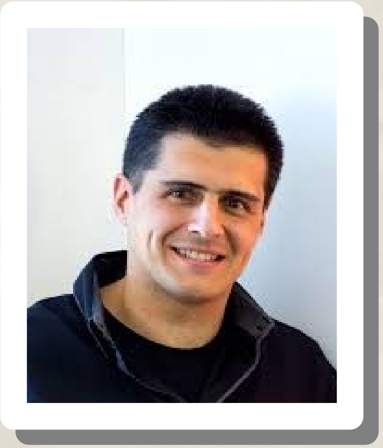
QUANTUM THERMAL ENGINEERING

University of Nottingham
UK | CHINA | MALAYSIA

LUIS A. CORREA





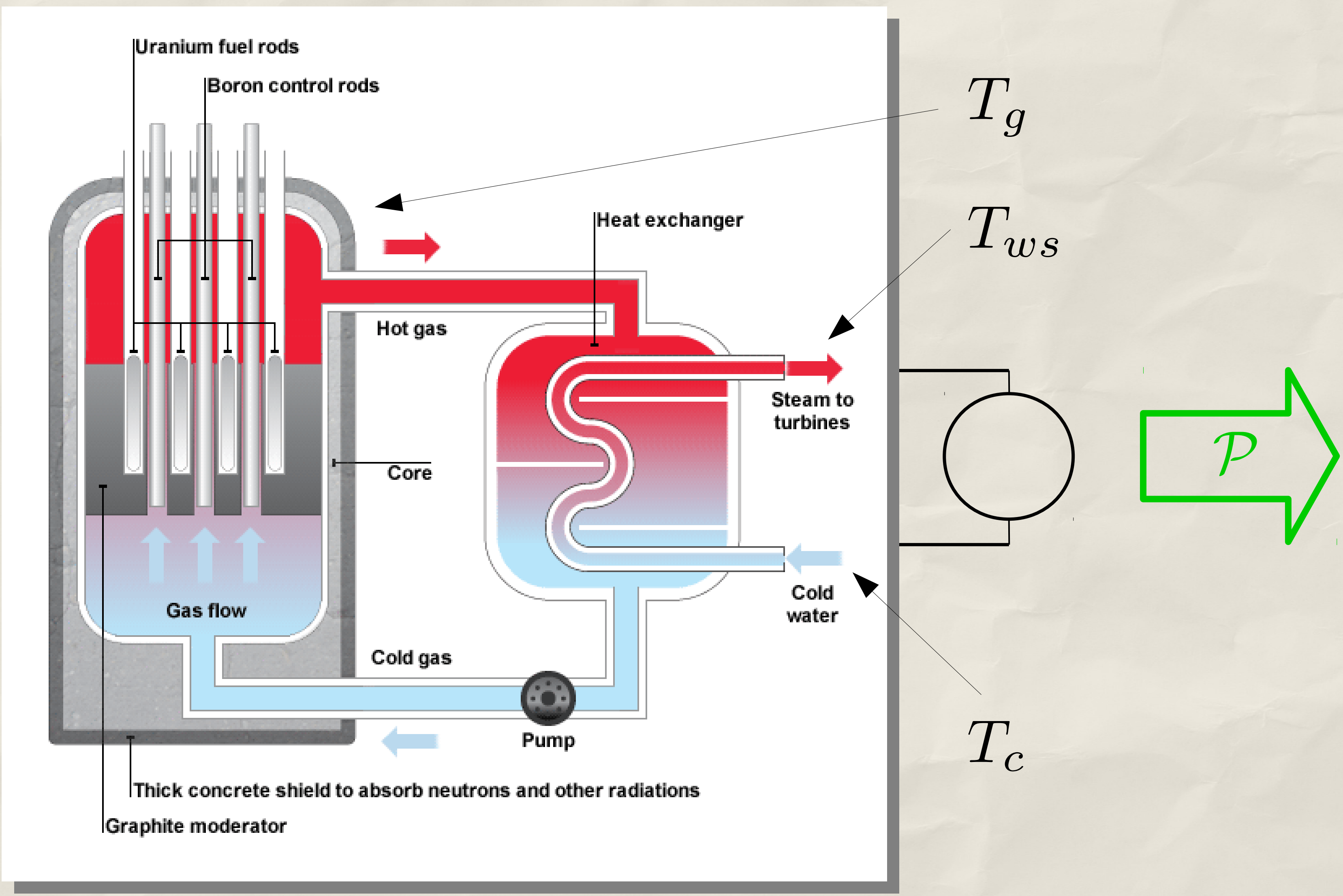


Daniel Alonso
Universidad de La Laguna

José P. Palao
Universidad de La Laguna

Gerardo Adesso
University of Nottingham

ENDOREVERSIBLE THERMODYNAMICS



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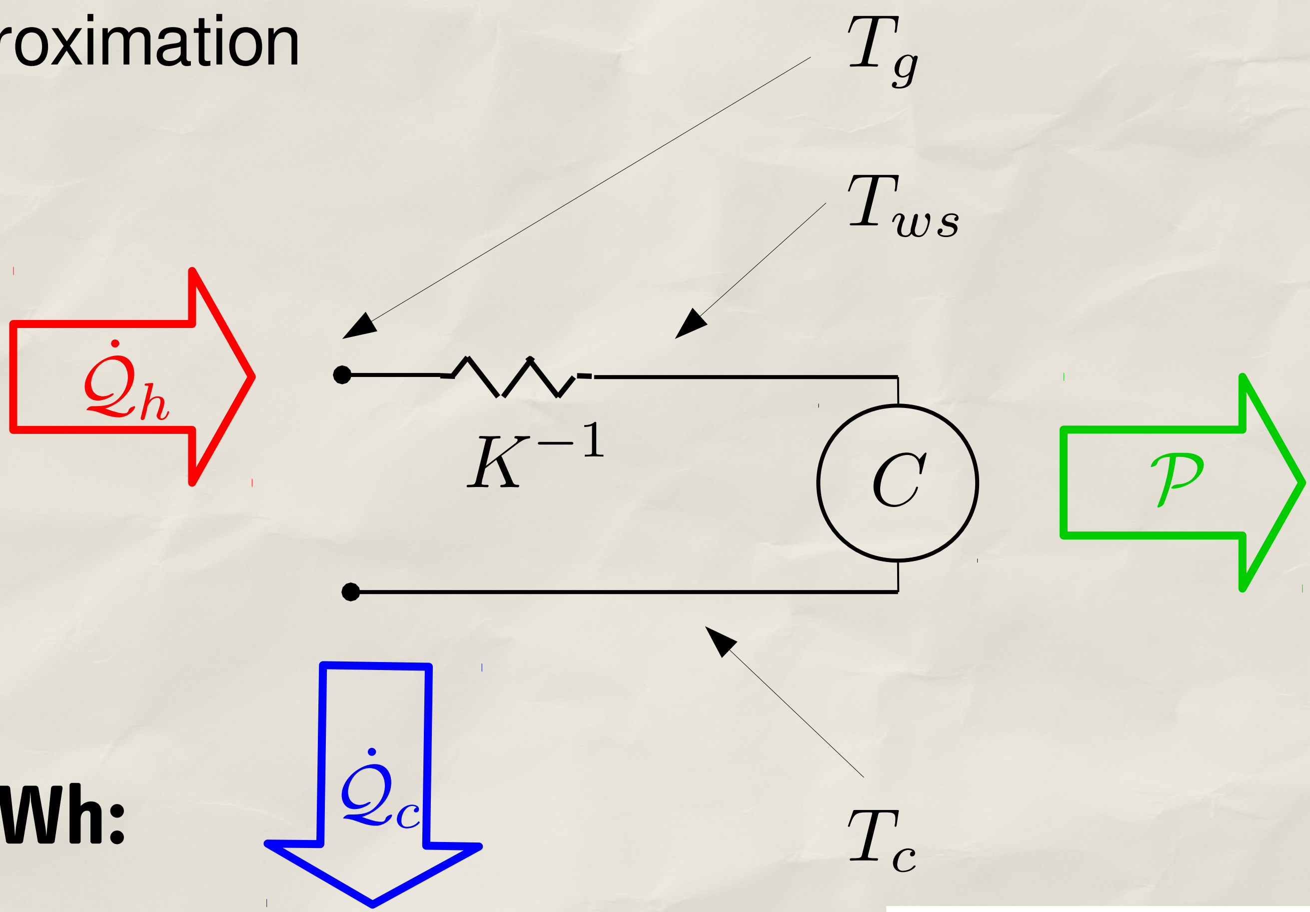
ENDOREVERSIBLE THERMODYNAMICS

Endoreversible approximation

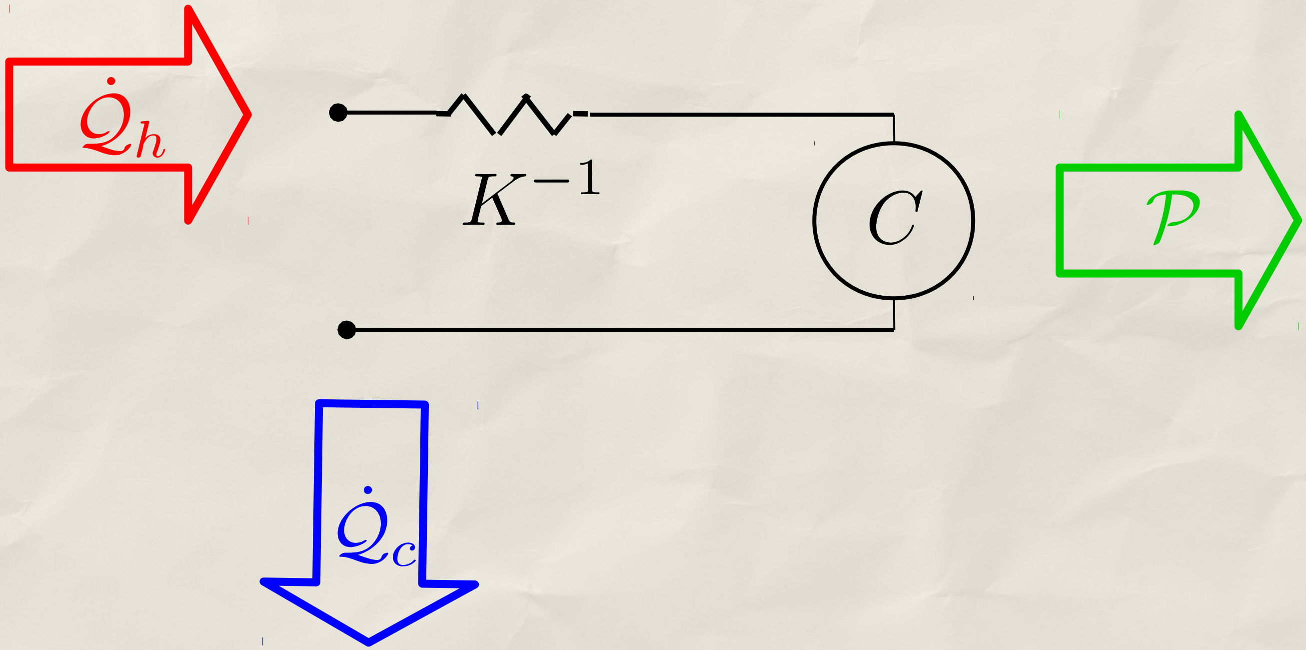


Cost of the kWh:

- Fuel: 25%
- O&M: 75%

$$\mathcal{P} = \dot{Q}_h \left(1 - \frac{T_c}{T_{ws}} \right)$$

CURZON-AHLBORN EFFICIENCY



$$\dot{\mathcal{Q}}_h \equiv K(T_g - T_{ws})$$

$$\mathcal{P} = \dot{\mathcal{Q}}_h \left(1 - \frac{T_c}{T_{ws}}\right)$$

$$\partial_{T_{ws}} \mathcal{P} = 0$$

$$T_{ws}^* = \sqrt{T_g T_c}$$

$$\eta_* = \frac{\mathcal{P}^*}{\dot{\mathcal{Q}}_h^*} = 1 - \sqrt{\frac{T_c}{T_g}}$$

CURZON-AHLBORN EFFICIENCY

Efficiency of a Carnot Engine at Maximum Power Output

F. L. CURZON
B. AHLBORN
Department of Physics
University of British Columbia
Vancouver, B.C., Canada
(Received 9 November 1973; revised 14 May 1974)

Curzon & Ahlborn, *Am. J. Phys.* **43**, 22 (1975)

