QUEEN'S UNIVERSITY BELFAST

GABRIELE DE CHIARA

LOCAL MASTER EQUATIONS ARE CONSISTENT WITH THERMODYNAMICS

+ 3-QUBIT REFRIGERATORS

MOTIVATIONS

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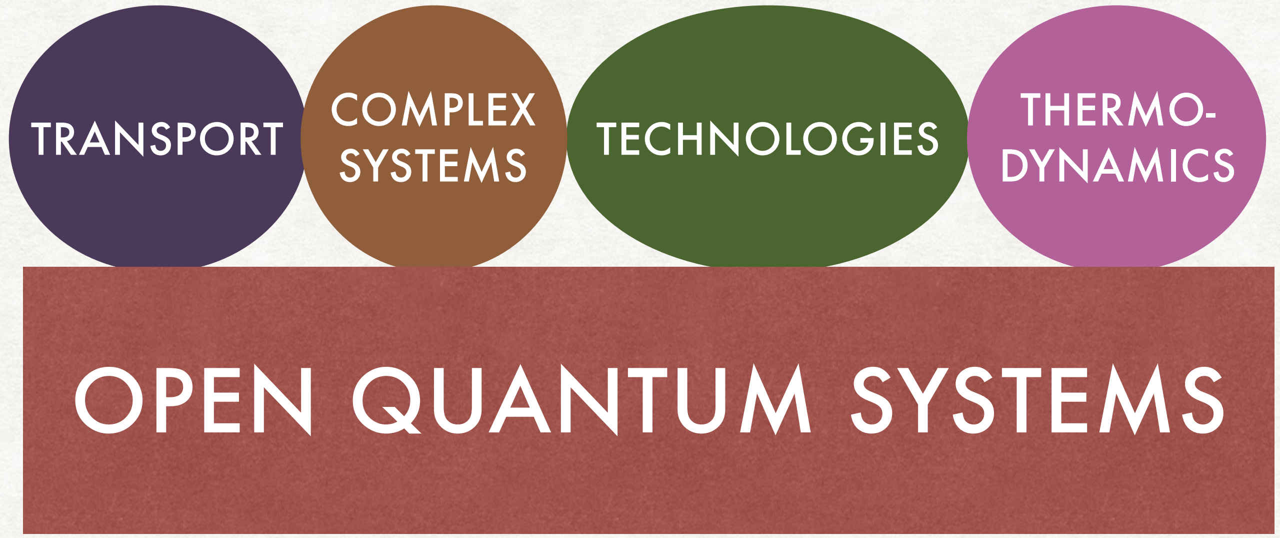

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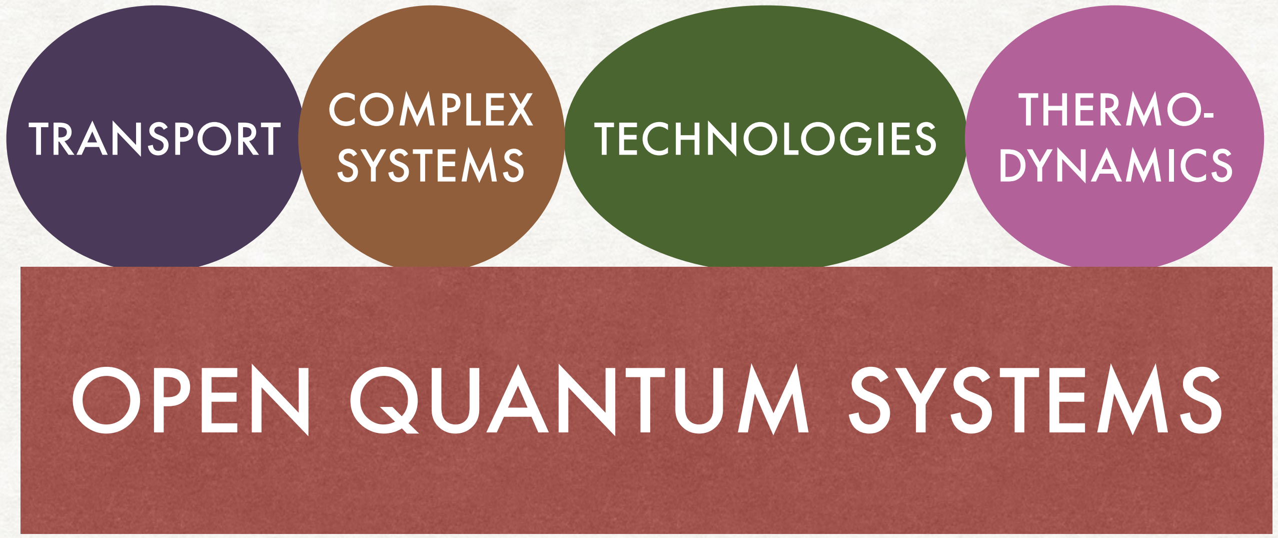

Common models:

- Caldeira-Leggett
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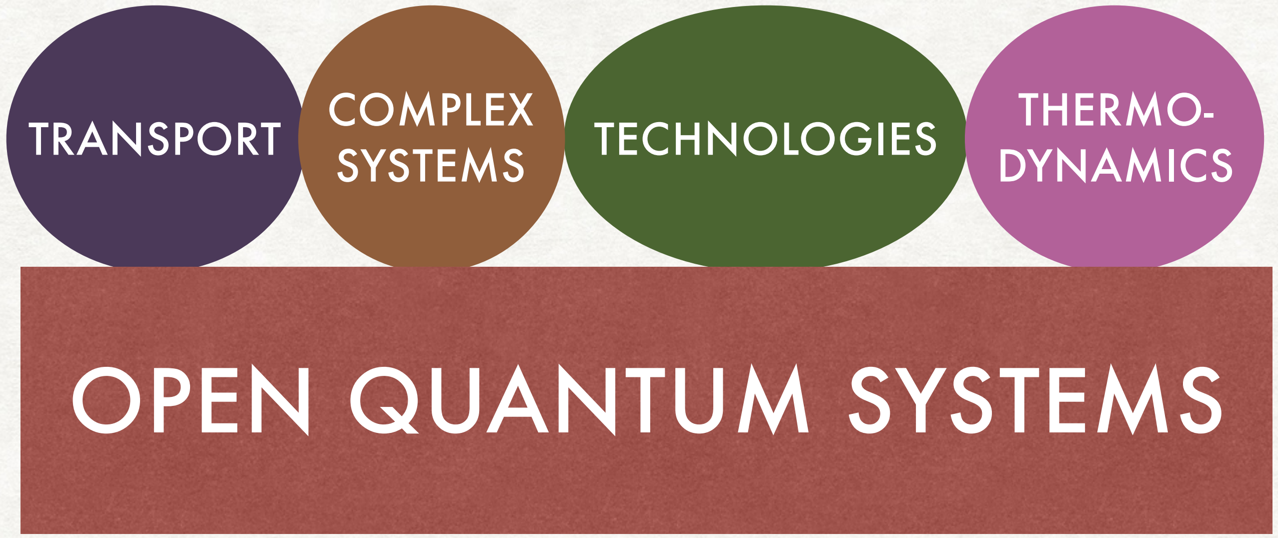

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MOTIVATIONS

TRANSPORT | COMPLEX SYSTEMS | TECHNOLOGIES | THERMO-DYNAMICS

OPEN QUANTUM SYSTEMS

Common models:
- Caldeira-Leggett
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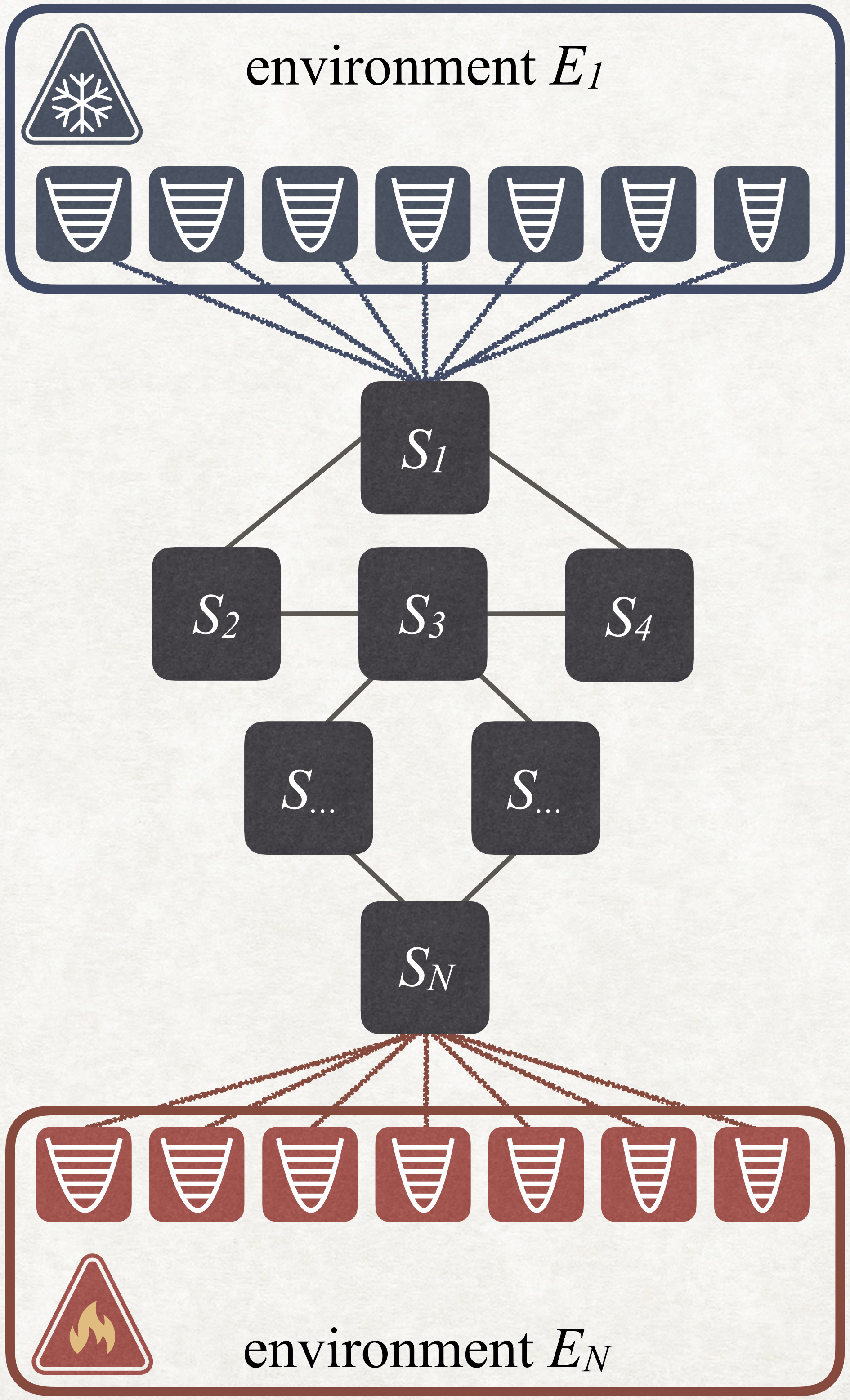
- Fermionic baths

