Information-thermodynamics in the quantum regime

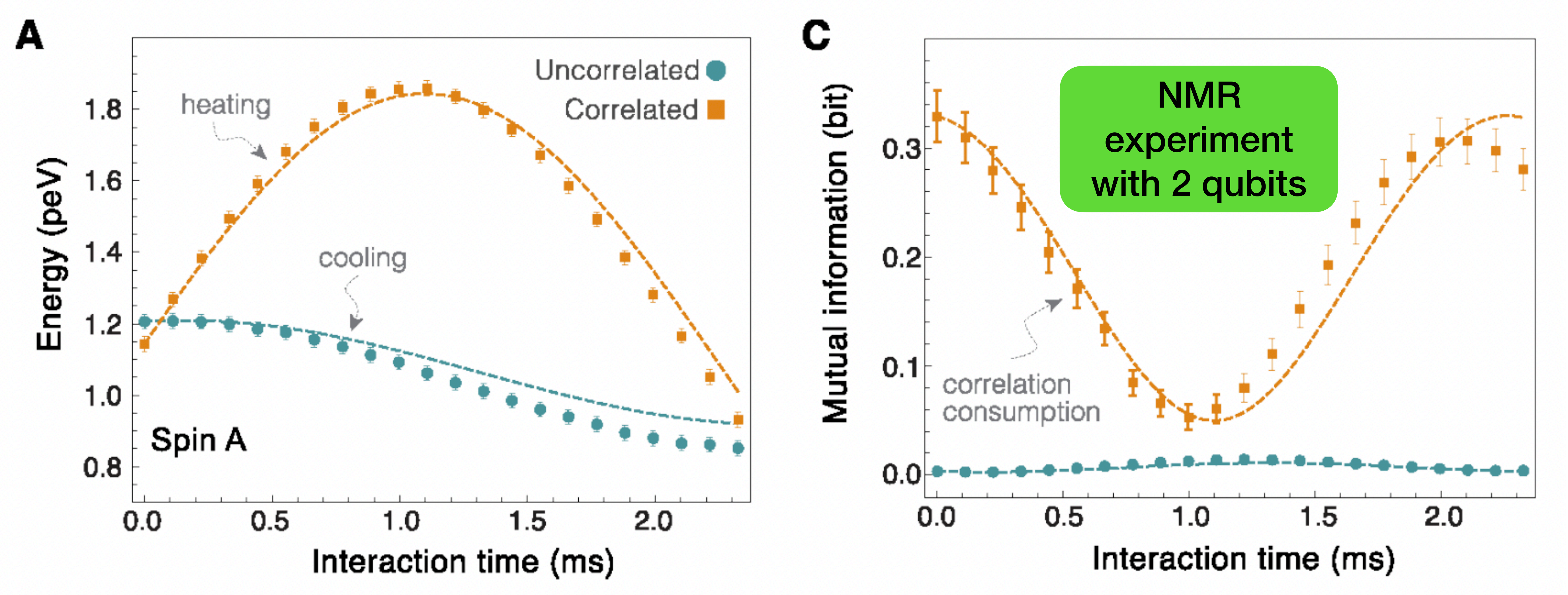
Gabriel T. Landi - Universidade de São Paulo

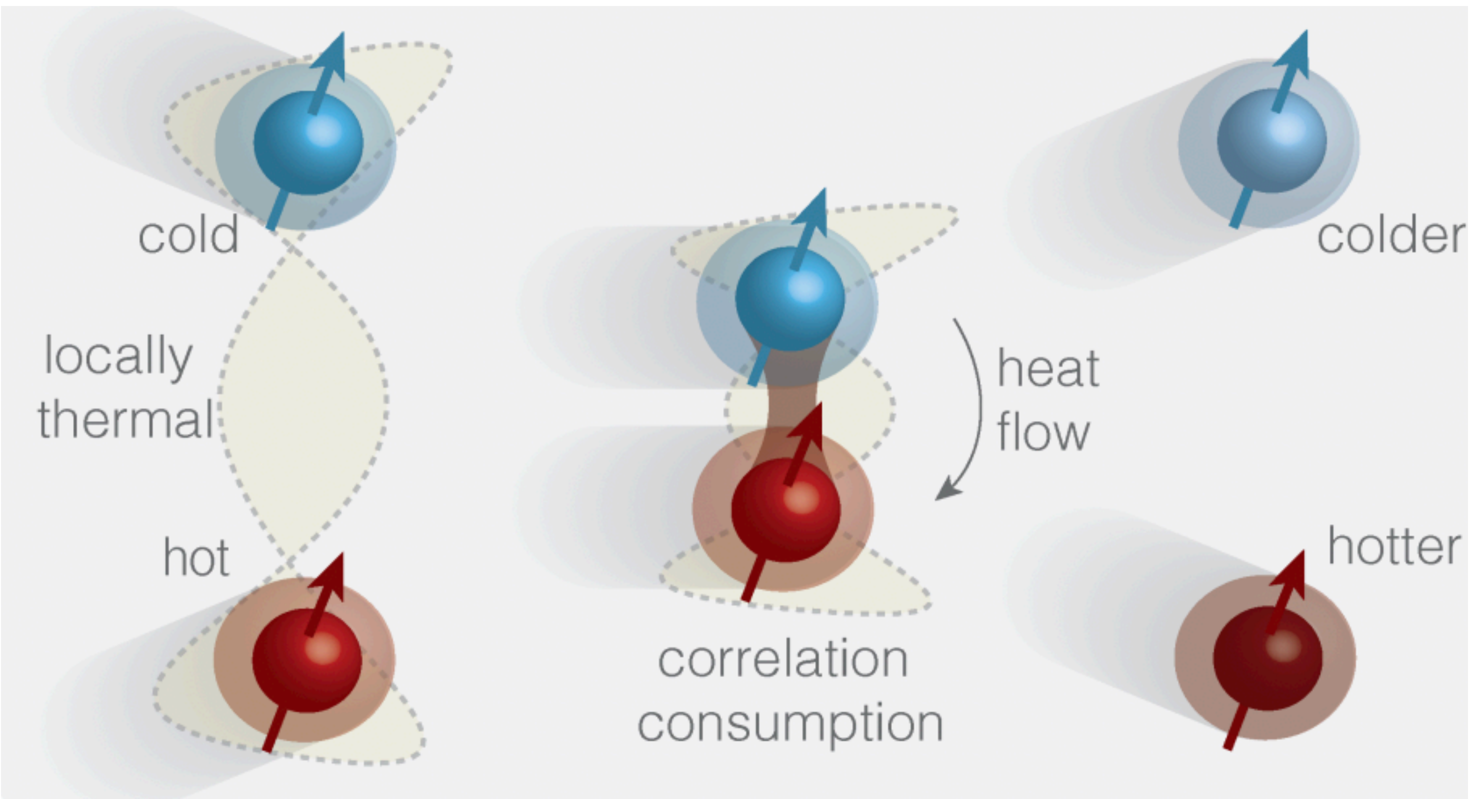
July 19th, 2022 - Universidade Federal Fluminense