CURZON-AHLBORN EFFICIENCY

Efficiency of a Carnot Engine at Maximum Power Output

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(Received 9 November 1973; revised 14 May 1974)

J. Nuclear Energy II, 1958, Vol. 7, pp. 125 to 128. Pergamon Press Ltd., London

THE EFFICIENCY OF ATOMIC POWER STATIONS
(A REVIEW)

I. I. NOVIKOV

I. I. Novikov, *J. Nuclear Energy* **II** (1958)

Curzon & Ahlborn, *Am. J. Phys.* **43**, 22 (1975)

CURZON-AHLBORN EFFICIENCY

Efficiency of a
Power Outpu

J. Nuclear Energy II, 1958, Vol. 7, pp.

THE E

PRÉSIDENCE DU CONSEIL

COMMISSARIAT A L'ÉNERGIE ATOMIQUE

LA PILE DE SACLAY

EXPERIENCE ACQUISE EN DEUX ANS SUR LE TRANSFERT

DE CHALEUR PAR GAZ COMPRIME

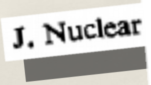
J. YVON

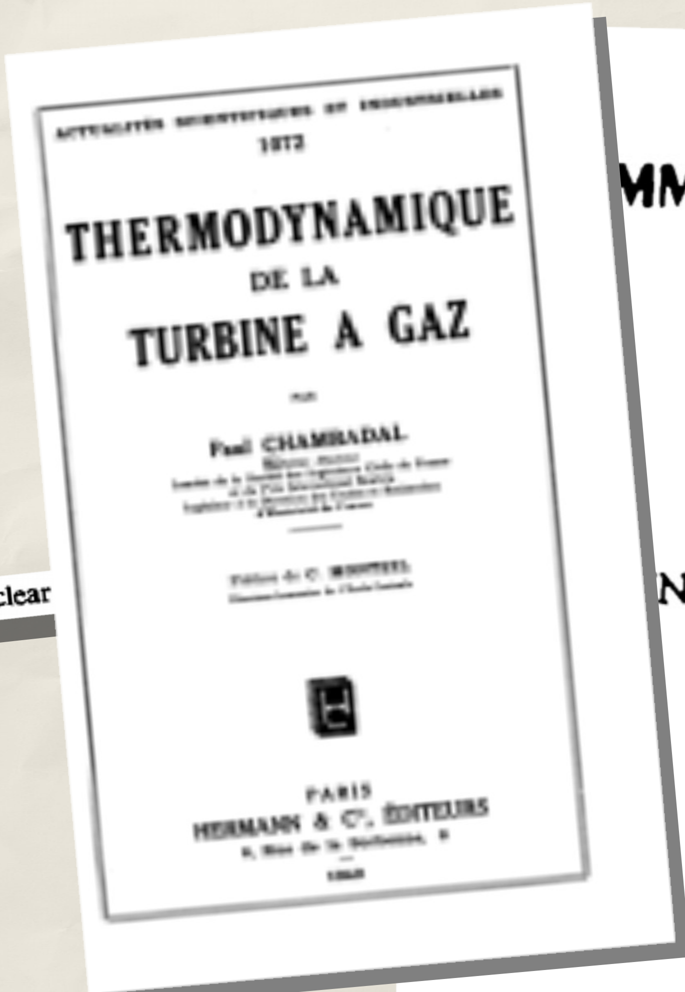
J. Yvon, *INIS*, C.E.A.-R 435 (1955)

I. I. Novikov, *J. Nuclear Energy* **II** (1958)

Curzon & Ahlborn, *Am. J. Phys.* **43**, 22 (1975)

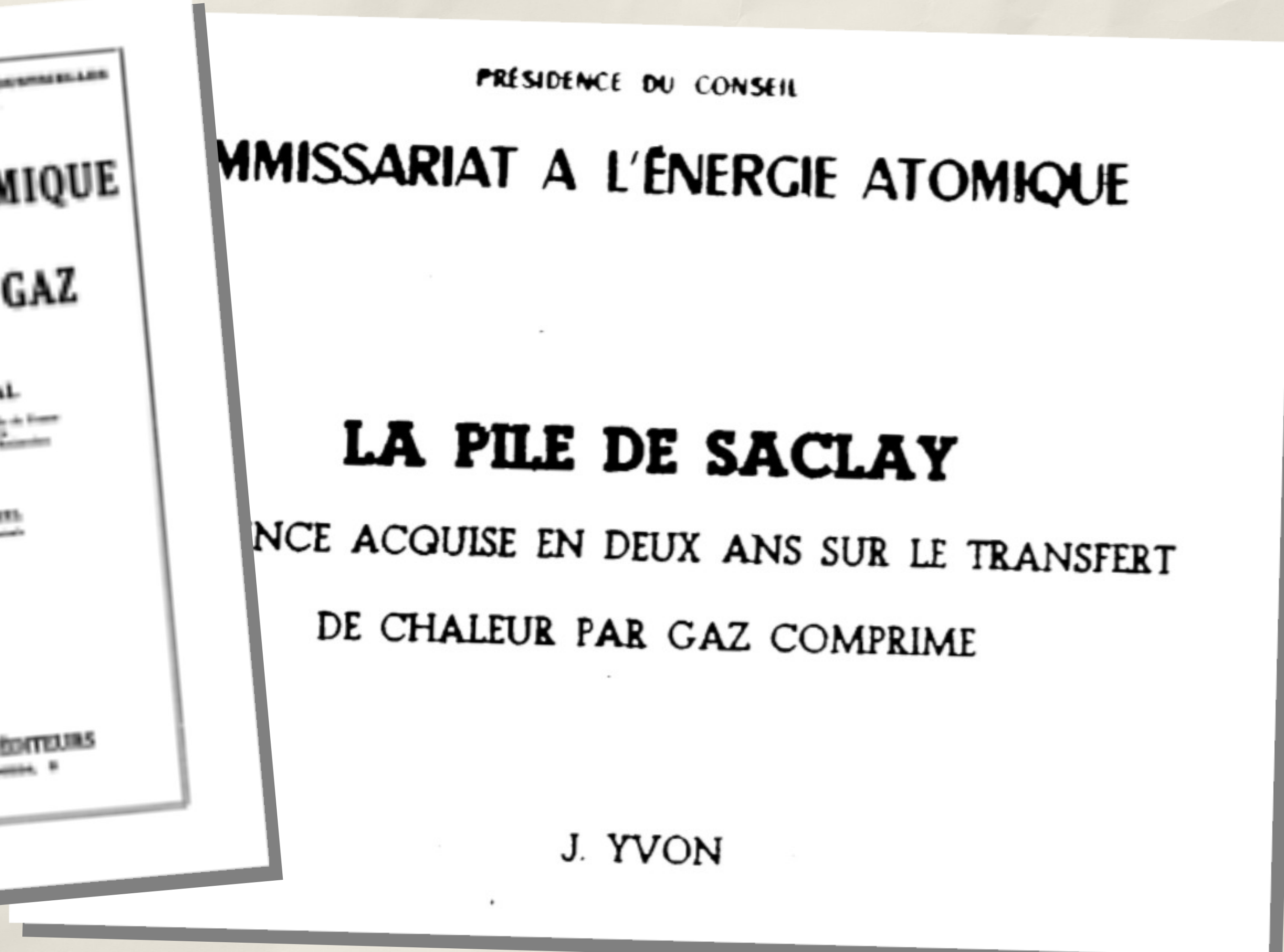
CURZON-AHLBORN EFFICIENCY


J. Nuclear


THERMODYNAMIQUE
DE LA
TURBINE A GAZ

Paul CHAMBADAL

PARIS
HERMANN & Cie, ÉDITEURS


PRÉSIDENCE DU CONSEIL

MMISSARIAT A L'ÉNERGIE ATOMIQUE

LA PILE DE SACLAY

NCE ACQUISE EN DEUX ANS SUR LE TRANSFERT

DE CHALEUR PAR GAZ COMPRIME

J. YVON

P. Chambadal, *“Thermodynamique de la Turbine à Gaz”*, Hermann & Cie, 1949

CURZON-AHLBORN EFFICIENCY

THERMODYNAMIQ
DE LA
TURBINE A GA

Paul CHAMBADAL

PARIS
HERMANN & C^{ie}, ÉDIT

J. Nuclear

Il est intéressant de voir comment interviennent dans ce coefficient d'utilisation global optimum les deux facteurs qui le caractérisent, à savoir le coefficient d'utilisation de la source payée (**u**) et le coefficient d'utilisation du cycle, autrement dit sa fraction disponible (**η**). On trouve ainsi, en substituant pour (**t**) dans les expressions respectives la valeur (**t₀**) qui vient d'être calculée, correspondant au maximum du travail :

— pour le coefficient d'utilisation de la source :

$$\mathbf{u}_0 = \sqrt{T_1}\,\frac{\sqrt{T_1}-\sqrt{T_2}}{T_1-T_2}$$

— pour la fraction disponible du cycle :

$$\eta_0 = \frac{\sqrt{T_1}-\sqrt{T_2}}{\sqrt{T_1}}$$

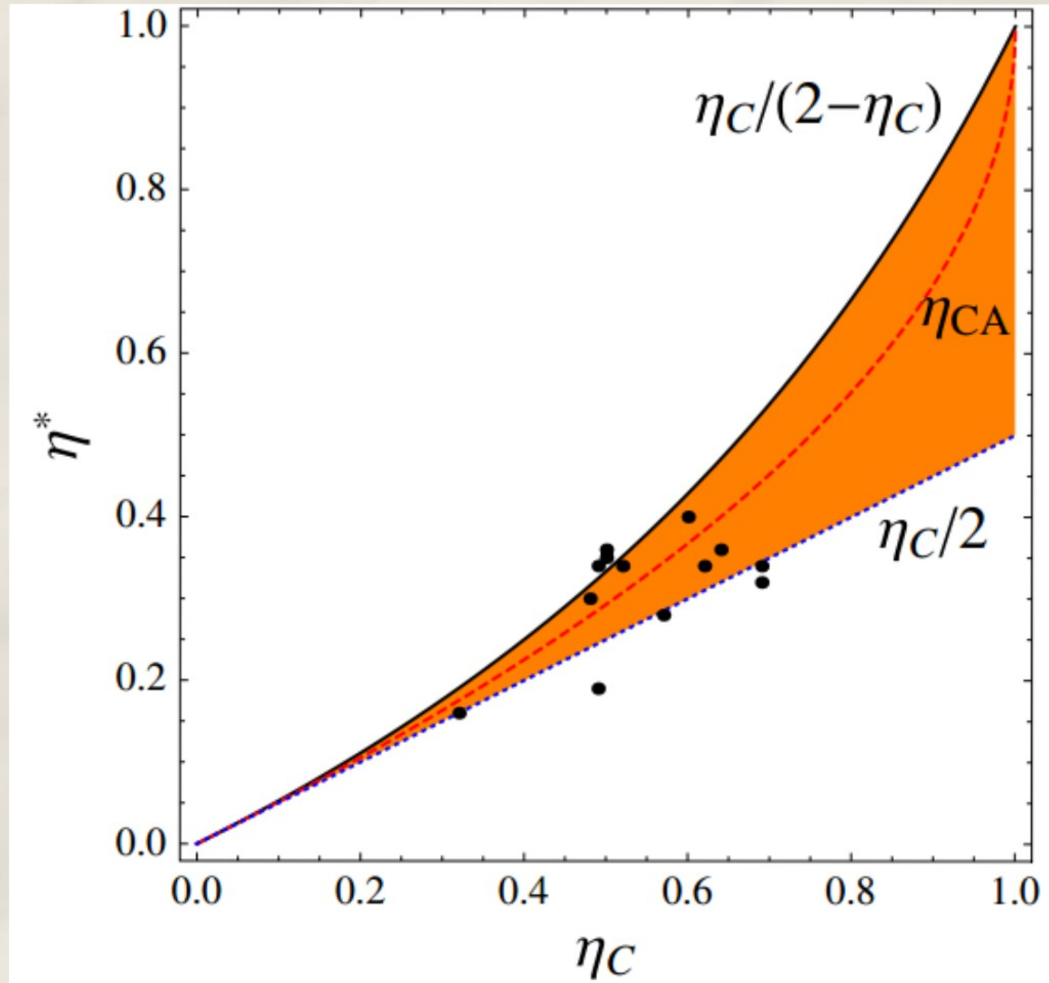
P. Chambadal, *"Thermodynamique de la Turbine à Gaz"*, Hermann & Cie (1949)