APPROXIMATIONS:
E.G. BORN-MARKOV

Lindblad Master Equation

GLOBAL VERSUS LOCAL MASTER EQUATIONS



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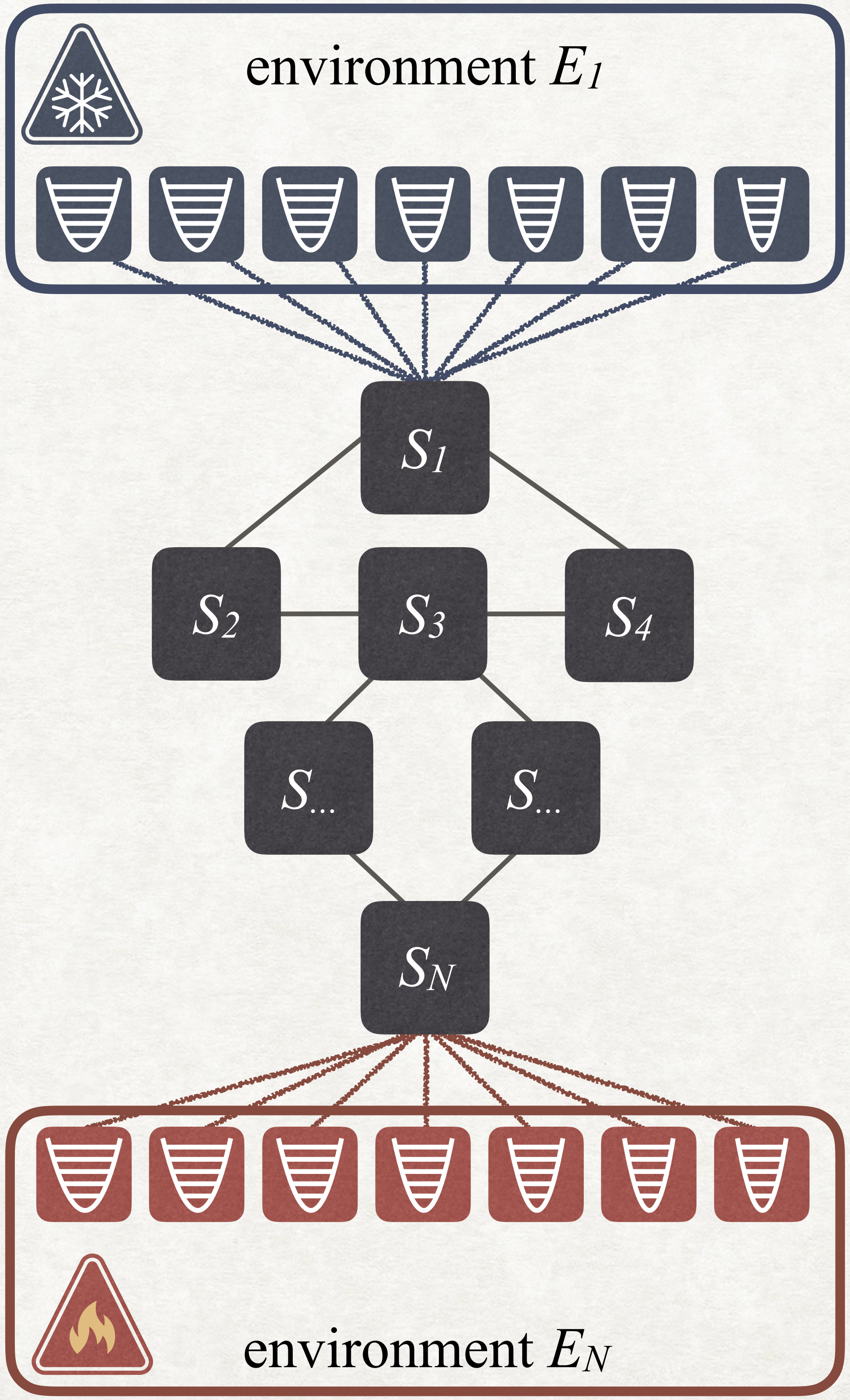

Global ME

Its derivation needs energy eigenstates of the whole system. Computationally hard!

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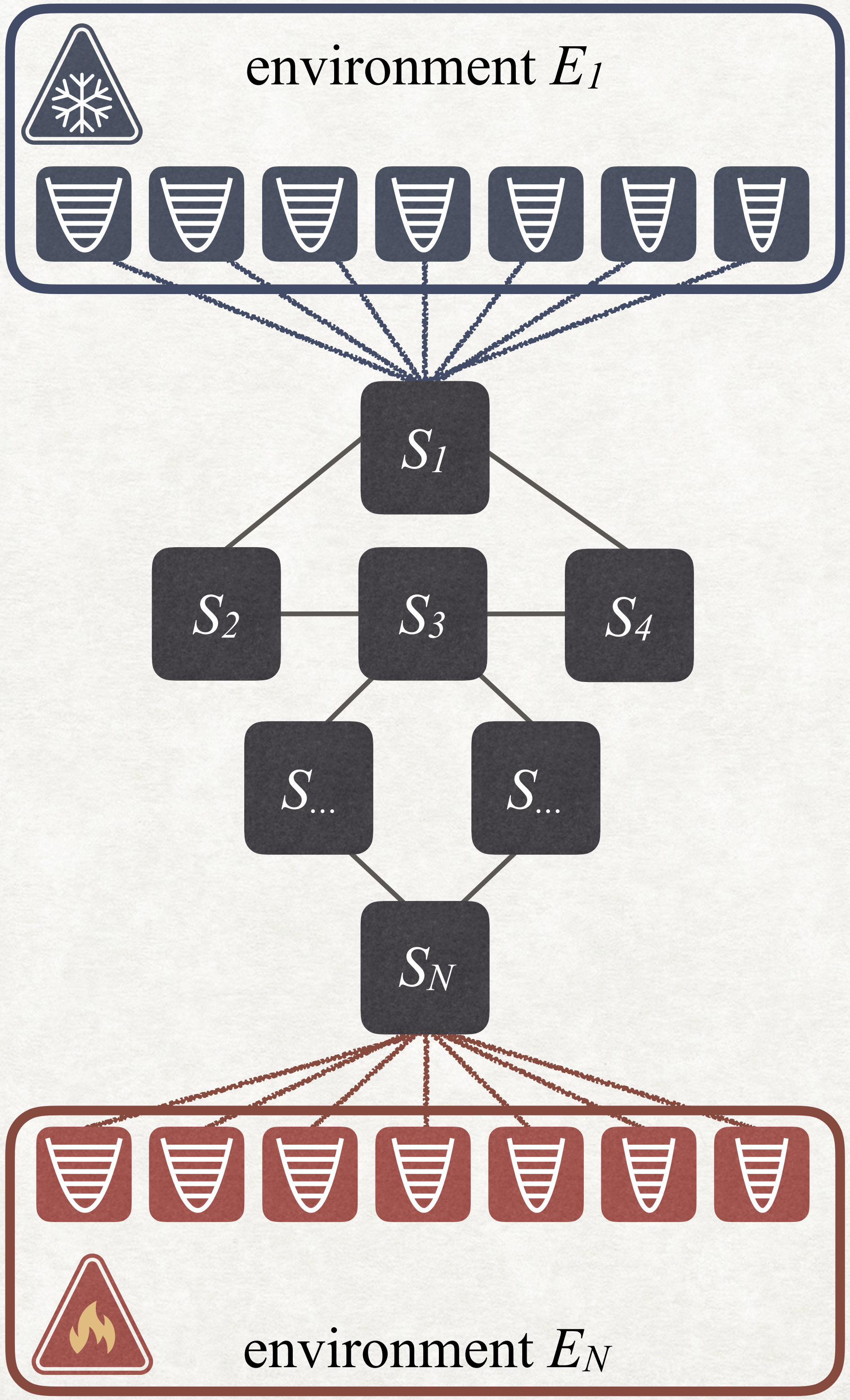