www.fmt.if.usp.br/~gtlandi

Heat flows from hot to cold

- To break that, we must pay a **price**: fridges consumes electricity.
  - *"Heat can never pass from a colder to a warmer body without some other change, connected therewith, occurring at the same time."* (Clausius' statement of the 2nd law)
- In the quantum domain, **information is also a resource.**





Kaonan Micadei, John P. S. Peterson, Alexandre M. Souza, Roberto S. Sarthour, Ivan S. Oliveira, Gabriel T. Landi, Tiago B. Batalhão, Roberto M. Serra, Eric Lutz, "**Reversing the direction of heat flow using quantum correlations**", *Nature Communications*, **10**, 2456 (2019)

Partovi, M. H., Phys. Rev. E, 77, 021110 (2008)
Jennings, D. & Rudolph, T., Phys. Rev. E, 81, 061130 (2010)

💡 How to incorporate information in thermodynamics ❓

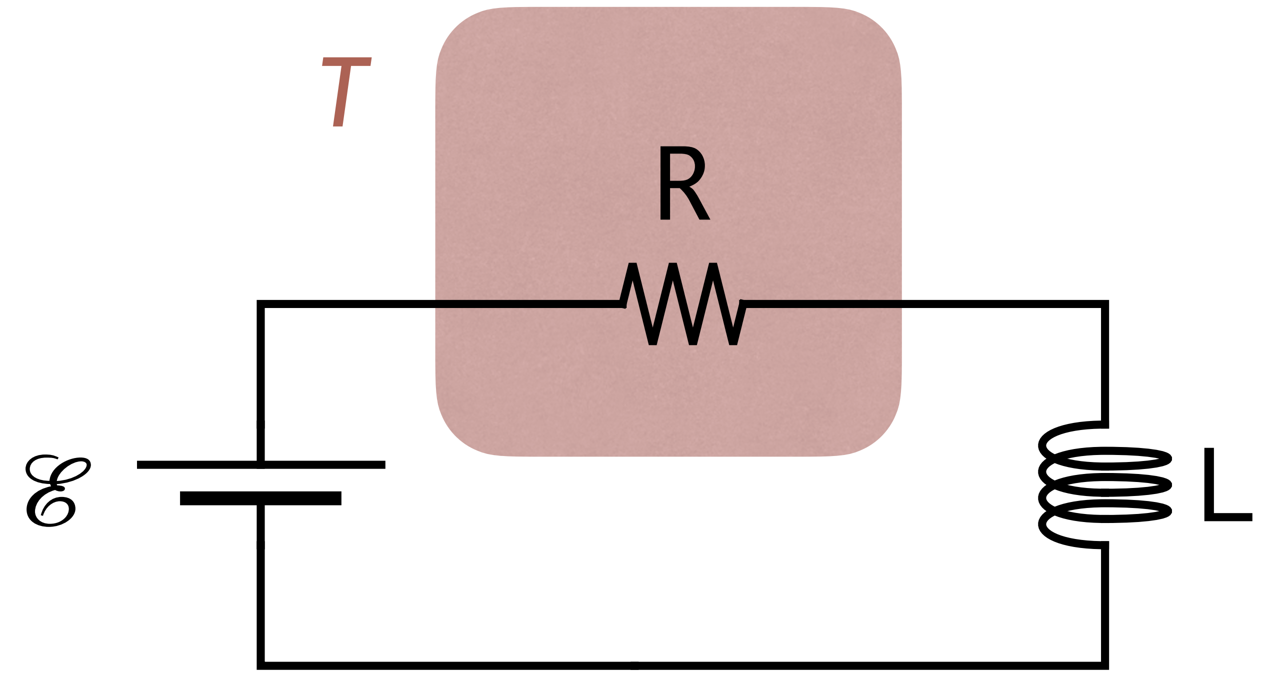
2nd law of thermodynamics

- ***E****very physical process is accompanied by an irreversible production of entropy*.
  - Entropy does not satisfy a conservation law.
- But the form of Σ depends on the problem in question.
- Ex: heat exchange ($\beta = 1/k_B T$)

$$\Sigma = Q\left(\beta_A - \beta_B\right) \geqslant 0$$

➡️ $T_A > T_B \quad \rightarrow \quad Q < 0$
(hot system looses energy; heat flows form hot to cold).