H. B. Reitlinger, *"Sur l'utilisation de la chaleur dans les machines à feu"*, Vaillant-Carmanne, Liège, Belgium (1929)

Alexandre Vaudrey *et al.*, *J. Non-Equilib. Thermodyn.*, **39** 199 (2014)

CURZON-AHLBORN EFFICIENCY

Plant
Doel 4 (Nuclear, Belgium) [6]
Almaraz II (Nuclear, Spain) [6]
Sizewell B (Nuclear, UK) [6]
Cofrentes (Nuclear, Spain) [6]
Heysham (Nuclear, UK) [6]
West Thurrock (Coal, UK) [1]
CANDU (Nuclear, Canada) [1]
Larderello (Geothermal, Italy)[1]
Calder Hall (Nuclear, UK) [6]
(Steam/Mercury,USA) [6]
(Steam, UK) [6]
(Gas Turbine, Switzerland) [6]
(Gas Turbine, France) [6]



M. Esposito *et al.*, *PRL* **105**, 150603 (2010)

T. Schmiedl & U. Seifert, *EPL* **81**, 20003 (2008)

CURZON-AHLBORN EFFICIENCY

Linear regime:

$$\eta_C = 1 - \frac{T_c}{T_h} \to 0$$

$$\eta_* = 1 - \sqrt{\frac{T_c}{T_h}} = \frac{1}{2}\eta_C + \frac{1}{8}\eta_C^2 + \mathcal{O}(\eta_C^3)$$

Low-dissipation engine:

$$\eta_* = 1 - \sqrt{T_c/T_g}$$

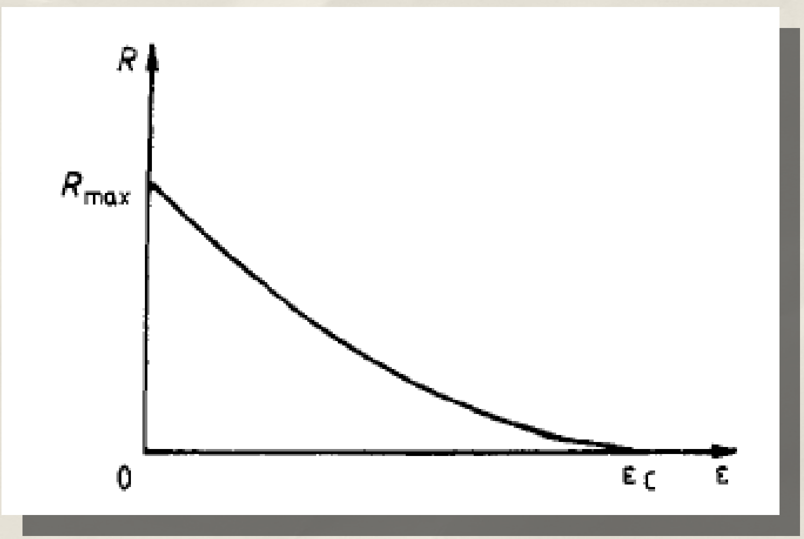
C. Van den Broeck *et al.*, *PRL* **95**, 190602 (2005)

M. Esposito & C. Van den Broeck, *PRL* **102**, 130602 (2009)

M. Esposito *et al.*, *PRL* **105**, 150603 (2010)

CURZON-AHLBORN FOR REFRIGERATORS?

$$\varepsilon = \dot{\mathcal{Q}}_c/\mathcal{P}$$



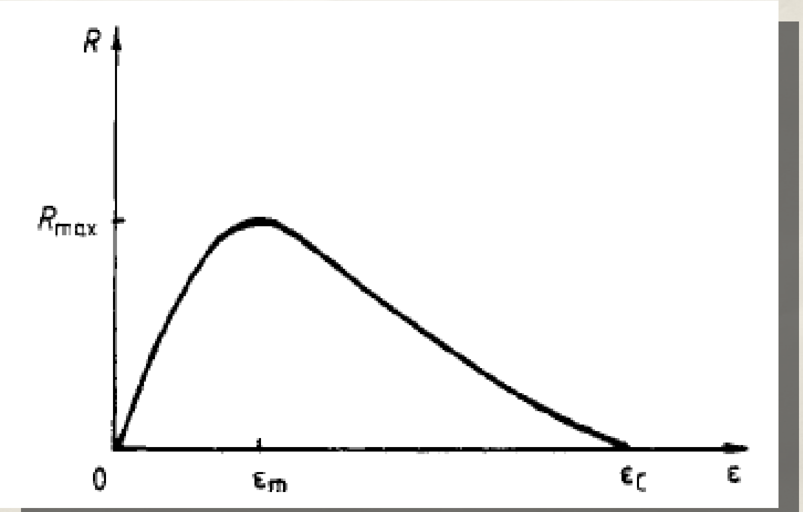
Assumptions:

- Cooling power as figure of merit
- Endoreversible approximation
- Linear heat transfer law

Z. Yan & J. Chen, *J. Phys. D: Appl. Phys.* **23**, 136 (1990)

CURZON-AHLBORN FOR REFRIGERATORS?

$$\varepsilon = \dot{\mathcal{Q}}_c / \mathcal{P}$$



Assumptions:

- Cooling power as figure of merit
- Endoreversible approximation
- ~~Linear heat transfer law~~

$$\dot{\mathcal{Q}}_c \equiv K(T_c^n - \tilde{T}_c^n)$$

Z. Yan & J. Chen, *J. Phys. D: Appl. Phys.* **23**, 136 (1990)

CURZON-AHLBORN FOR REFRIGERATORS?

$$\varepsilon = \dot{\mathcal{Q}}_c/\mathcal{P}$$

$$\chi \equiv \varepsilon \dot{\mathcal{Q}}_c$$

$$\chi \equiv \varepsilon/\tau$$

$$\chi \equiv \dot{\mathcal{Q}}_c/(\varepsilon_C T_h)$$

Assumptions:

* ~~Cooling power as figure of merit~~
* Endoreversible approximation
* Linear heat transfer law

B. Jiménez de Cisneros *et al.*, *PRE* **73**, 057103 (2006)

S. Velasco *et al.*, *PRL* **78**, 3241 (1997)

Z. Yan & J. Chen, *J. Phys. D: Appl. Phys.* **23**, 136 (1990)

CURZON-AHLBORN FOR REFRIGERATORS?

$$\varepsilon = \dot{\mathcal{Q}}_c / \mathcal{P}$$

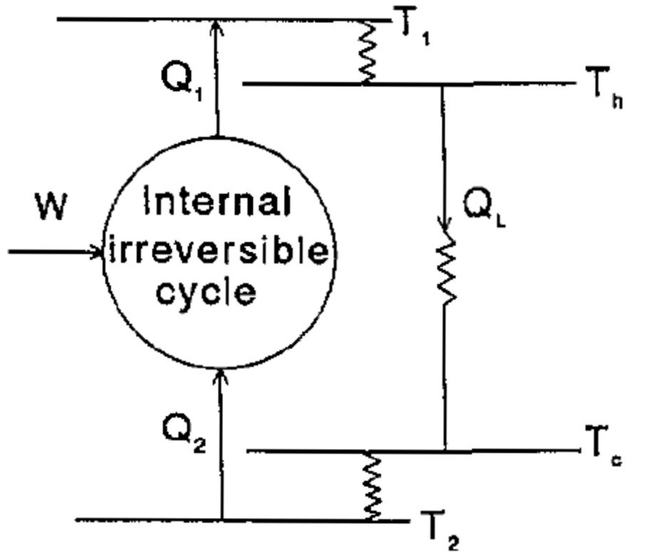


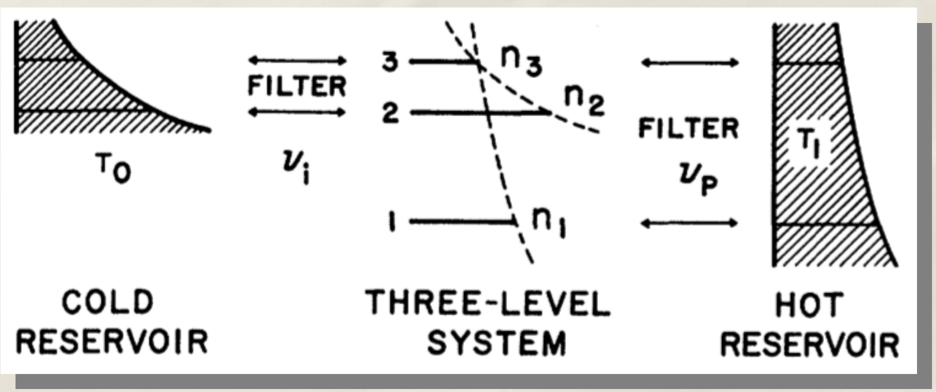
Figure 1. Schematic diagram of a refrigeration system.

Assumptions:

* Cooling power as figure of merit
* ~~Endoreversible approximation~~
* Linear heat transfer law

J. Chen, *J. Phys. A* **27** 6395 (1994)

CURZON-AHLBORN FOR REFRIGERATORS?



Assumptions:

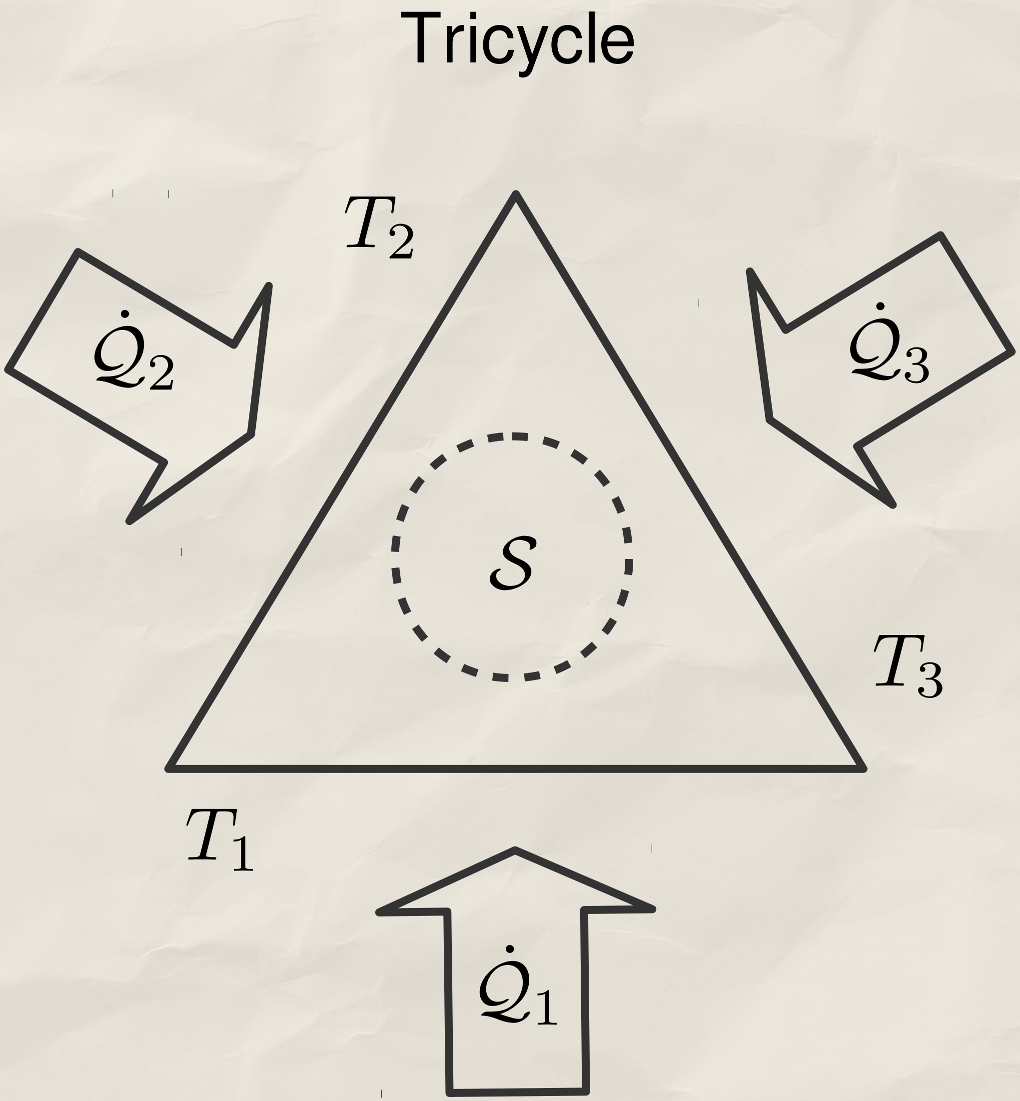
* Cooling power as figure of merit
* ~~Endoreversible approximation~~
* ~~Linear heat transfer law~~