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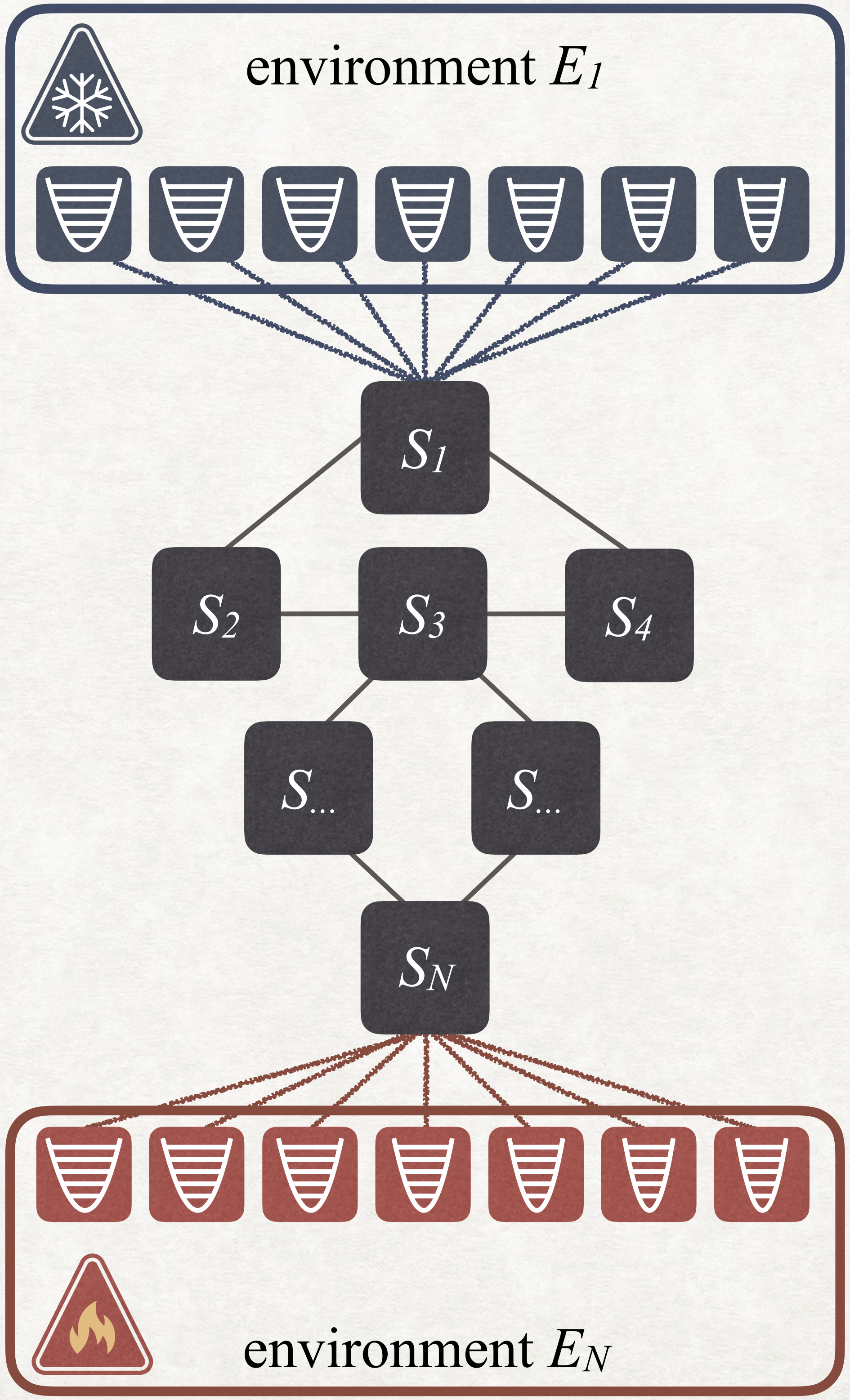

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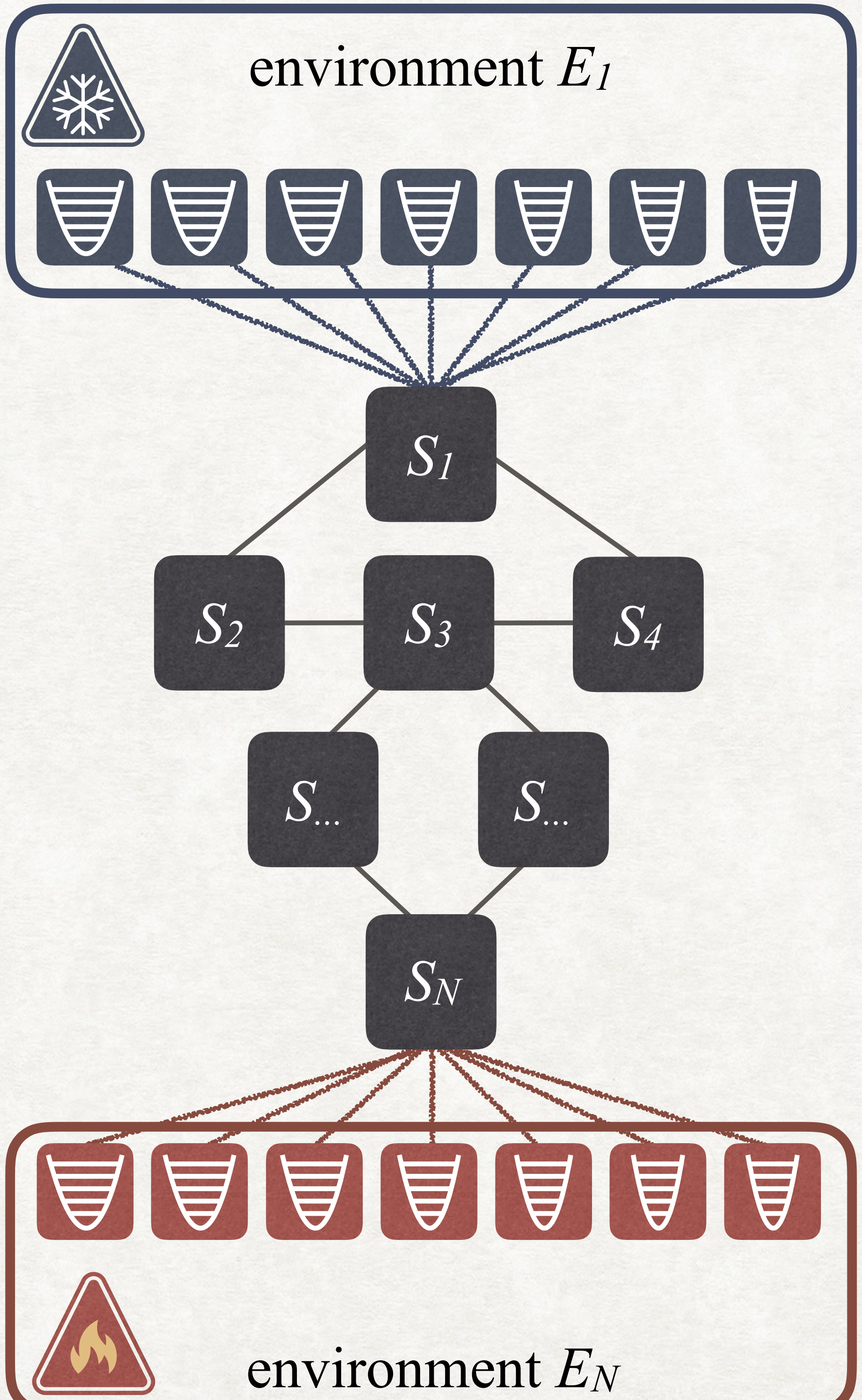

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See Marco Cattaneo's poster!

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"INADEQUACY" OF LOCAL ME?

Comparisons Global vs Local & Reviews:

Rivas et al., NJP 2010; Correa et al., PRE 2013; Guimarães et al., PRE 2016; Gonzalez et al., OSID, 2017; Hofer et al., NJP 2017; Stockburger&Motz FP 2017; Mitchison&Plenio, NJP 2018; Naseem et al., PRA 2018; Shammah et al., PRA 2018, S. Seah et al. PRE 2018, M. Cattaneo et al. 2019…& many more!

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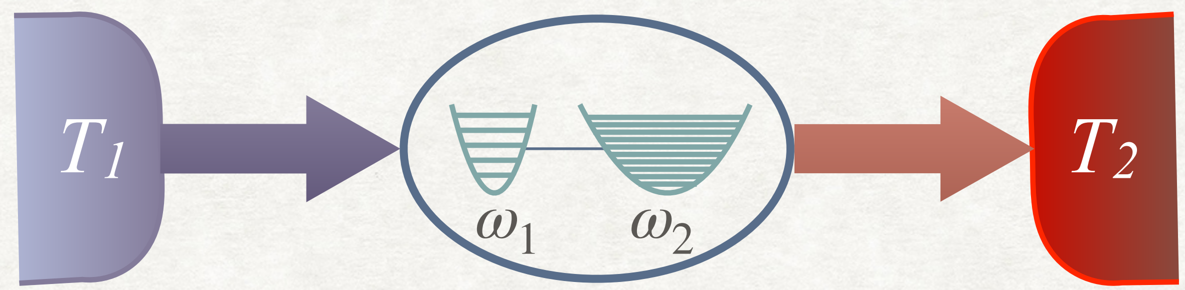
Levy-Kosloff: "The local approach to quantum transport may violate the second law of thermodynamics", EPL 2014



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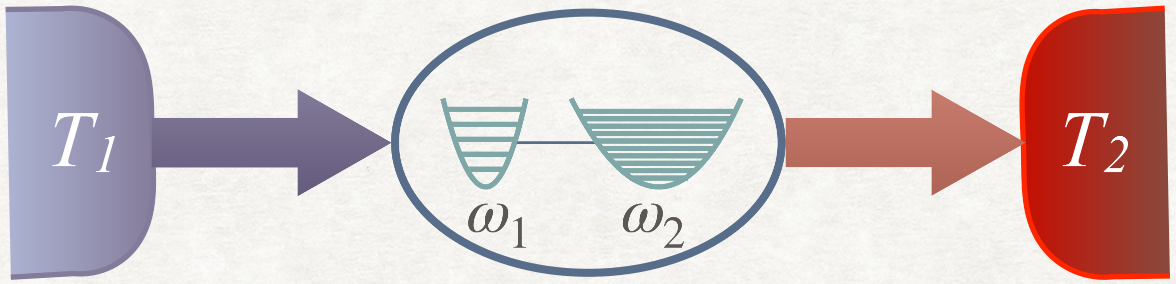

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$$n_i = \frac{1}{e^{\beta_i \omega_i} - 1}$$

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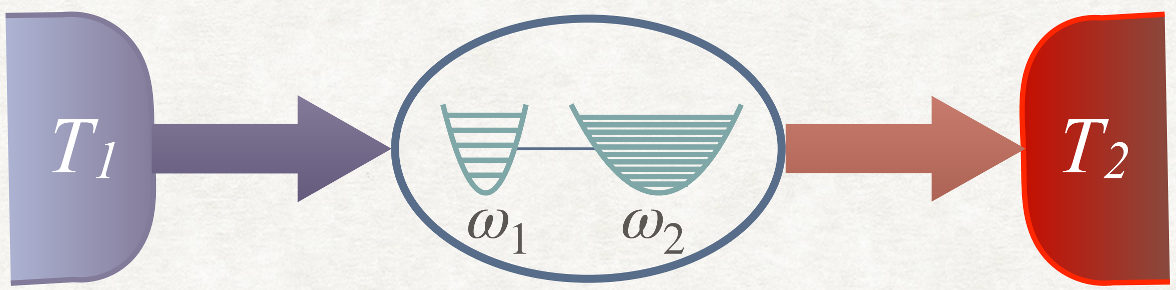