ENTROPY PRODUCTION $\Sigma \geqslant 0$

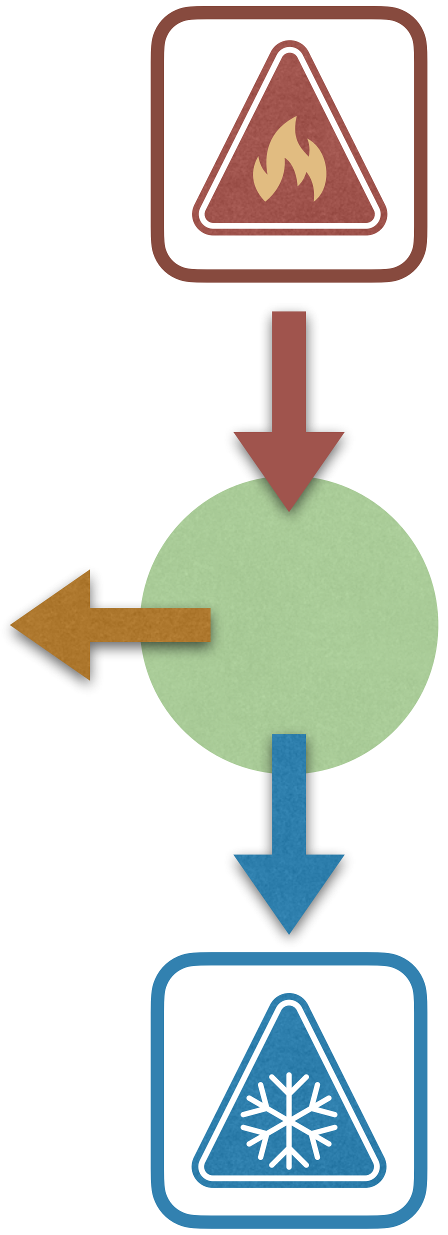


$$\dot{\Sigma} = \frac{\mathscr{E}^2}{RT}$$

As long as there is juice in the battery, there is entropy being produced.

Gabriel T. Landi and Mauro Paternostro, "**Irreversible entropy production, from quantum to classical**", *Review of Modern Physics*, **93**, 035008 (2021)

Why entropy production matters



- **Cyclic heat engine**:

  1st law: $Q_h + Q_c = W_{\text{ext}}.$

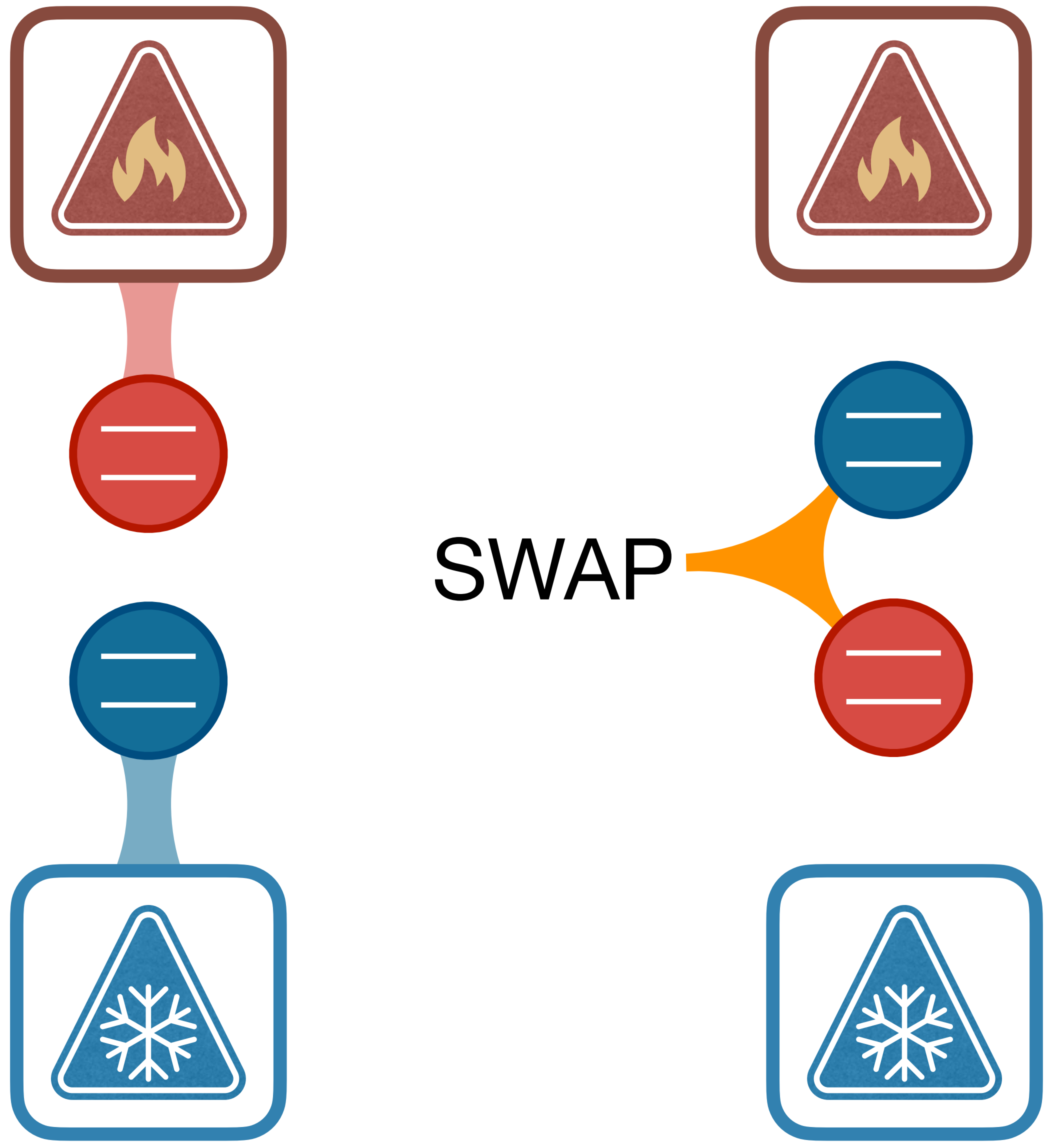
  2nd law: $\Sigma = \beta_h Q_h + \beta_c Q_c \quad \Longrightarrow \quad \eta = \dfrac{W}{Q_h} = \eta_c - \dfrac{T_c}{Q_h}\Sigma$