H. E. D. Scovil & O. Schulz-DuBois, *PRL* **2**, 262 (1959)

OUTLINE

1. ~~Motivation~~
2. Quantum tricycles
3. Performance bounds for quantum absorption chillers
4. Heat leaks and internal dissipation

STRONGLY COUPLED QUANTUM TRICYCLE



$$T_1 < T_2 < T_3$$

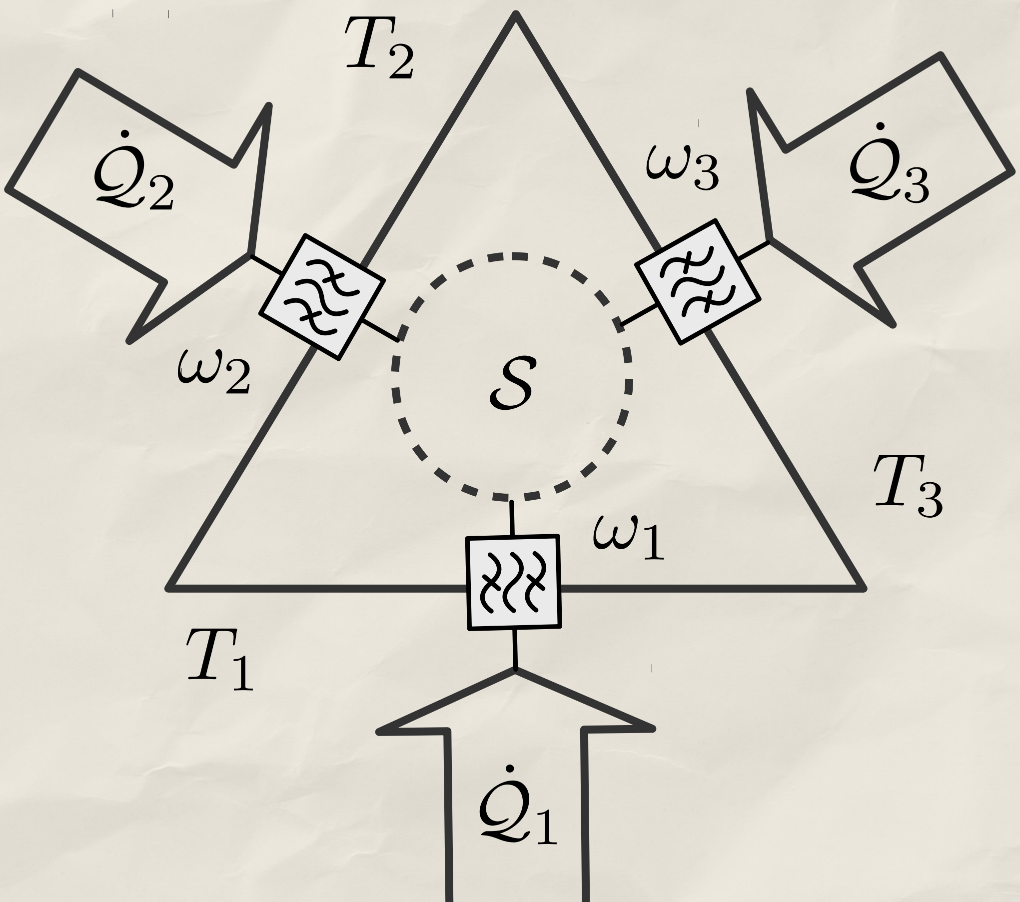
$$\dot{\mathcal{Q}}_1 + \dot{\mathcal{Q}}_2 + \dot{\mathcal{Q}}_3 = 0$$

$$\frac{\dot{\mathcal{Q}}_1}{T_1} + \frac{\dot{\mathcal{Q}}_2}{T_2} + \frac{\dot{\mathcal{Q}}_3}{T_3} \leq 0$$

B. Andresssen *et al.*, *J. Chem. Phys.* **66**, 1571 (1977)

STRONGLY COUPLED QUANTUM TRICYCLE

Quantum tricycle



$$T_1 < T_2 < T_3$$

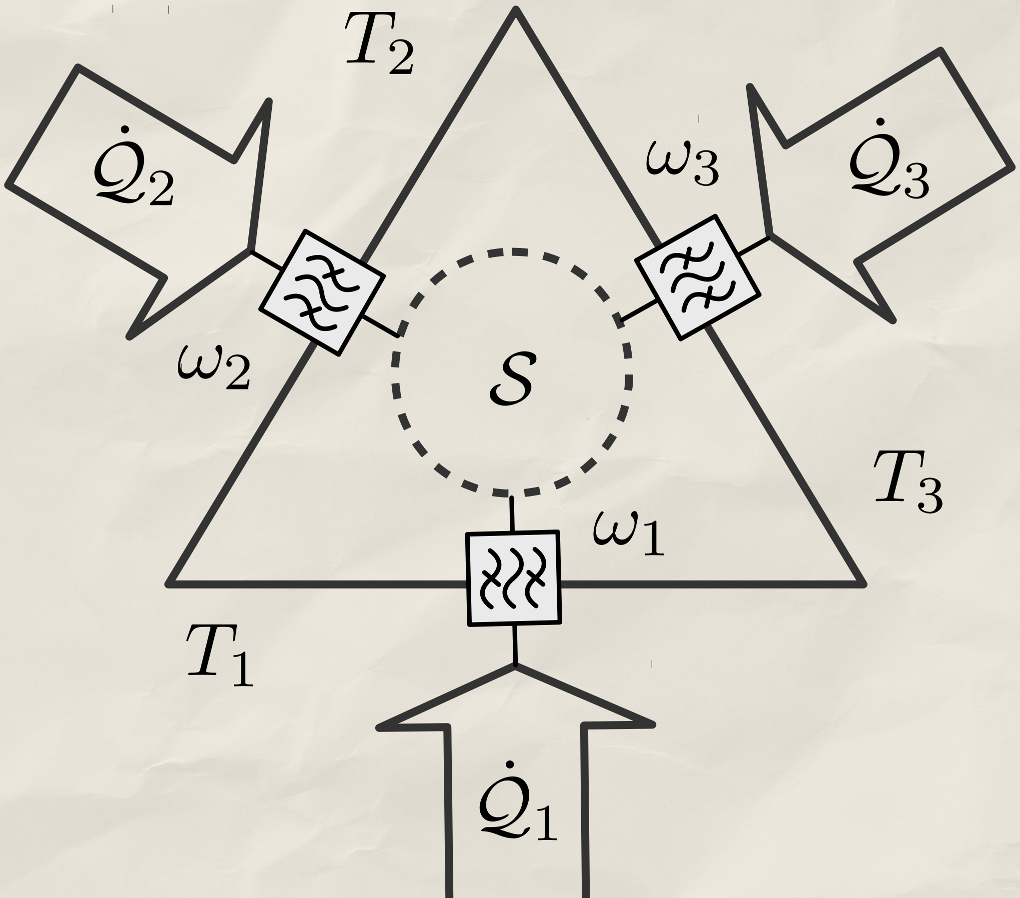
$$\dot{\mathcal{Q}}_1 + \dot{\mathcal{Q}}_2 + \dot{\mathcal{Q}}_3 = 0$$

$$\frac{\dot{\mathcal{Q}}_1}{T_1} + \frac{\dot{\mathcal{Q}}_2}{T_2} + \frac{\dot{\mathcal{Q}}_3}{T_3} \leq 0$$

R. Kosloff & A. Levy, *Annu. Rev. Phys. Chem.* **65,** 365 (2014)

STRONGLY COUPLED QUANTUM TRICYCLE

Strongly coupled quantum tricycle



$$T_1 < T_2 < T_3$$

$$\dot{\mathcal{Q}}_1 + \dot{\mathcal{Q}}_2 + \dot{\mathcal{Q}}_3 = 0$$

$$\frac{\dot{\mathcal{Q}}_1}{T_1} + \frac{\dot{\mathcal{Q}}_2}{T_2} + \frac{\dot{\mathcal{Q}}_3}{T_3} \leq 0$$

$$\dot{\mathcal{Q}}_i = \omega_i \mathcal{I}$$

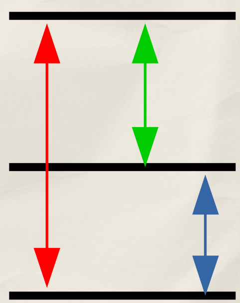
$$\omega_3 = \omega_2 - \omega_1$$

Endoreversibility

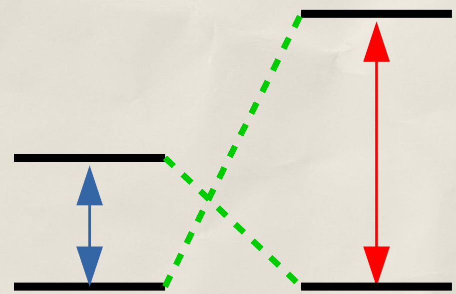
R. Kosloff & A. Levy, *Annu. Rev. Phys. Chem.* **65,** 365 (2014)

EXAMPLES

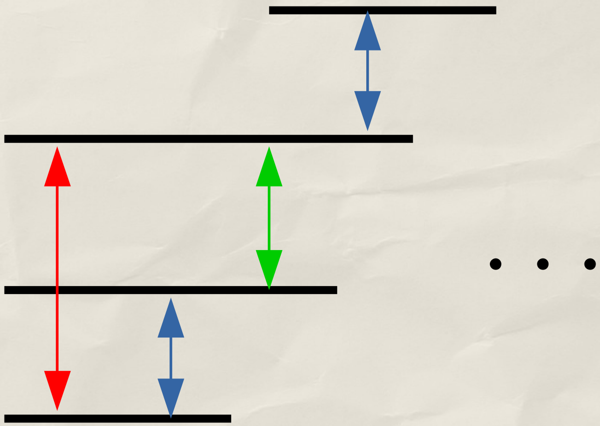
Strongly coupled quantum tricycles



J. P. Palao & R. Kosloff,
PRE **64**, 056130 (2001)

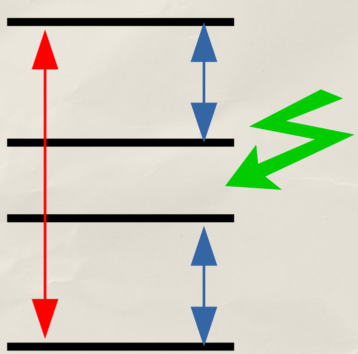


A. Levy & R. Kosloff,
PRL **108**, 070604 (2012)

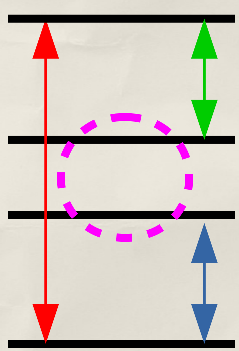


LAC, *PRE* **89**, 042128 (2014)

“Leaky” quantum tricycles



R. Kosloff & A. Levy,
Annu. Rev. Phys. Chem. **65**, 365 (2014)



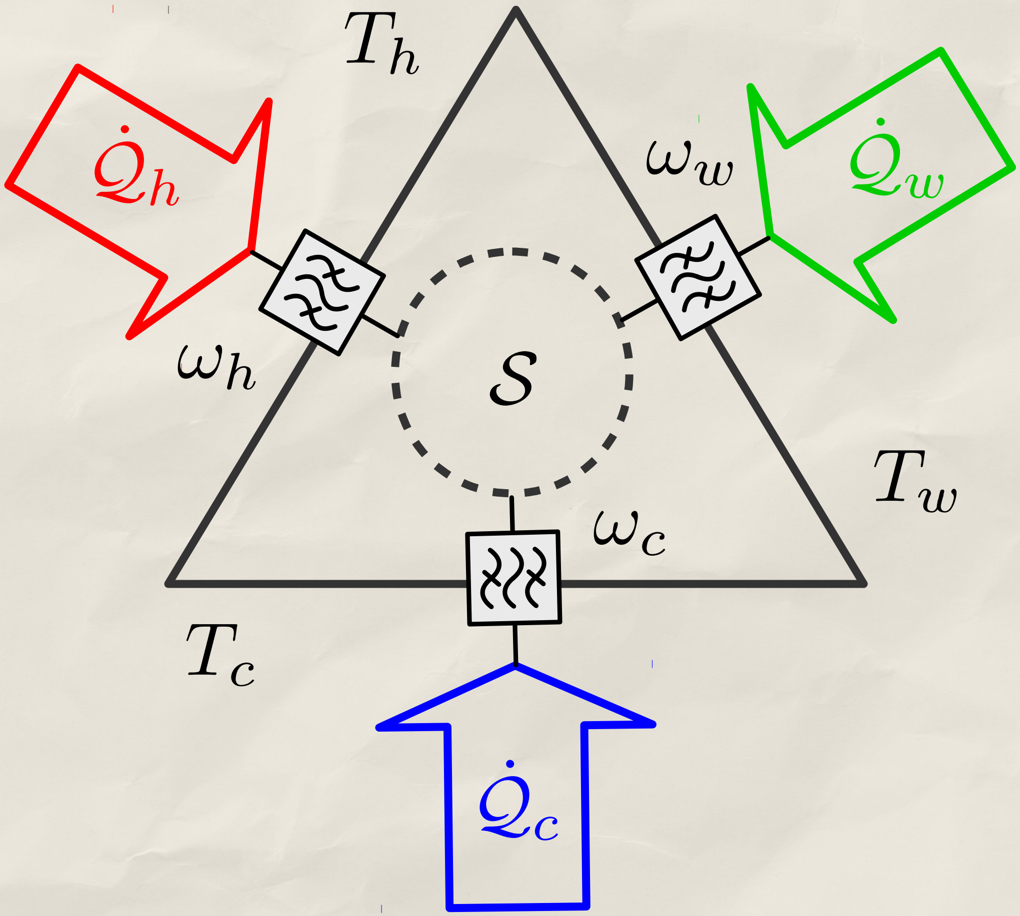
LAC *et al.*, *PRE* **92**, 032136 (2015)