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The sign of the current depends on the sign of: $\dfrac{T_1}{\omega_1} - \dfrac{T_2}{\omega_2}$

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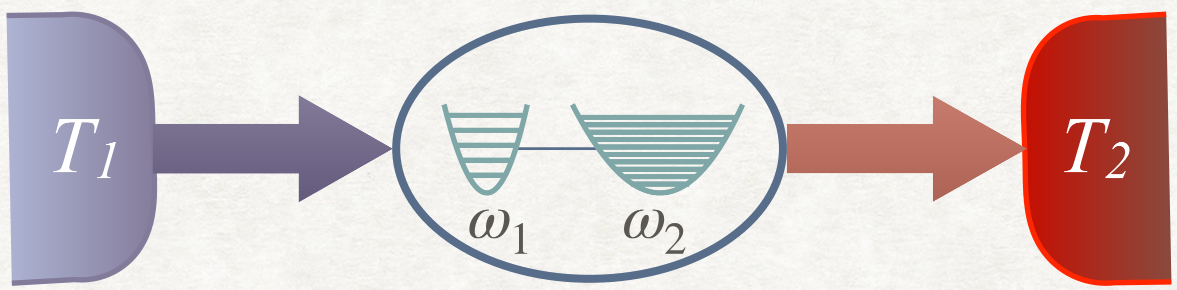

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LME predicts spontaneous cold to hot current!

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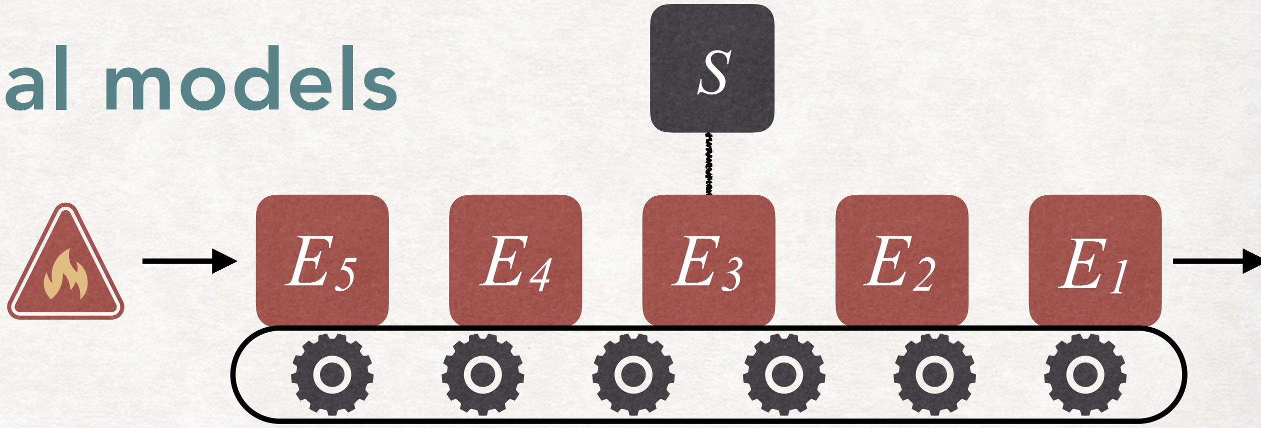

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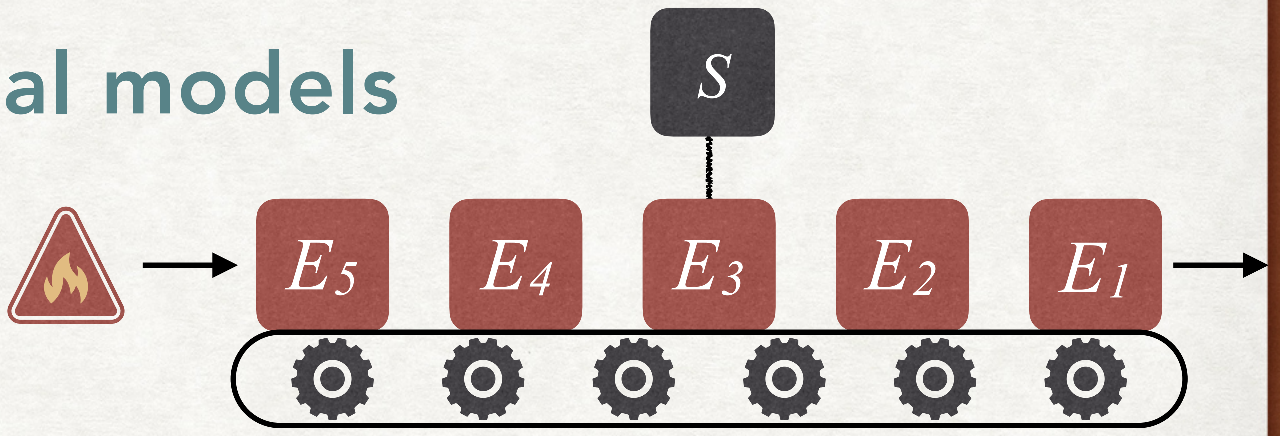
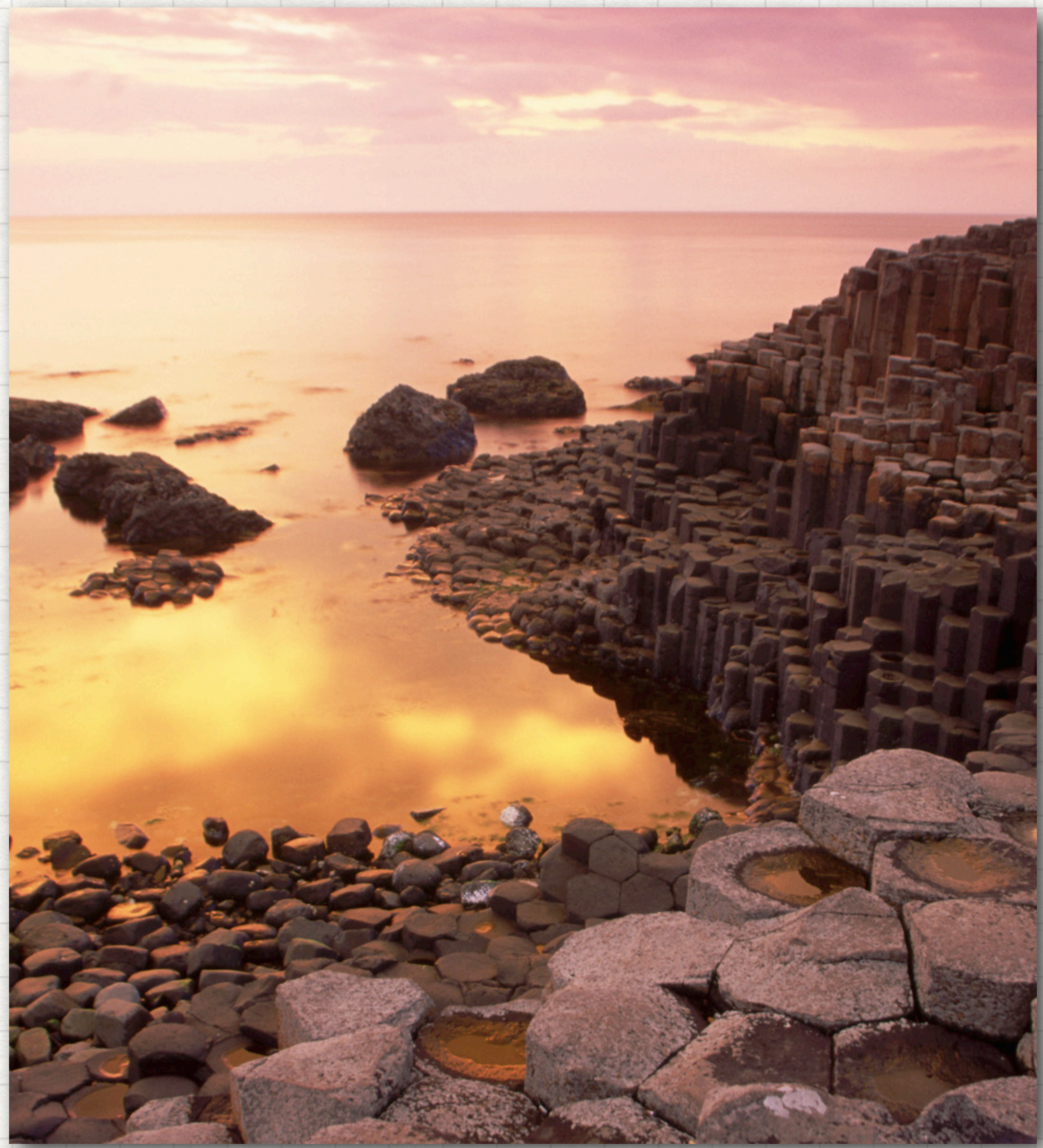


The goal of this talk is to show:
Thermodynamic laws are observed provided one includes all energy/entropy contributions.