  Efficiency is reduced from $\eta_c = 1 - T_c/T_h$ by a factor proportional to the entropy production.

- 2-stroke quantum engines:

  $$\Sigma = \frac{1}{\epsilon_c}(\beta_h \epsilon_h - \beta_c \epsilon_c) Q_h \geqslant 0$$

  SWAP unitaries do work.



Otavio A. D. Molitor and Gabriel T. Landi Phys. Rev. A **102**, 042217

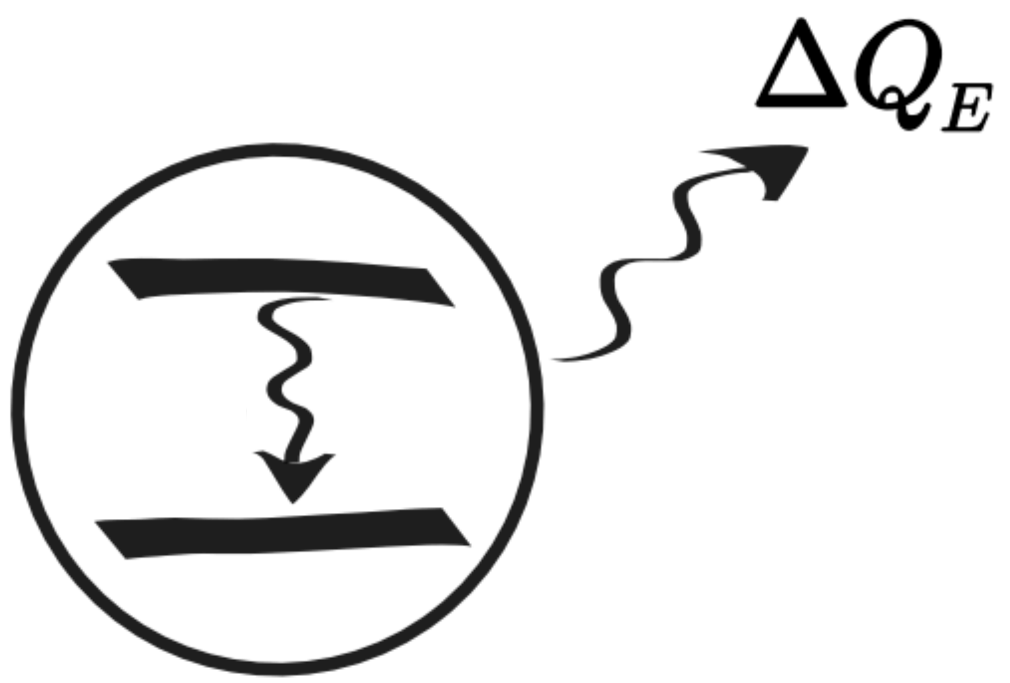
- **Landauer's erasure:**

$$\Sigma = \Delta S_{\text{bit}} + \beta \Delta Q_{\text{E}} \geqslant 0$$

Minimum cost to erase information of a bit: $\Delta Q_{\text{E}} \geqslant k_B T \ln 2$.

- What about $T \simeq 0$? (very relevant for quantum computation).
  - Spontaneous emission is an erasure task.
- We proved that even at $T = 0$ there is still a finite cost.
  - Ex: when eraser = waveguide