OUTLINE

1. ~~Motivation~~
2. ~~Quantum tricycles~~
3. Performance bounds for quantum absorption chillers
4. Heat leaks and internal dissipation

QUANTUM ABSORPTION CHILLER

$$\varepsilon \equiv \dot{\mathcal{Q}}_c/\dot{\mathcal{Q}}_w$$



$$\dot{\mathcal{Q}}_c > 0,\ \dot{\mathcal{Q}}_h < 0,\ \dot{\mathcal{Q}}_w > 0$$

$$\frac{\omega_c}{T_c} - \frac{\omega_h}{T_h} + \frac{\omega_h - \omega_c}{T_w} < 0$$

$$\Downarrow$$

$$\omega_c < \omega_{c,\text{rev}} \equiv \frac{T_c(T_w - T_h)}{T_h(T_w - T_c)}$$

Cooling window

$$\omega_c > \omega_{c,\text{rev}}$$

$$\{\dot{\mathcal{Q}}_c < 0,\ \dot{\mathcal{Q}}_h > 0,\ \dot{\mathcal{Q}}_w < 0\}$$

Heat transformer

J. P. Palao & R. Kosloff, *PRE* **64**, 056130 (2001)
A. Levy & R. Kosloff, *PRL* **108**, 070604 (2012)

PERFORMANCE OPTIMISATION

Refrigerator

$$\dot{S} = \frac{\dot{\mathcal{Q}}_c}{T_c} + \frac{\dot{\mathcal{Q}}_h}{T_h} = x_c \mathcal{I}_c + x_h \mathcal{I}_h \qquad (T_w \to \infty)$$

$$x_\alpha \equiv \omega_\alpha / T_\alpha \qquad \mathcal{I}_c = -\mathcal{I}_h = \mathcal{I}$$

$$\mathcal{I}(x_c^*, x_h) + x_c^* \, \partial_{x_c^*} \mathcal{I}(x_c^*, x_h) = 0$$

Large temperature limit $(x_\alpha \to 0)$**:**

$$x_c^* = C \, x_h \Rightarrow \frac{\varepsilon}{\varepsilon_C} = \frac{C}{(1-C)\varepsilon_C + 1}$$

LAC et al., *PRE* **90**, 062124 (2014)

PERFORMANCE OPTIMISATION

Engine

$$\dot{S} = \frac{\dot{Q}_c}{T_c} + \frac{\dot{Q}_h}{T_h} = x_c \mathcal{I}_c + x_h \mathcal{I}_h \qquad (T_w \to \infty)$$

$$x_\alpha \equiv \omega_\alpha / T_\alpha \qquad \mathcal{I}_c = -\mathcal{I}_h = -\mathcal{I}$$

$$(x_h - (1 - \eta_C) x_c) \partial_{x_c} \mathcal{I} - (1 - \eta_c) \mathcal{I} = 0$$

Large temperature limit $(x_\alpha \to 0)$ **:**

$$x_c^* = \frac{1}{2} x_h \Rightarrow \frac{\eta_*}{\eta_C} = \frac{1}{2}$$

J. P. Palao *et al.*, *Braz. J. Phys.* **46**, 282 (2016)

PERFORMANCE OPTIMISATION

Refrigerator

$$\dot{S} = \frac{\dot{Q}_c}{T_c} + \frac{\dot{Q}_h}{T_h} = x_c \mathcal{I}_c + x_h \mathcal{I}_h \qquad (T_w \to \infty)$$

$$x_\alpha \equiv \omega_\alpha / T_\alpha \qquad \mathcal{I}_c = -\mathcal{I}_h = \mathcal{I}$$

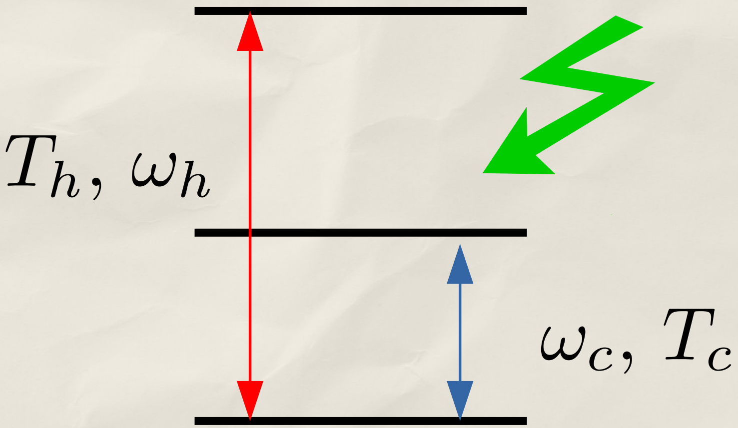
$$\mathcal{I}(x_c^*, x_h) + x_c^* \, \partial_{x_c^*} \mathcal{I}(x_c^*, x_h) = 0$$

Linear regime $(T_h \to T_c \Rightarrow \varepsilon_C \to \infty)$**:**

$$\varepsilon_* = \frac{\varepsilon_C}{\varepsilon_C + 2} \Rightarrow \frac{\varepsilon_*}{\varepsilon_C} \to 0$$

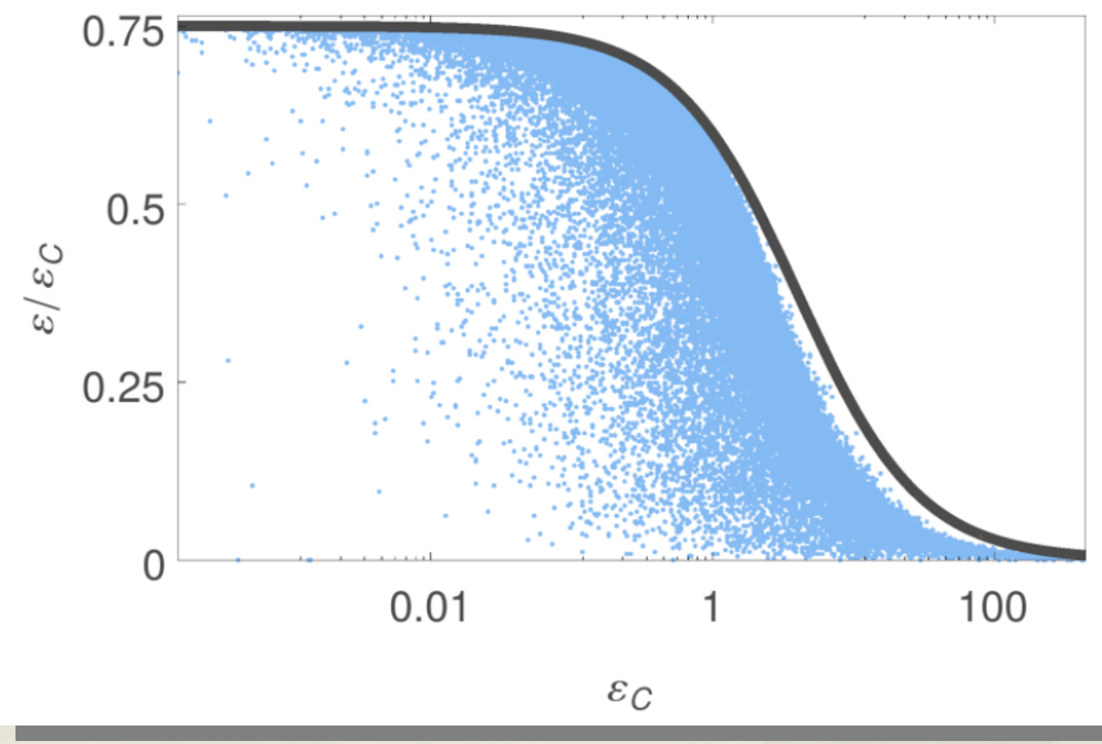
LAC et al., *PRE* **90**, 062124 (2014)

EXAMPLES



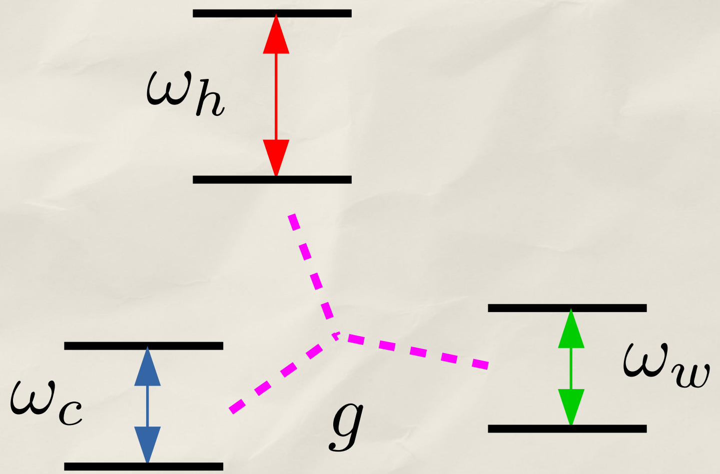
Non-endoreversible

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



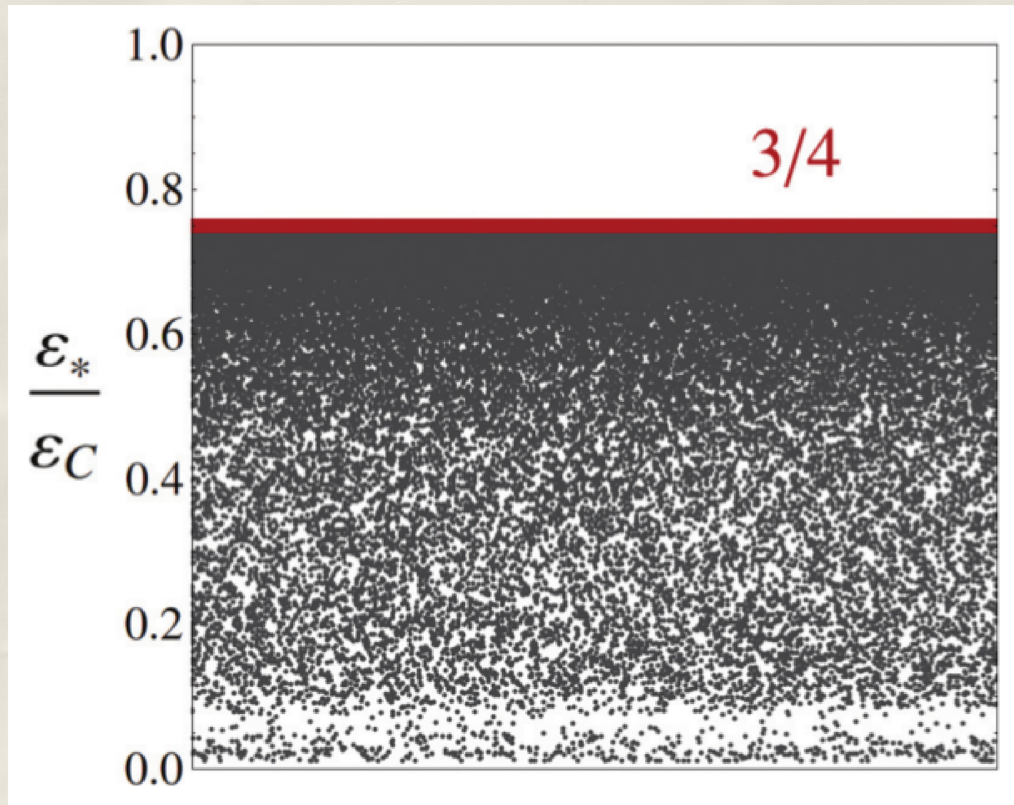
LAC et al., *PRE* **90**, 062124 (2014)