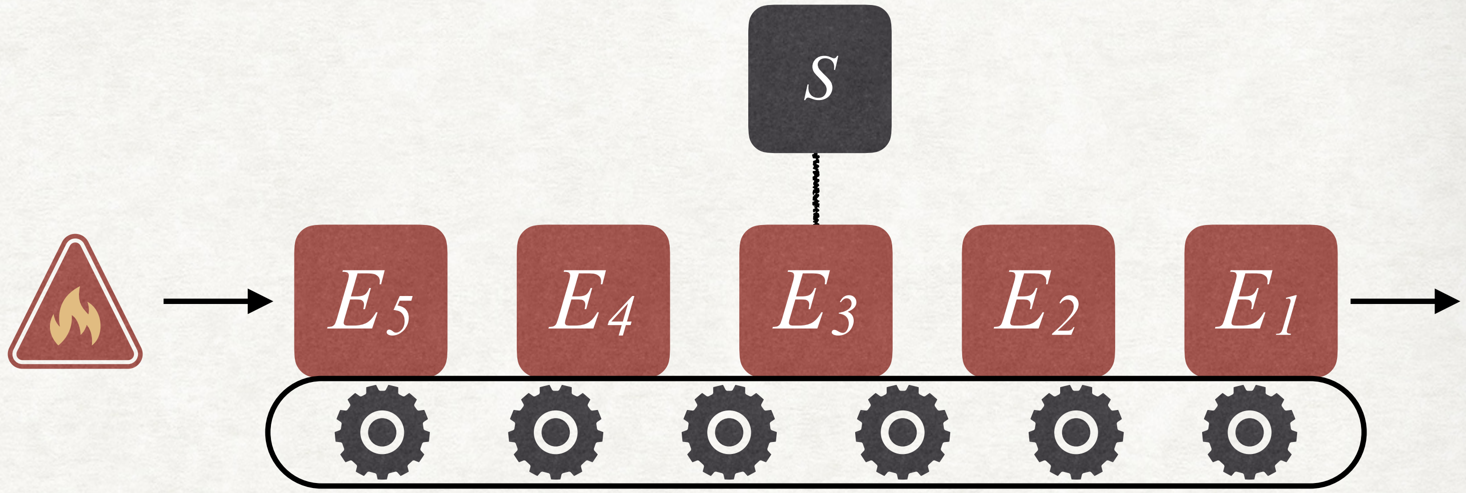
OUTLINE

- Collisional models
- Thermodynamic cost of Local Master Equations
- Further considerations
- Bonus: Three-qubit refrigerators with two-body interactions
(see Adam's poster)
- Conclusions



COLLISIONAL MODELS (1)

Effect of environment is modelled by collisions with external units.



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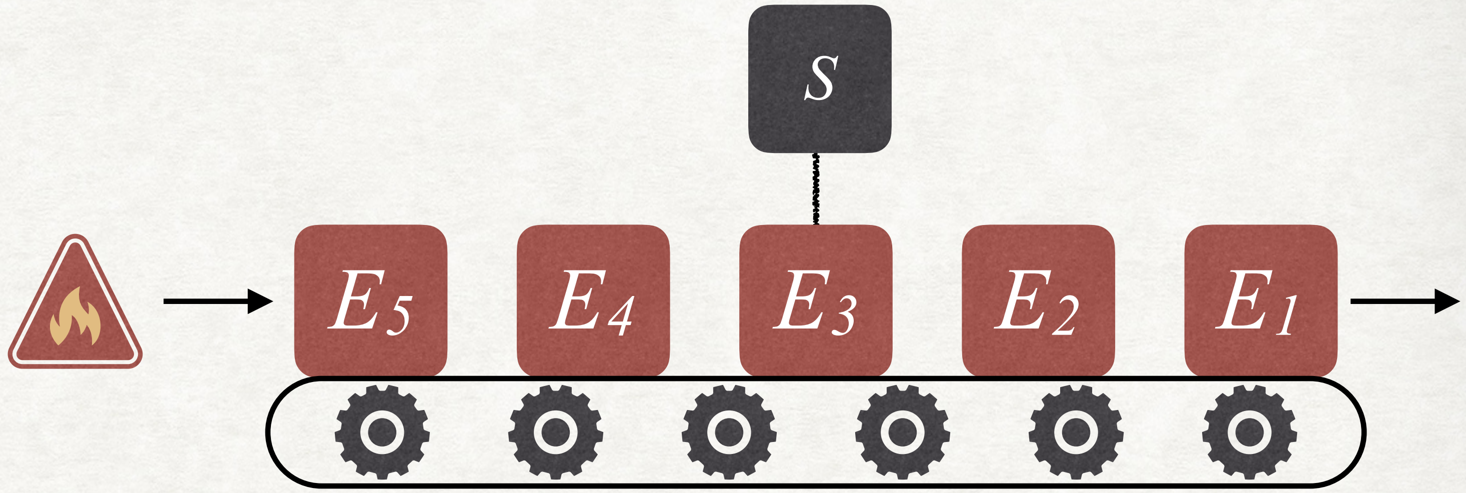
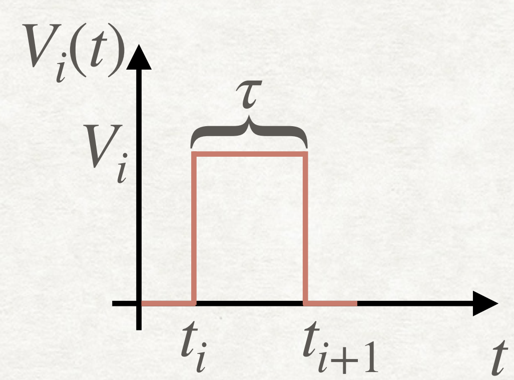


$$H_{\text{tot}} = H_S + \sum_{i=1}^{N} H_{E_i} + \frac{1}{\sqrt{\tau}} \sum_{i=1}^{N} V_i$$

System-Unit interaction:



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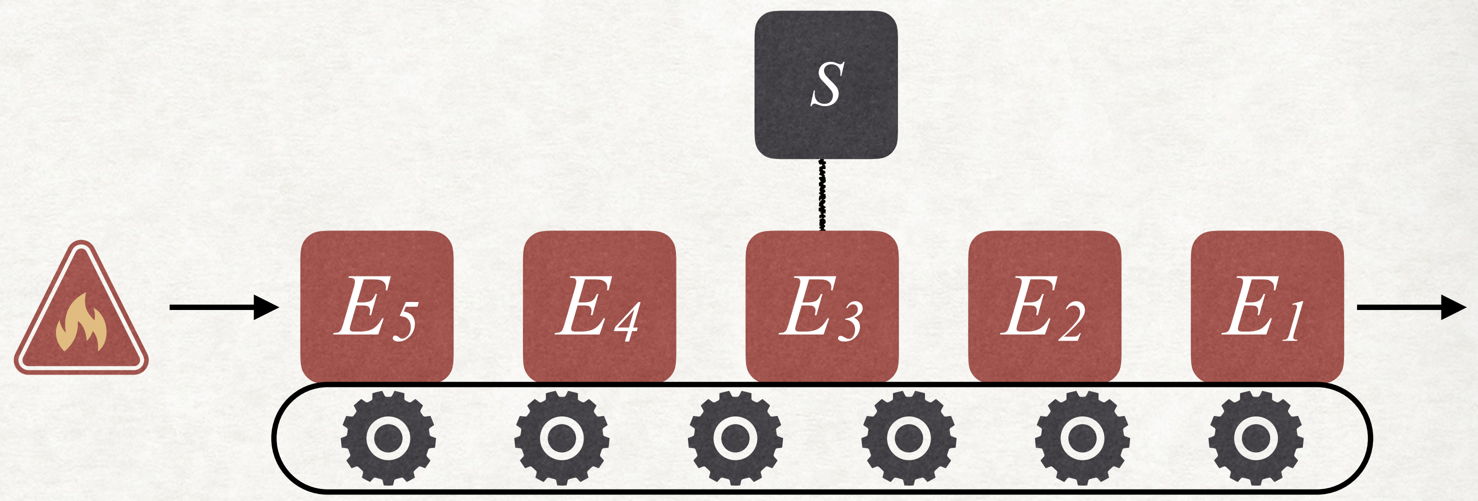

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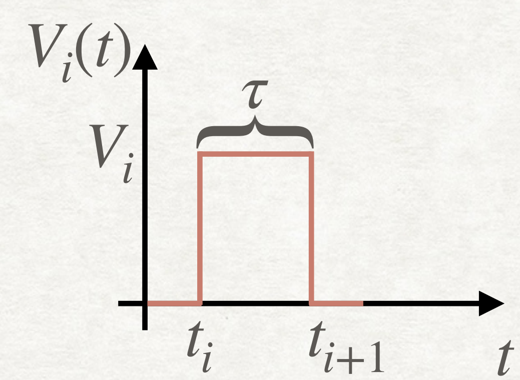

$$\rho_S[(n+1)\tau] = \mathrm{Tr}_E \left\{ e^{-i\tau H_{\text{tot}}}\, \rho_S(n\tau) \otimes \rho_{E_n}\, e^{i\tau H_{\text{tot}}} \right\}$$

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Next steps:

1)Assume thermal ancillas: $\rho_E = \bigotimes_{i=1}^{N} \frac{e^{-\beta_i H_{E_i}}}{\mathrm{Tr}\, e^{-\beta_i H_{E_i}}}$

2)Second order expansion in τ

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$$\frac{d\rho_S}{dt} = -i[H_S, \rho_S] + \sum_{i=1}^{N} D_i(\rho_S), \qquad D_i(\rho_S) = -\frac{1}{2}\mathrm{Tr}_{E_i}[V_i, [V_i, \rho_S \otimes \rho_{E_i}]] \, .$$

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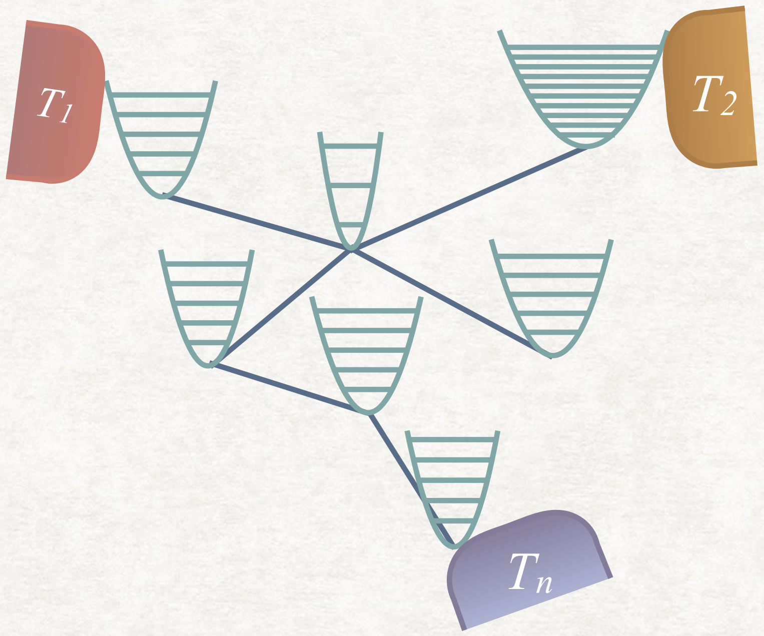
EXAMPLE: HARMONIC OSCILLATORS

$$H_S = \sum_i \omega_i a_i^\dagger a_i + \sum_{i \neq j} K_{ij} a_i^\dagger a_j + L_{ij} a_i a_j$$