$$\Delta Q_{\text{E}} \geqslant k_B T \ln 2 + \frac{3\hbar c}{\pi L} \ln^2(2)$$

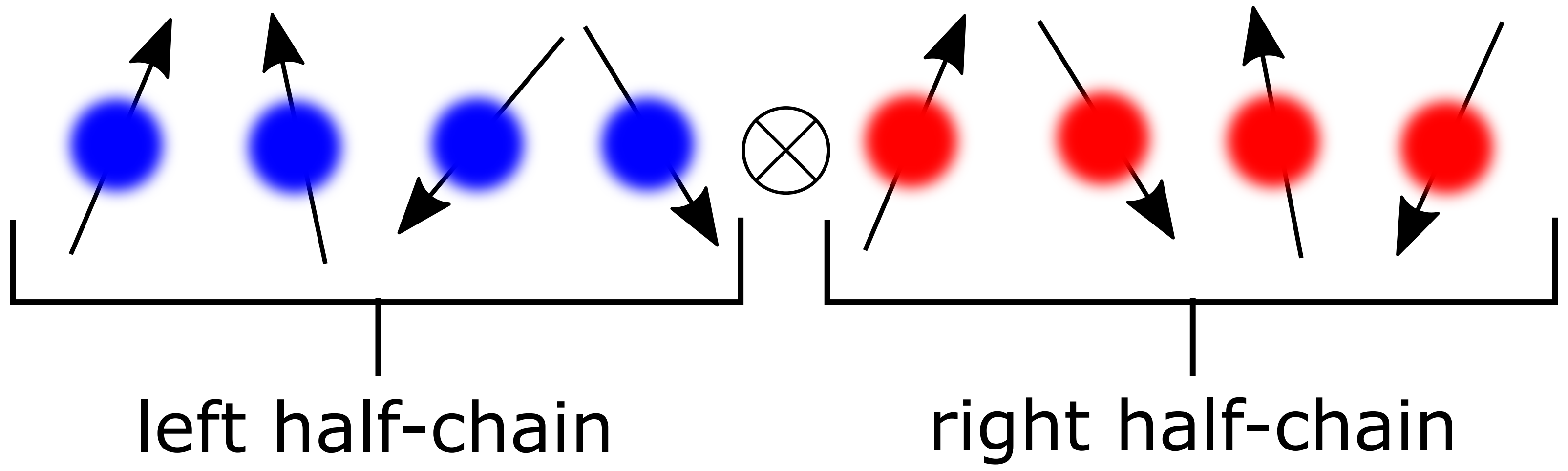


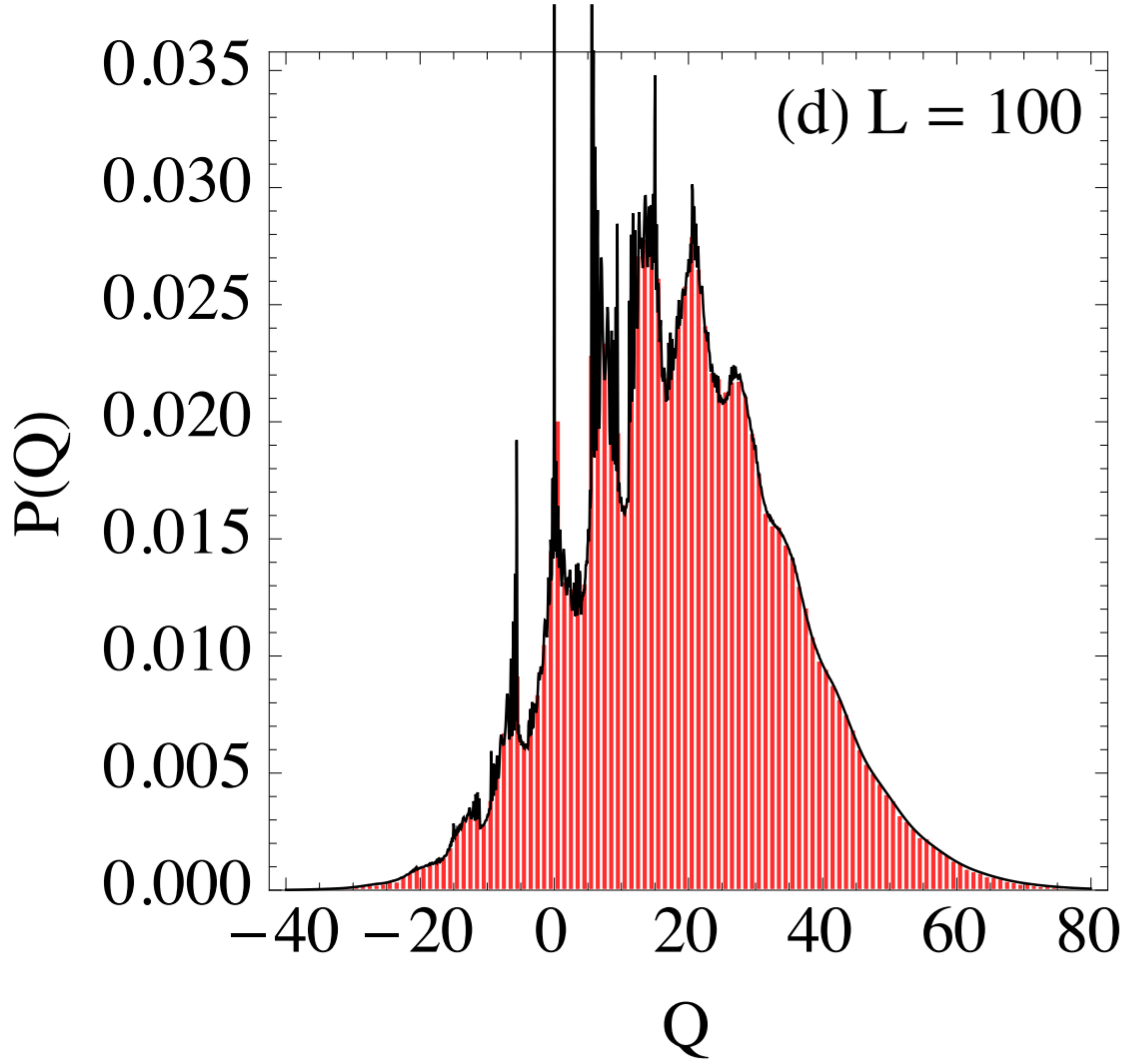
R. Landauer, IBM Journal of Research and Development **5**, 183 (1961).