EXAMPLES



Non-endoreversible

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



N. Linden *et al.*, *PRL* **105**, 130401 (2010)

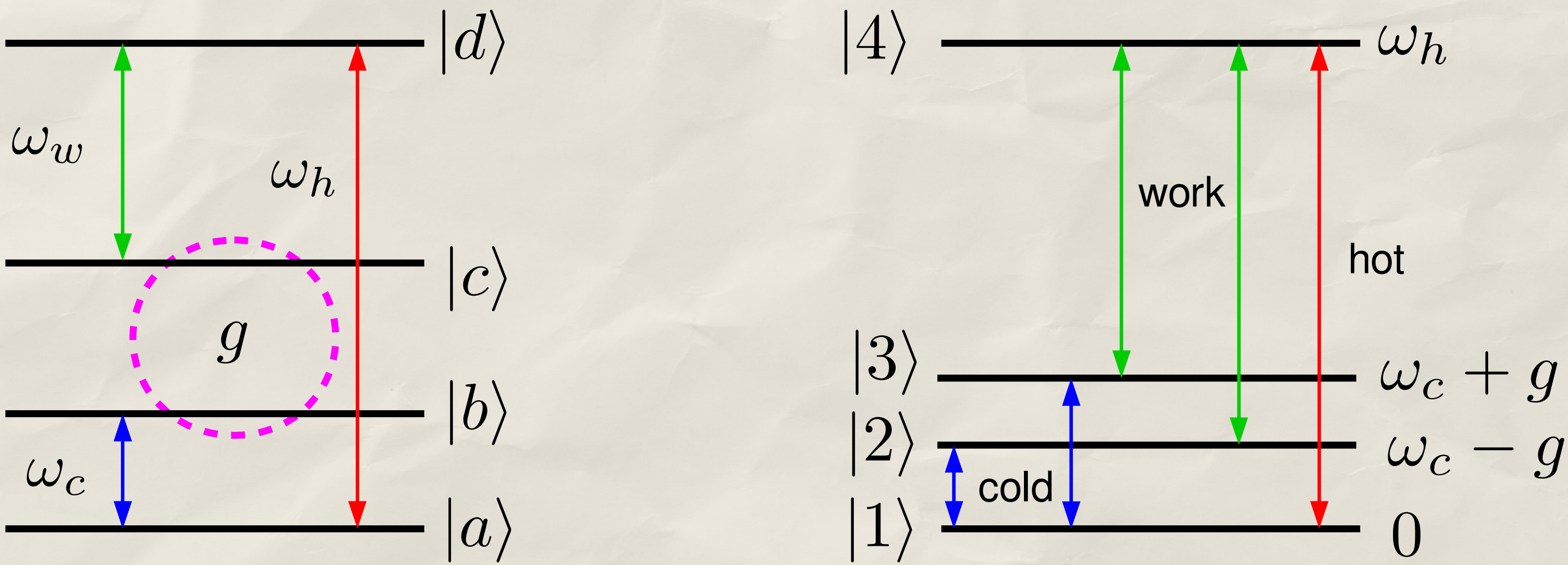
LAC et al., *PRE* **87**, 042131 (2013)

LAC *et al.*, *Sci. Rep.* **4**, 3949 (2014)

OUTLINE

1. ~~Motivation~~
2. ~~Quantum tricycles~~
3. ~~Performance bounds for quantum absorption chillers~~
4. Heat leaks and internal dissipation

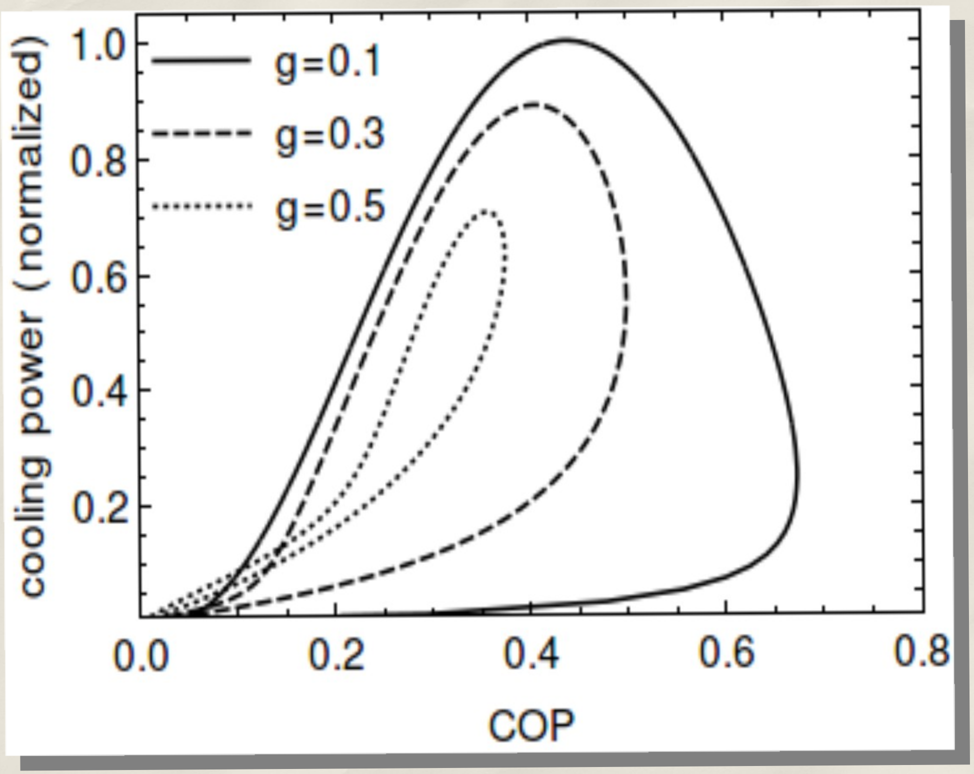
THE "LEAKY" 4-LEVEL CHILLER

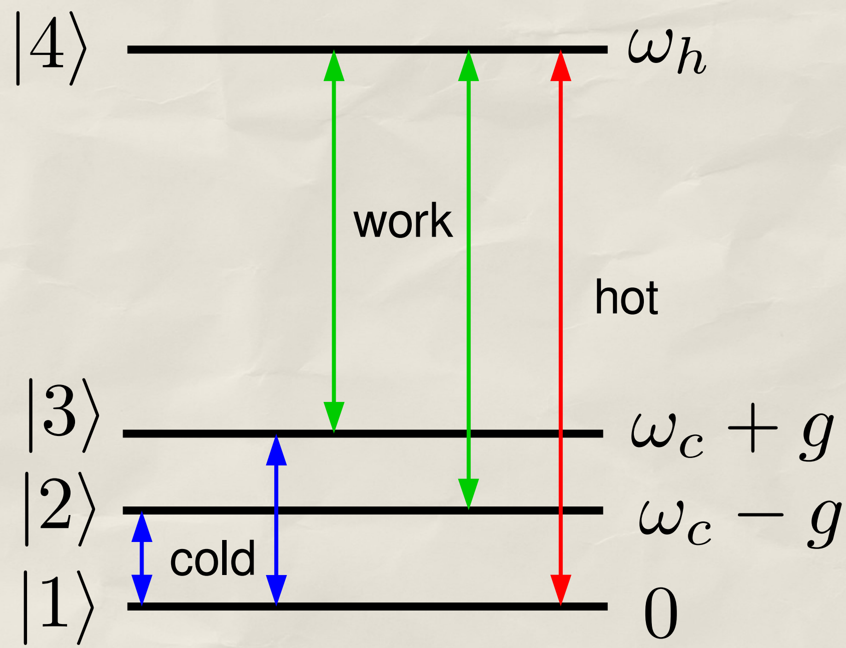


$$H_4 = \omega_c(|b\rangle\langle b| + |c\rangle\langle c|) + \omega_h |d\rangle\langle d| + g\,(|b\rangle\langle c| + |c\rangle\langle b|)$$

LAC et al., *PRE* **92**, 032136 (2015)

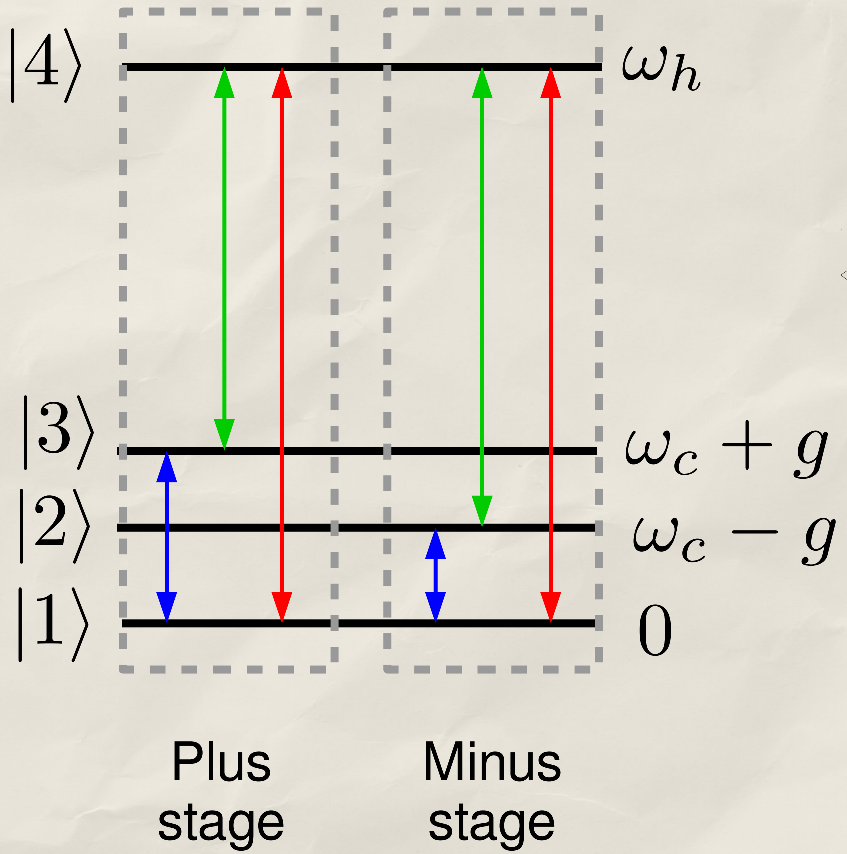
THE "LEAKY" 4-LEVEL CHILLER

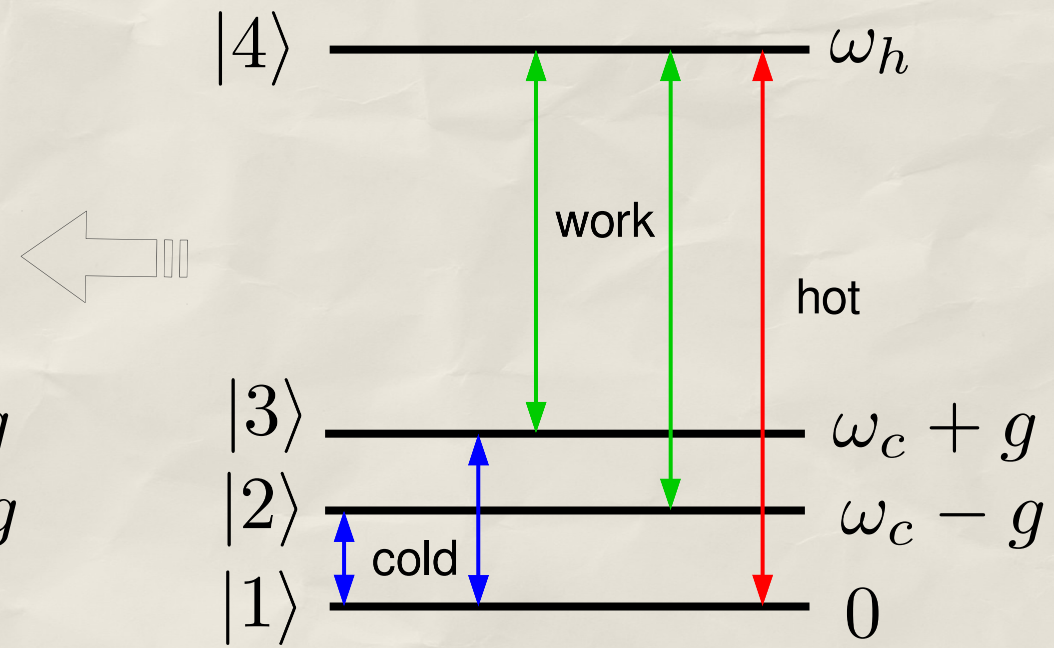




LAC et al., *PRE* **92**, 032136 (2015)