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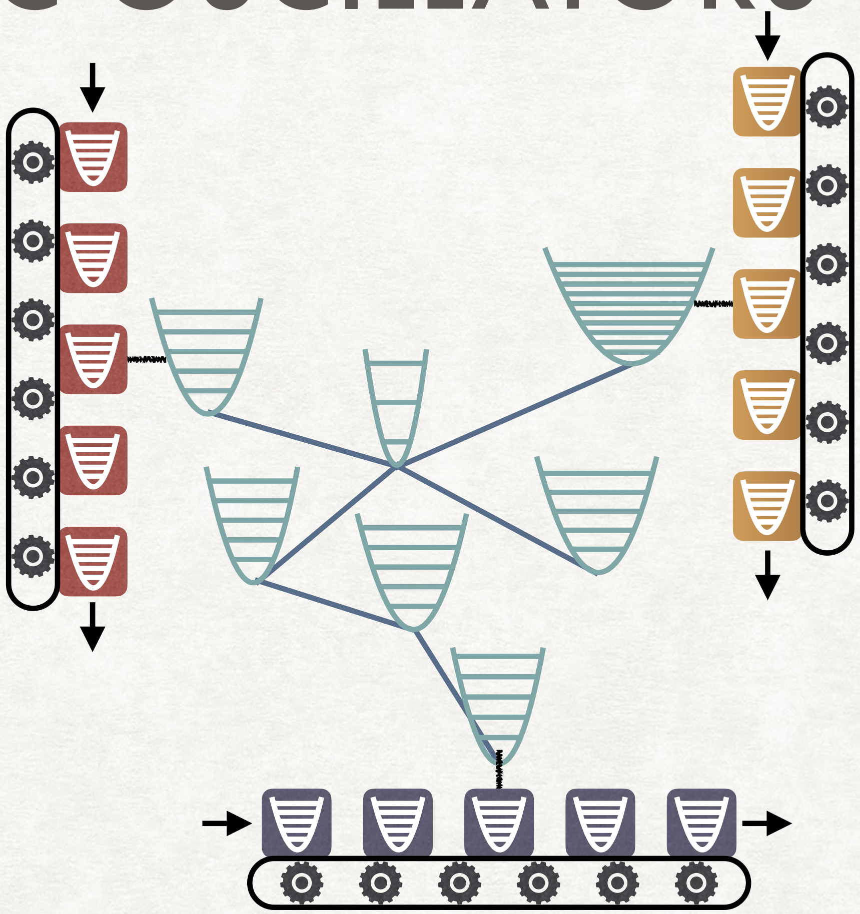

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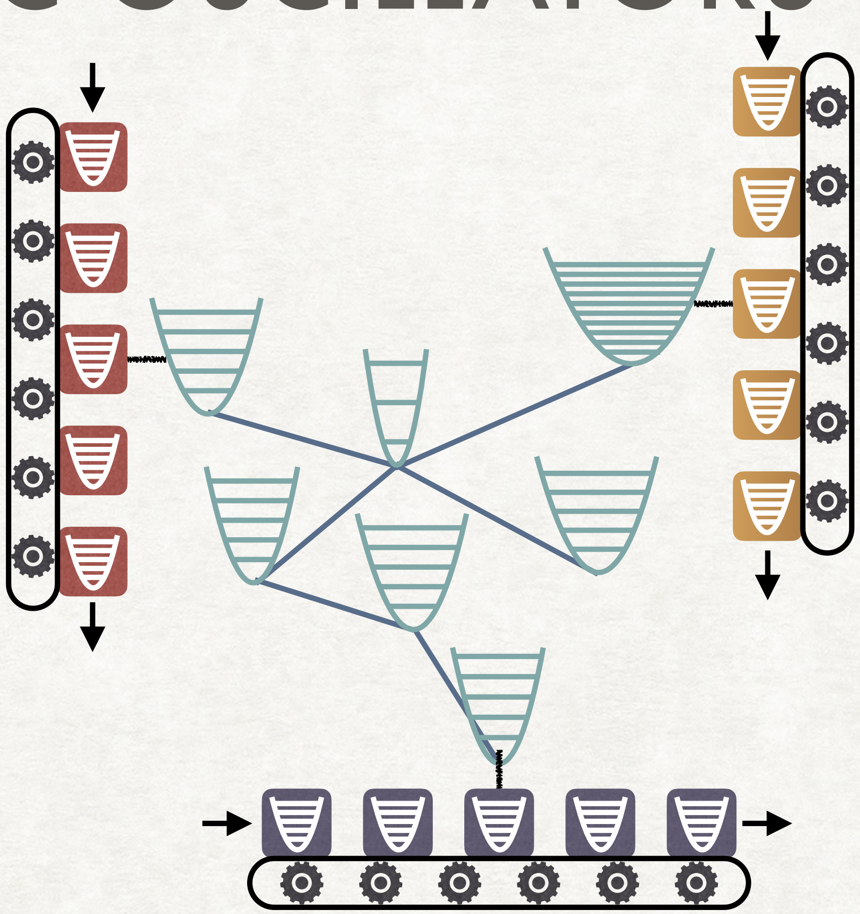
$$\Downarrow$$



Local Master equation!

$$\frac{d\rho_S}{dt} = -i[H_S, \rho_S] + \sum_{i=1}^{N_{\text{baths}}} D_i(\rho_S),$$

$$n_i = \frac{1}{e^{\beta_i \omega_i} - 1} \qquad \gamma_i = g_i^2$$

$$D_i(\rho_S) = \gamma_i(n_i + 1)\mathscr{L}_{a_i}(\rho_S) + \gamma_i n_i \mathscr{L}_{a_i^\dagger}(\rho_S)$$

$$\mathscr{L}_\sigma(\rho_S) = 2\sigma\rho_S\sigma^\dagger - \sigma^\dagger\sigma\rho_S - \rho_S\sigma^\dagger\sigma$$

THERMODYNAMICS

At steady state: $\dot{U} = 0$

$$\dot{Q}_i = \mathrm{tr}\left[D_i(\rho_S)H_i\right] = \gamma_i\omega_i(n_i - \langle a_i^\dagger a_i\rangle)$$

De Chiara, Landi, Hewgill, Reid, Ferraro, Roncaglia, Antezza, NJP 20, 113024 (2018)
see also: Barra, Sci. Rep. 2015; Strasberg et al., PRX 2017

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$$\delta W_{\mathrm{ext}} = \int_{n\tau}^{(n+1)\tau} \left\langle \frac{\partial H_{\mathrm{tot}}}{\partial t} \right\rangle dt \, .$$

First law:

$$\dot{W}_{\mathrm{ext}} = -\sum_i^{N_{\mathrm{baths}}} \dot{Q}_i = -\sum_i^{N_{\mathrm{baths}}} \gamma_i\omega_i(n_i - \langle a_i^\dagger a_i\rangle)$$

Lack of detailed balance is responsible for the external work

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EXAMPLE: 2 HARMONIC OSCILLATORS

$$H_S = H_1 + H_2 + H_I$$

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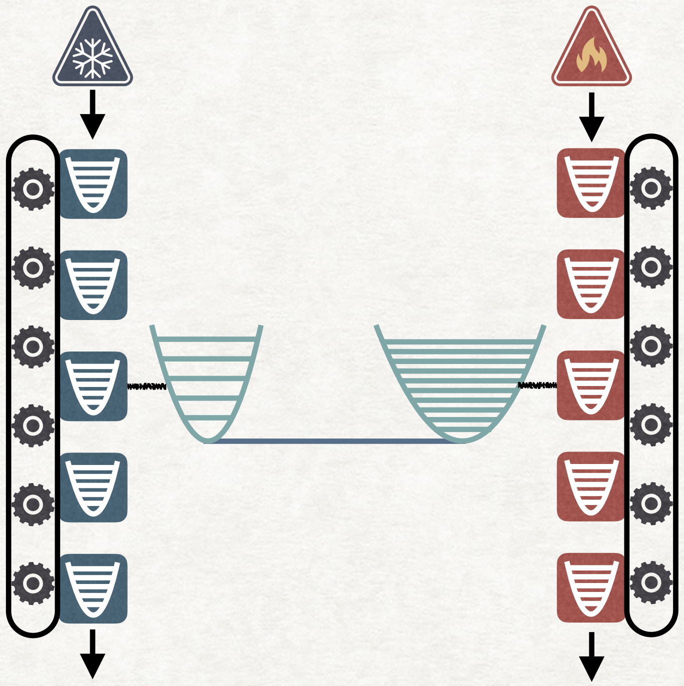

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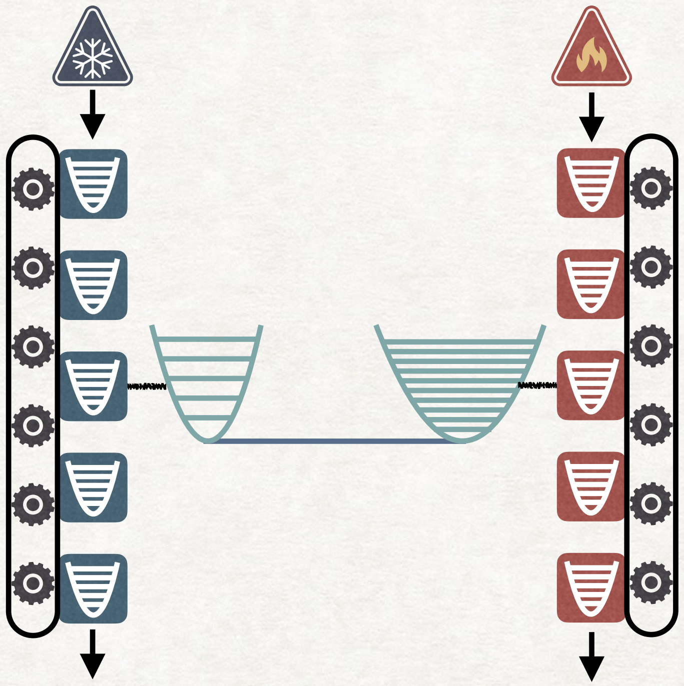