André M. Timpanaro, Jader P. Santos, and Gabriel T. Landi, Phys. Rev. Lett. **124**, 240601 (2020)

Fluctuations are significant in the micro-world

- Macro-world: heat flows from hot → cold.
- Micro-world: heat ***usually*** flows from hot → cold.





Heat Exchange Fluctuation Theorem

$$P(-Q) = e^{-(\beta_A-\beta_B)Q}P(Q)$$

Implies 2nd law:

$$\langle Q\rangle\left(\beta_A-\beta_B\right) \geqslant 0$$

Gabriel T. Landi and Dragi Karevski Phys. Rev. E **93**, 032122

Jarzynski and Wójcik, Phys. Rev. Lett. 92, 230602 (2004)
G. E. Crooks, Journal of Statistical Physics, **90**, 1481–1487 (1998)

- **Thermodynamic uncertainty relations:**

  Fluctuation-dissipation trade-off (valid arbitrar

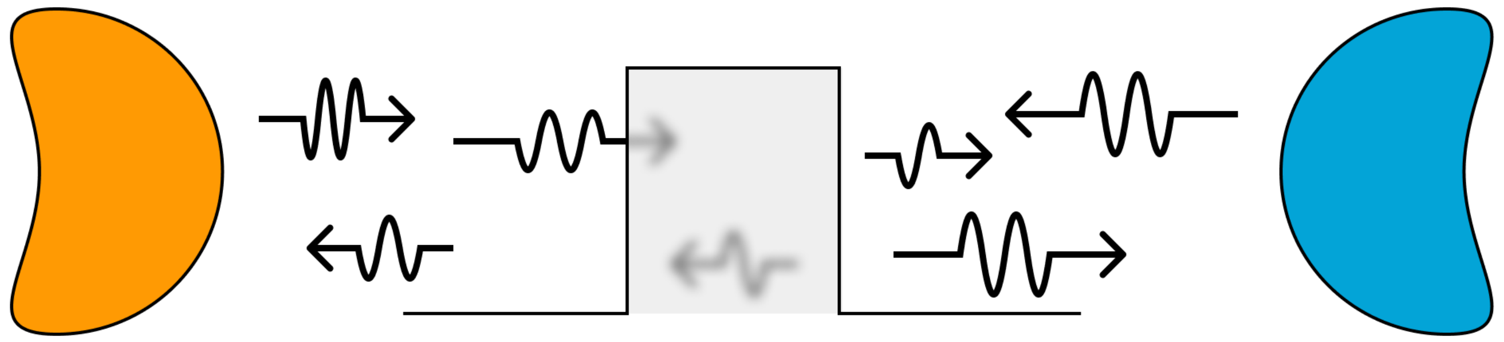
- Counter-intuitive: to reduce dissipation, one ha
  - Irreversible is good (when fluctuations are b
- TURs only hold for classical Markov processes.
  - Can be violated in quantum coherent transport.
  - e.g. scattering through quantum dots
    (quantum thermoelectricity)

Major open questions in the field:

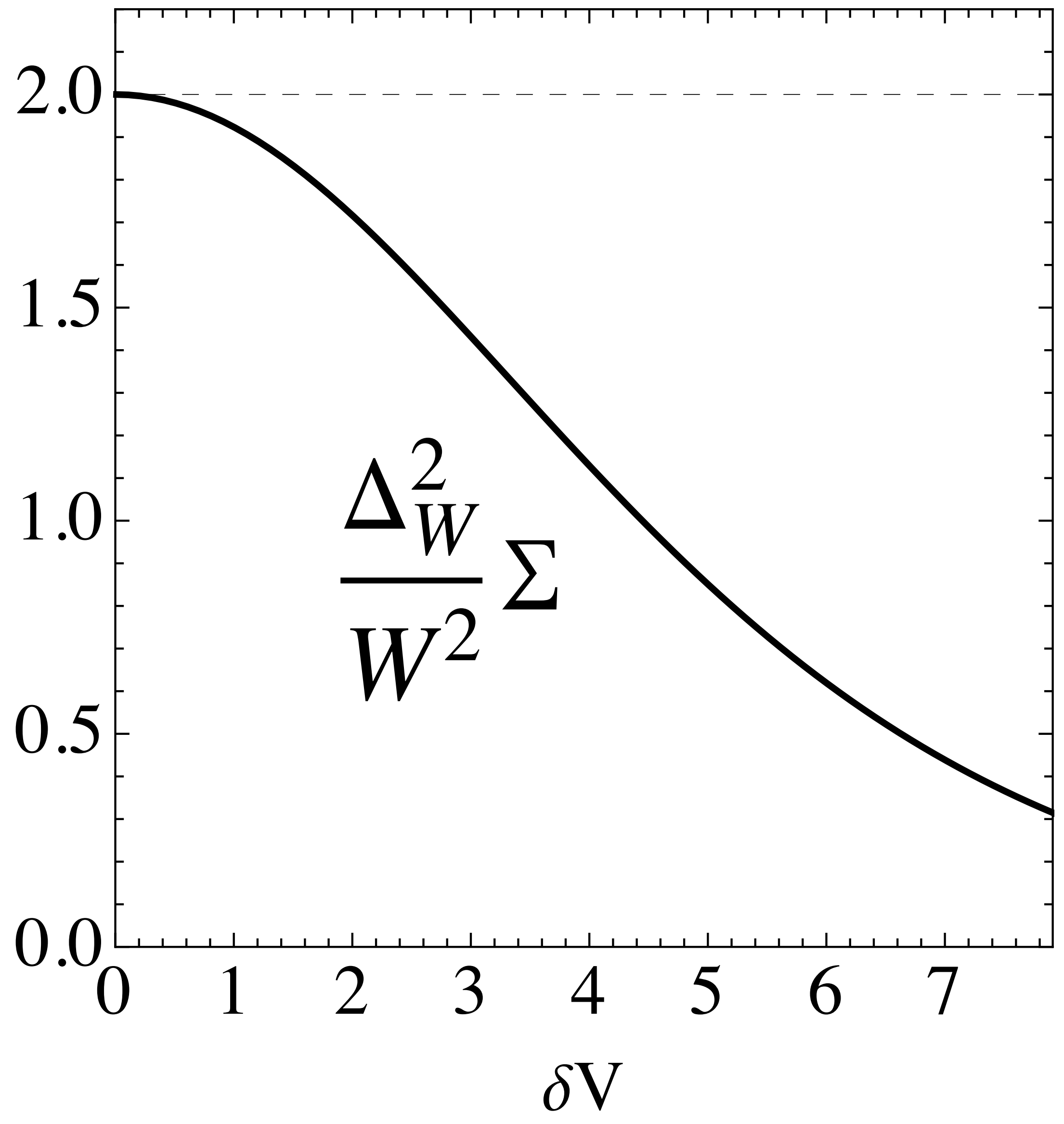
- Why quantum coherence?