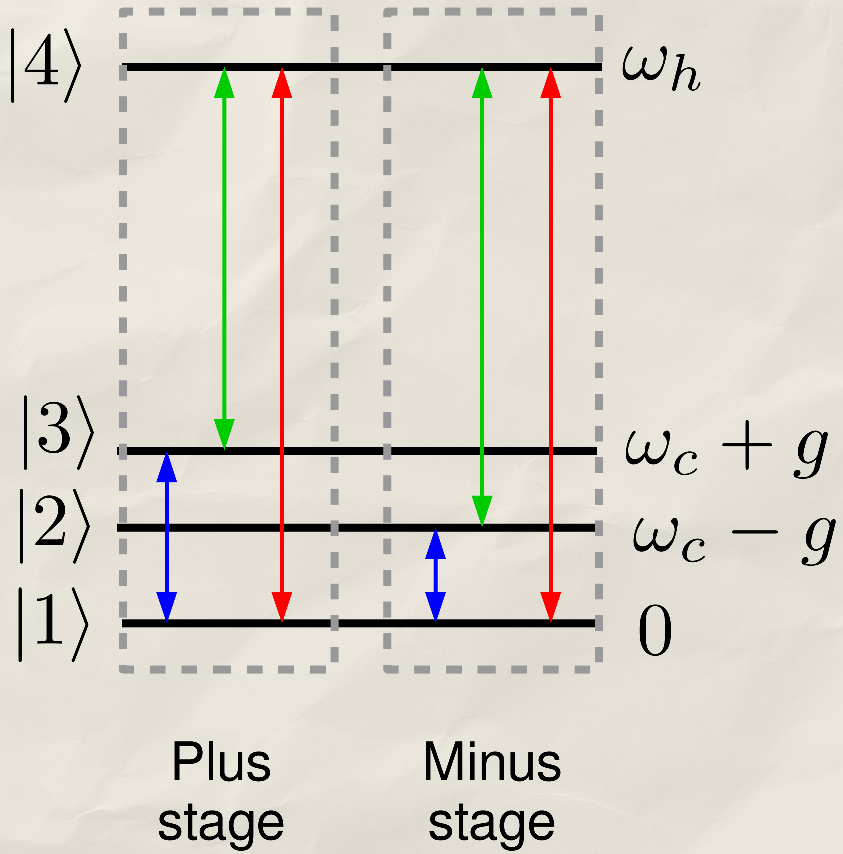
THE "LEAKY" 4-LEVEL CHILLER

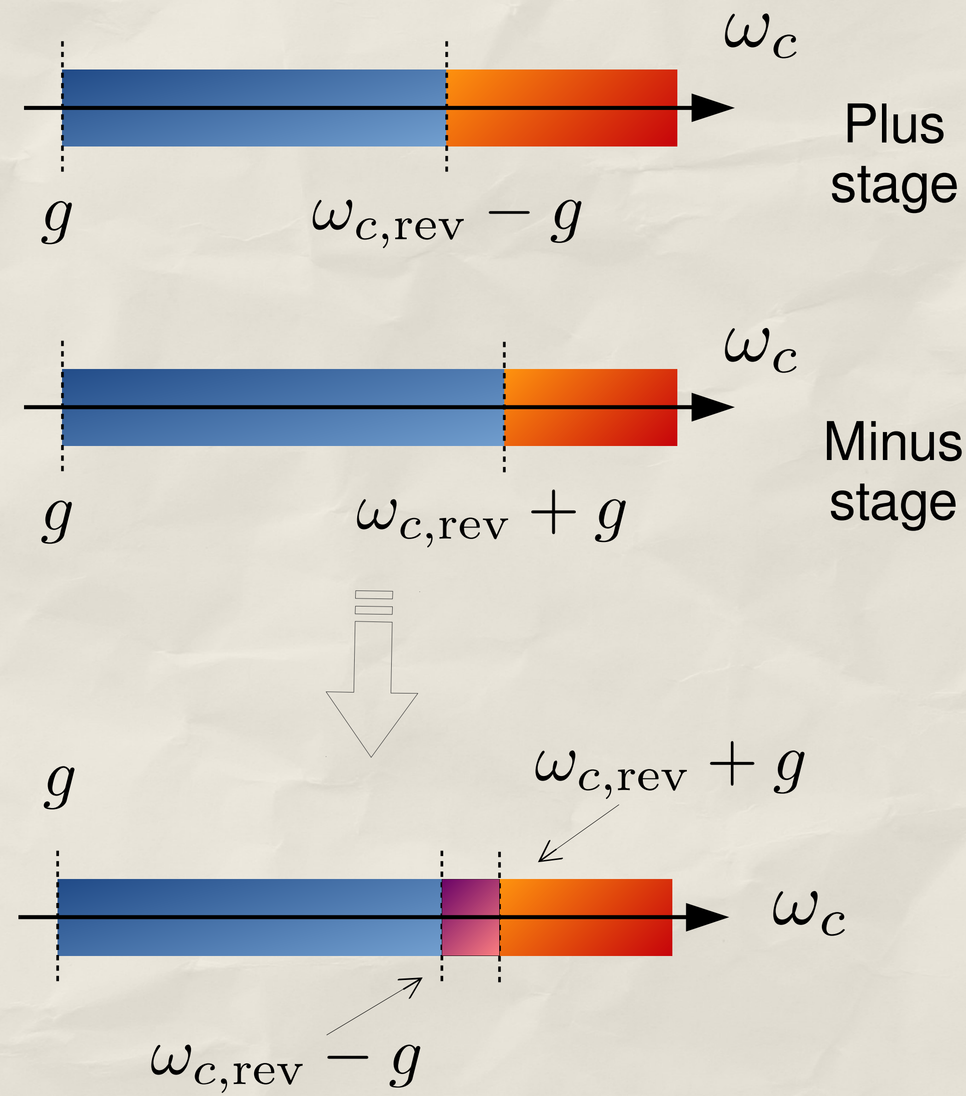




LAC et al., *PRE* **92**, 032136 (2015)

INTERNAL DISSIPATION





LAC et al., *PRE* **92**, 032136 (2015)

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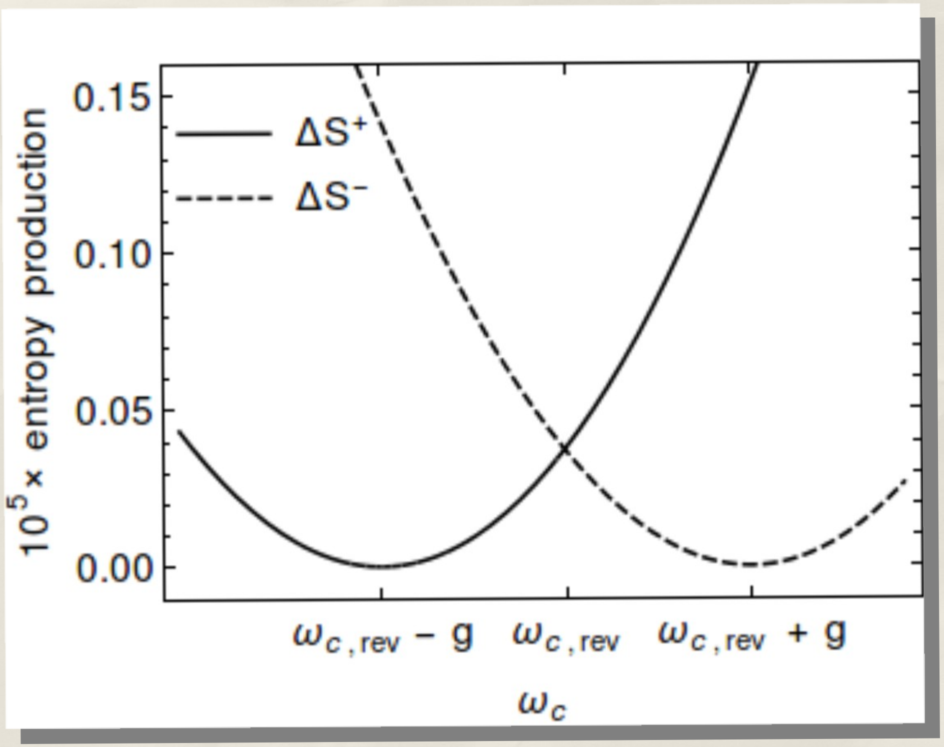
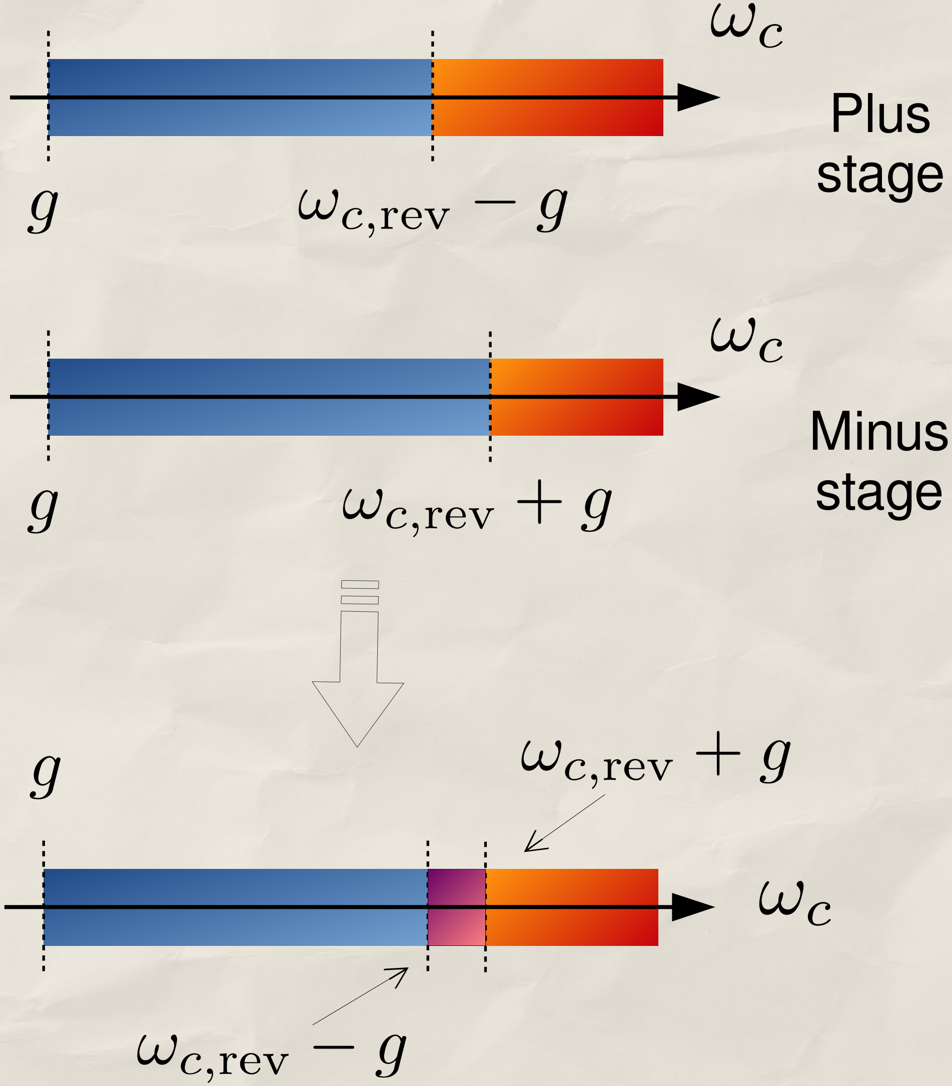
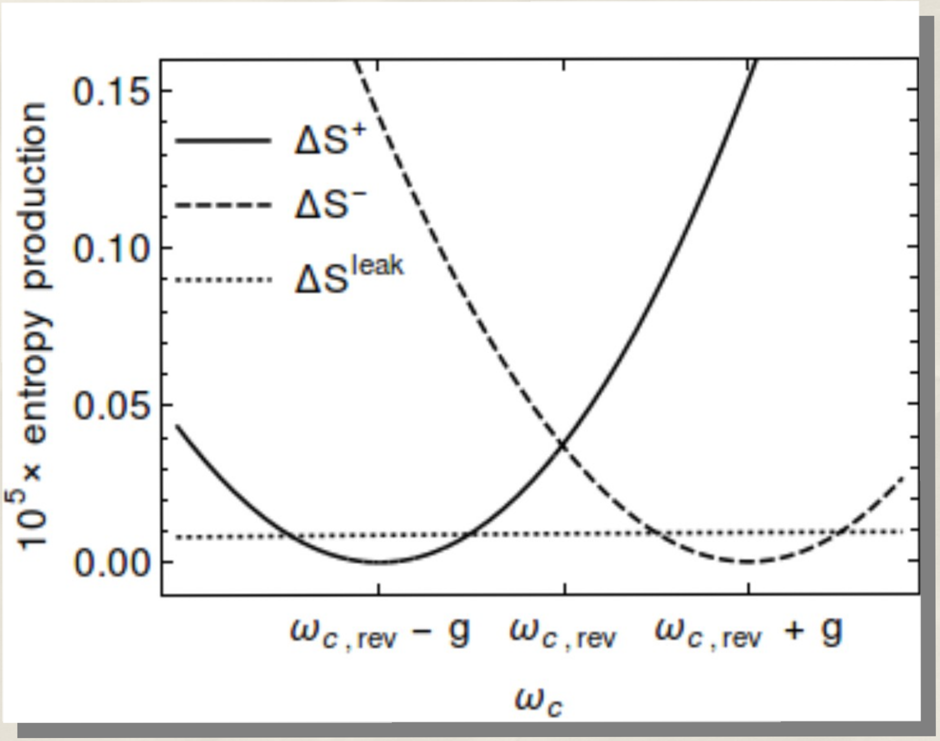
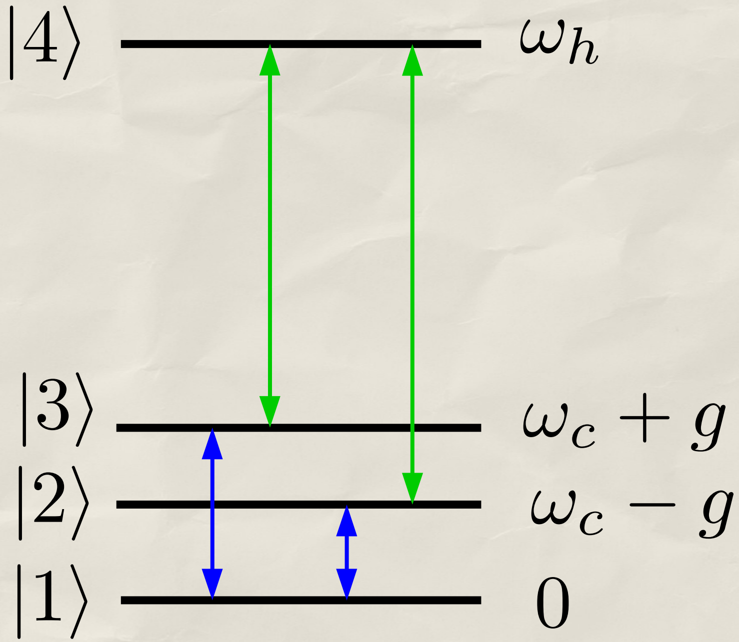