Steady state:

$$\dot{Q}_1 = \frac{2\gamma\epsilon^2}{\Delta^2}\omega_1(n_1 - n_2),$$

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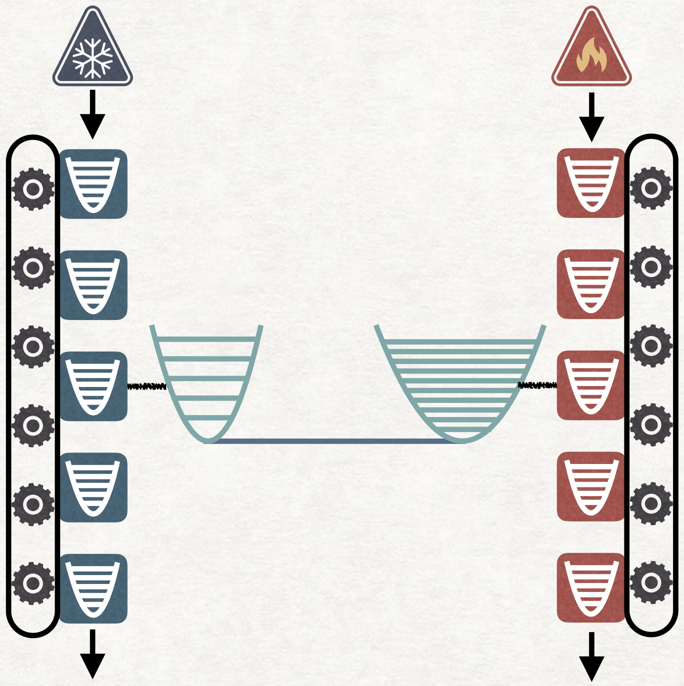

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Considerations:

$\dot{Q}_1$ and $\dot{Q}_2$ do not depend on $T_1 - T_2$ but rather on $n_1 - n_2$

$\omega_1 = \omega_2 \;\Rightarrow\; \dot{Q}_1 = -\dot{Q}_2 \Rightarrow \dot{W}_{\text{ext}} = 0$

De Chiara, Landi, Hewgill, Reid, Ferraro, Roncaglia, Antezza, NJP 20, 113024 (2018)

2 OSCILLATORS: MODES OF OPERATION

De Chiara, Landi, Hewgill, Reid, Ferraro, Roncaglia, Antezza, NJP 20, 113024 (2018)

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Oven
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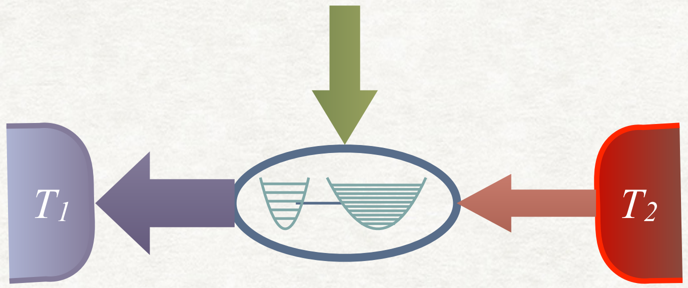

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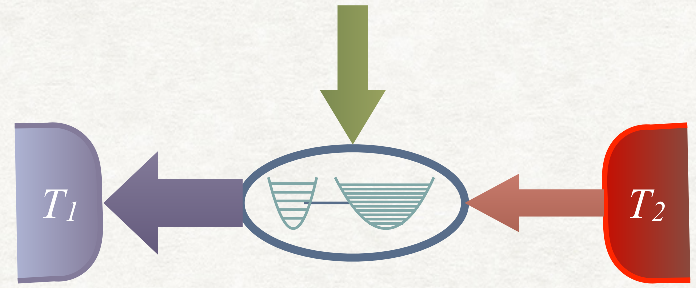

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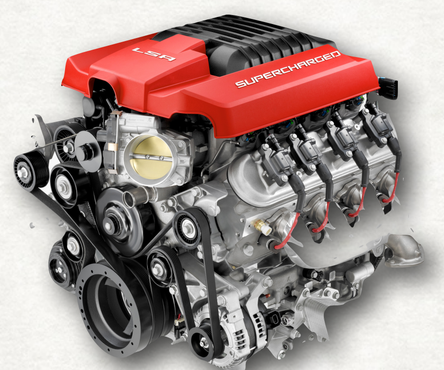
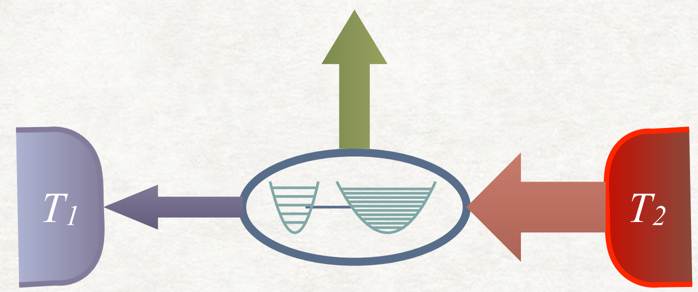
Engine





$$\frac{T_1}{T_2} < \frac{\omega_1}{\omega_2} < 1$$

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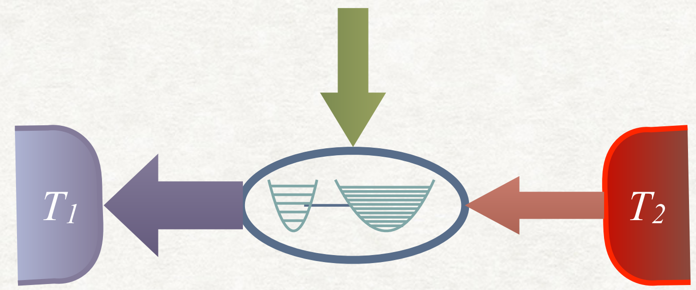
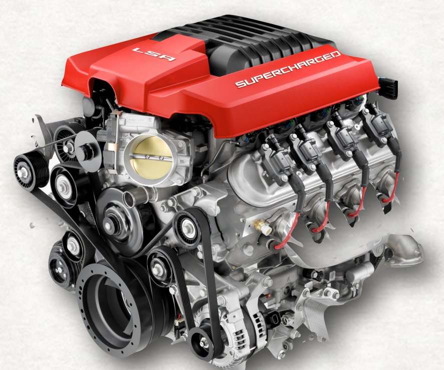
2 OSCILLATORS: MODES OF OPERATION

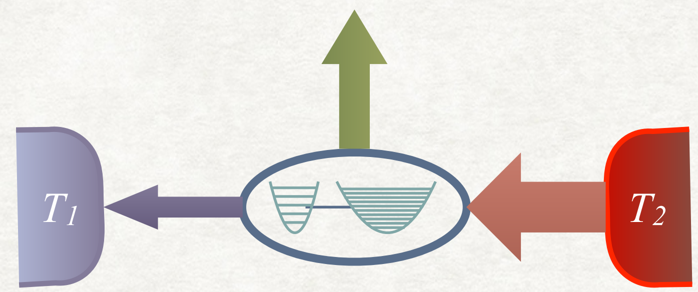
Oven
(or accelerator)



$$1 < \frac{\omega_1}{\omega_2}$$

Engine





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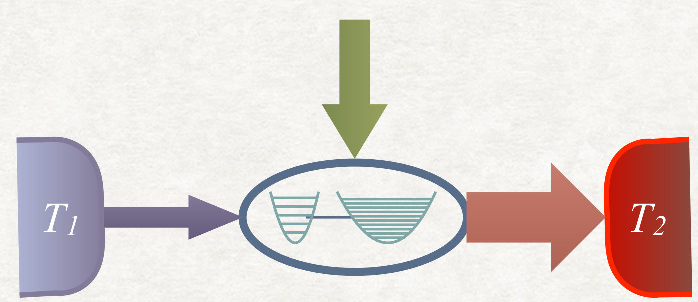
Refrigerator



$$\frac{\omega_1}{\omega_2} < \frac{T_1}{T_2}$$

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2 OSCILLATORS: EFFICIENCY AND PERFORMANCE

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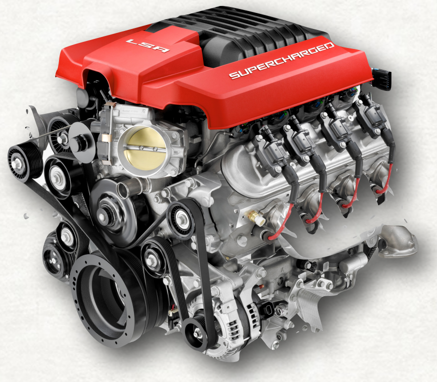

$$\frac{T_1}{T_2} < \frac{\omega_1}{\omega_2} < 1 \qquad \eta = \frac{|\dot{W}_{\text{ext}}|}{\dot{Q}_2} = 1 - \frac{\omega_1}{\omega_2}$$

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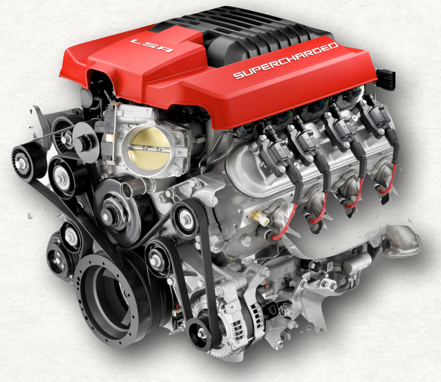

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Refrigerator

$$\frac{\omega_1}{\omega_2} < \frac{T_1}{T_2} \qquad \text{COP} = \frac{\dot{Q}_1}{\dot{W}_{\text{ext}}} = \frac{\omega_1}{\omega_2 - \omega_1}$$