- What limits the precision in the quantum world?

- Is there a trade-off?



A. C. Barato, U. Seifert, Physical Review Letters, **114**, 158101 (2015)
P. Pietzonka and U. Seifert, Phys. Rev. Lett., **120**, 190602 (2017)



Andre M. Timpanaro, Giacomo Guarnieri, and Gabriel T. Landi, arXiv 2106.10205

⚛️ Information theoretic formulation of entropy production

Gabriel T. Landi and Mauro Paternostro, "**Irreversible entropy production, from quantum to classical**", *Review of Modern Physics*, **93**, 035008 (2021)

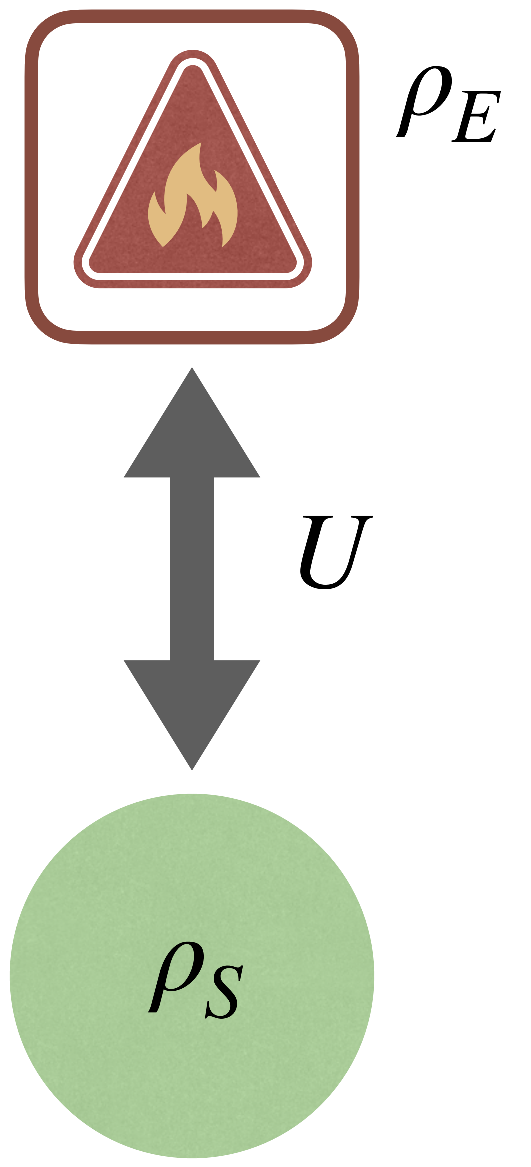
Information theoretic formulation of entropy production

- **Operational notion of irreversibility:** *a process is irreversible because some information becomes inaccessible in practice.*

- Entropy production for a system in contact with a bath:

$$\Sigma = I'(S:E) + D(\rho'_E || \rho_E)$$

$$\rho'_{SE} = U(\rho_S \otimes \rho_E)U^\dagger$$



Mutual Information:

$$I'(S:E) = S(\rho'_S) + S(\rho'_E) - S(\rho'_{SE})$$

Quantifies all correlations (classical + quantum)