LAC et al., *PRE* **92**, 032136 (2015)

HEAT LEAKS





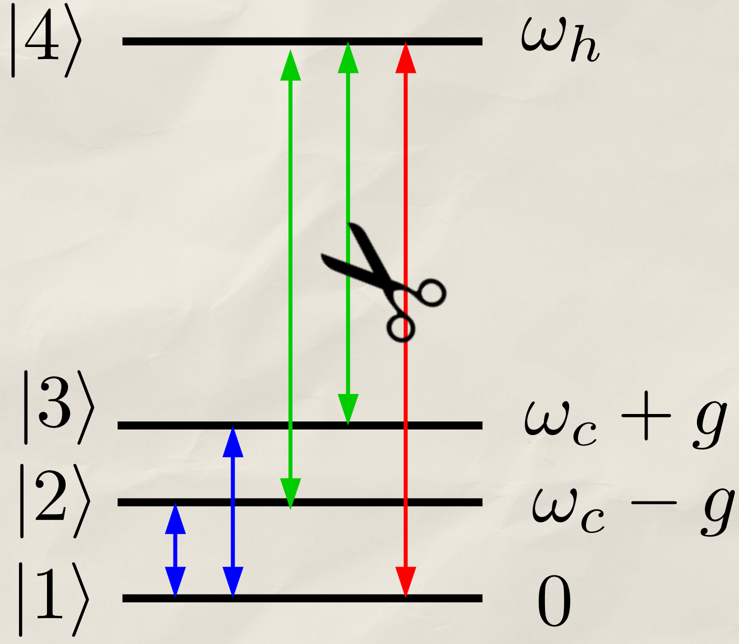
Heat leak stage

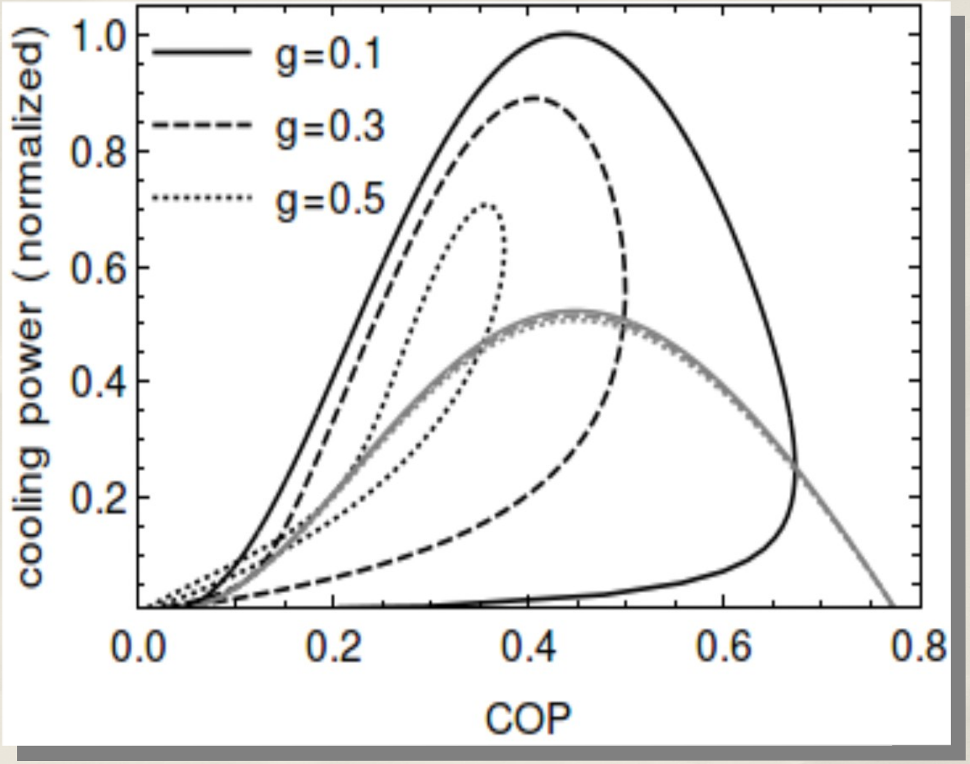
Systematic breakdown of quantum trycicles in stages

J. O. González *et al*, *NJP* **19**, 113037 (2017)

LAC et al., *PRE* **92**, 032136 (2015)

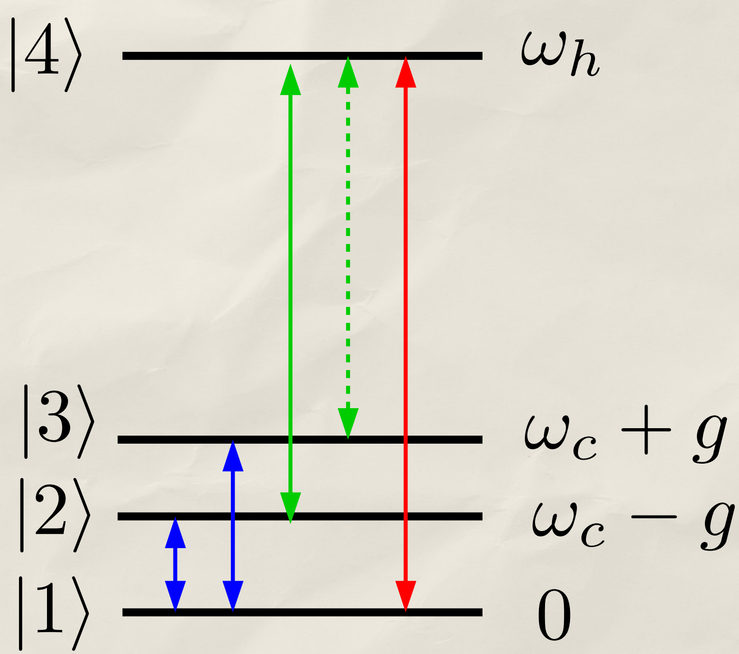
ELIMINATING IRREVERSIBILITY

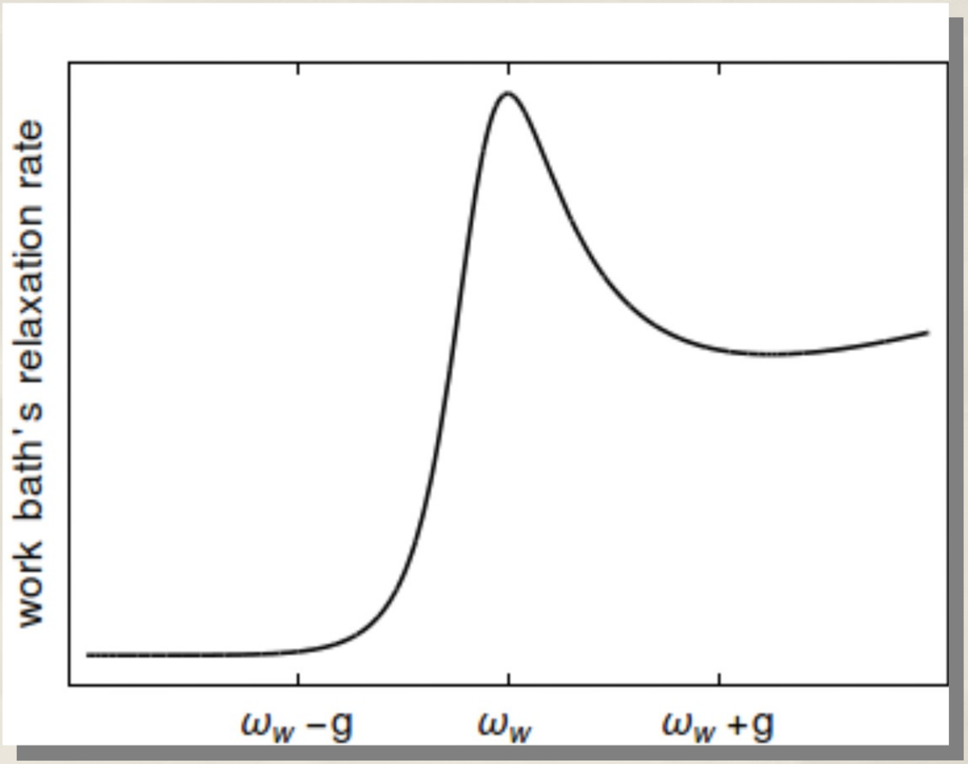




LAC et al., *PRE* **92**, 032136 (2015)

ELIMINATING IRREVERSIBILITY





D. Gelbwaser-Klimovsky *et al*, *PRE* **87**, 012140 (2013)

A. G. Kofman *et al.*, *J. Mod. Opt.* **41**, 353 (1994)

LAC et al., *PRE* **92**, 032136 (2015)

WRAP-UP

Quantum tricycles

* Strongly coupled quantum tricycles provide a good framework for endoreversible (quantum) thermodynamics.

Performance optimisation

* The COP at maximum cooling power of strongly coupled quantum tricycles is non-universal.
* The long-time bath correlation properties set the ultimate performance bound on refrigeration.

Heat leaks and internal dissipation

* The competition between alternative dissipative decay paths can be avoided by reservoir engineering.