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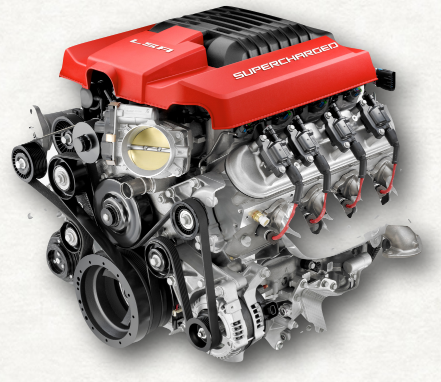

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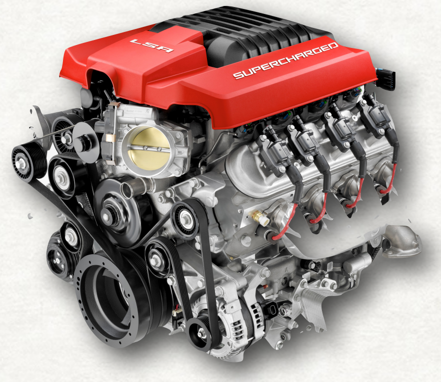

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Otto

Refrigerator

$$\frac{\omega_1}{\omega_2} < \frac{T_1}{T_2} \qquad \text{COP} = \frac{\dot{Q}_1}{\dot{W}_{\text{ext}}} = \frac{\omega_1}{\omega_2 - \omega_1}$$

Carnot's limit:
zero work/zero cooling

$$\frac{\omega_1}{\omega_2} = \frac{T_1}{T_2} \qquad \eta = 1 - \frac{T_1}{T_2}$$

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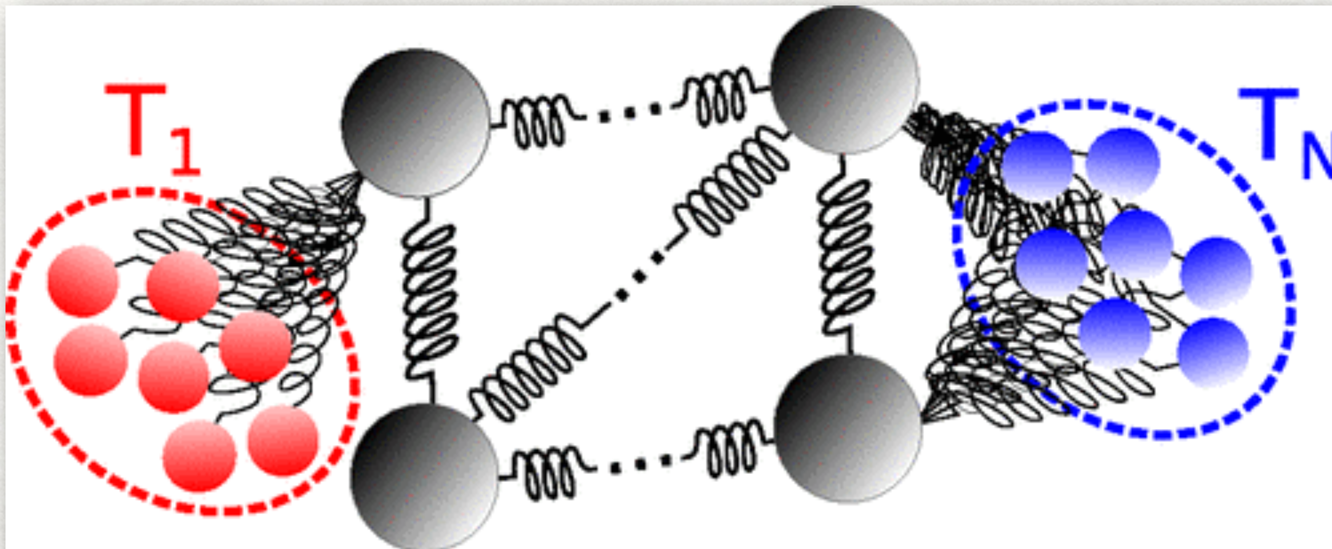
RELATION TO MARTINEZ & PAZ, PRL 2013



"It is impossible to build a quantum absorption refrigerator using [static] linear networks"

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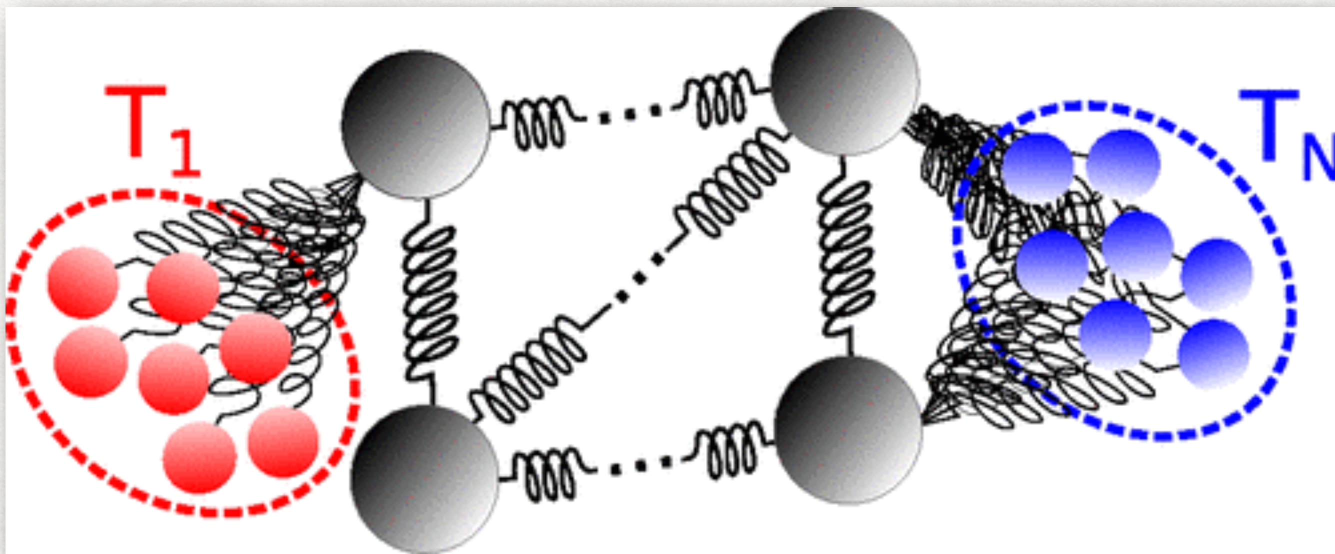

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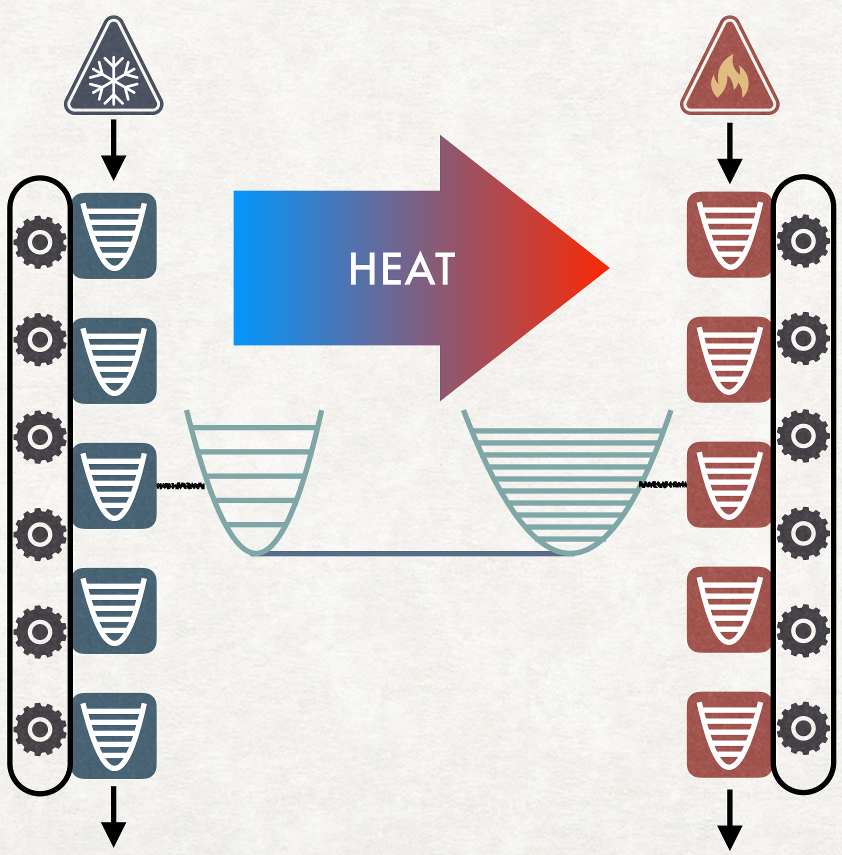

Although our network is linear, it uses time-dependent Hamiltonians so the network is essentially driven.

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FURTHER CONSIDERATIONS

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- **1st and 2nd law of thermodynamics are fulfilled**: energy conservation and positive entropy production hold.

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- Our analysis is general and works for quantum systems of **any dimension**.

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- Our analysis is general and works for quantum systems of **any dimension**.
- See our paper for a chain of many oscillators coupled by general interactions, e.g. **counter-rotating terms**.

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SEE ADAM'S POSTER

SPECIAL ISSUE

- **"Fluctuation Relations and Nonequilibrium Thermodynamics in Classical and Quantum Systems"**
- Journal: MDPI Entropy (IF 2.3)
- Topics:
  - Fluctuation relations in classical stochastic thermodynamics
  - Definitions of work, heat, and entropy and related fluctuation theorems in quantum systems
  - Quantum engines and refrigerators
  - Resource theory of quantum thermodynamics
  - Role of quantum correlations and coherence in quantum thermodynamics
- **Deadline: 31/12/2019**

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- Brendan Reid, Los Angeles
- Augusto J. Roncaglia, Buenos Aires

- Daniel Alonso, Tenerife
- J. Onam González, Tenerife

EPSRC

Engineering and Physical Sciences
Research Council

Postdoc position on Quantum Thermodynamics to start in Spring 2020!

Thank You!