Relative entropy

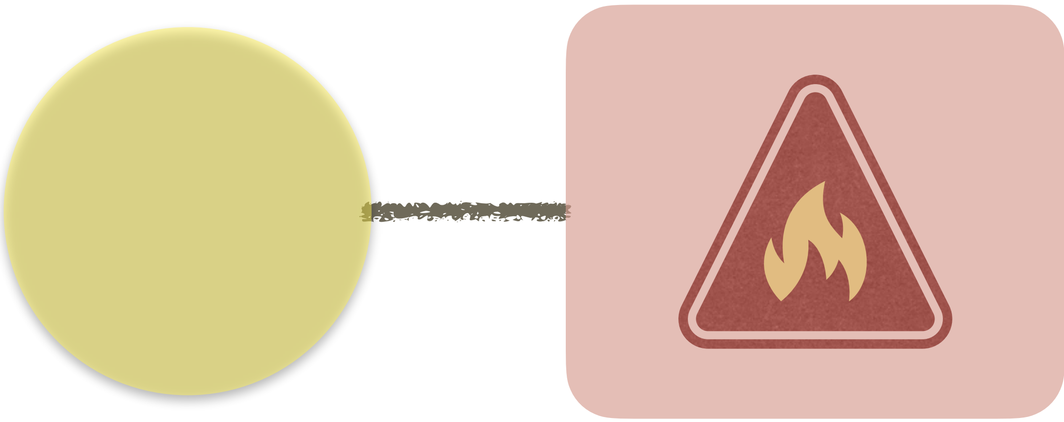
$$D(\rho'_E || \rho_E) = \mathrm{tr}\left(\rho'_E \ln \rho'_E - \rho'_E \ln \rho_E\right)$$

"Distance" between density matrices

```
Describes an enormous
variety of processes!
(maybe a complicated U)
```

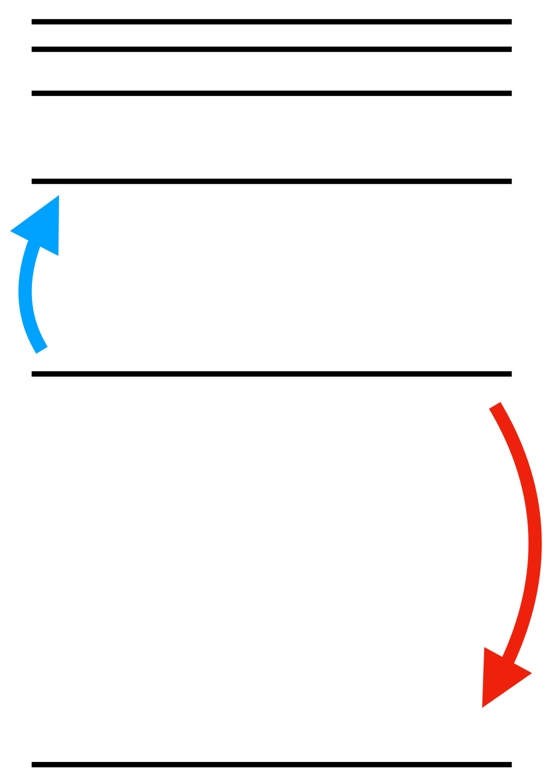
M. Esposito, K. Lindenberg, C. Van den Broeck, "**Entropy production as correlation between system and reservoir**". *New Journal of Physics*, **12**, 013013 (2010).

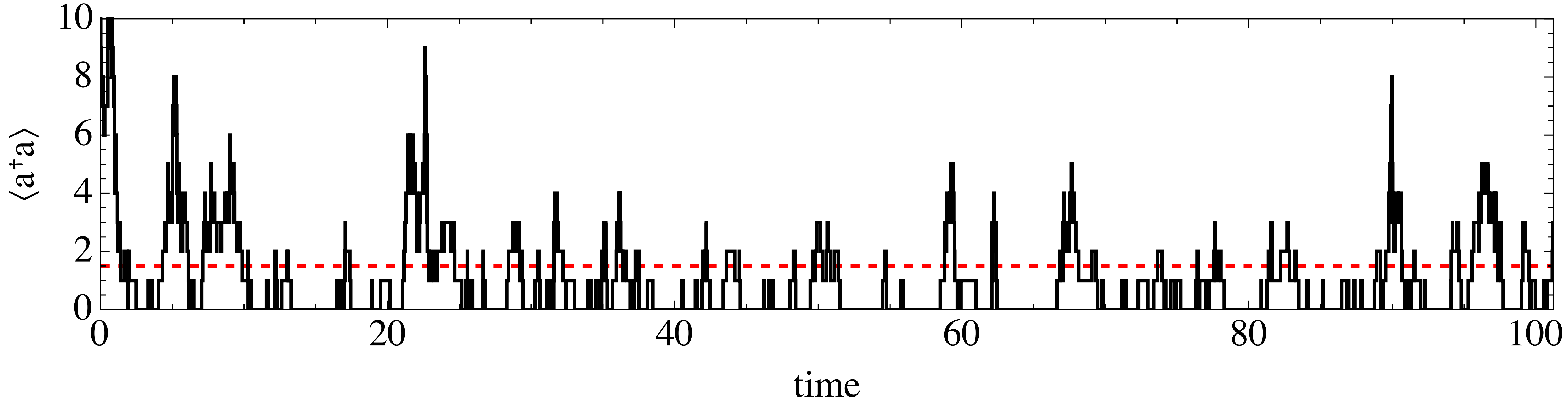
Relaxation towards equilibrium



- Imagine an atomic system relaxing towards equilibrium.
  - Population in energy eigenstates fluctuate until they reach thermal equilibrium.
- In addition: destroy any superpositions (**decoherence**).
- Entropy production rate can be split as

$$\Sigma = \Sigma_{\text{pop}} + \Sigma_{\text{coh}}$$

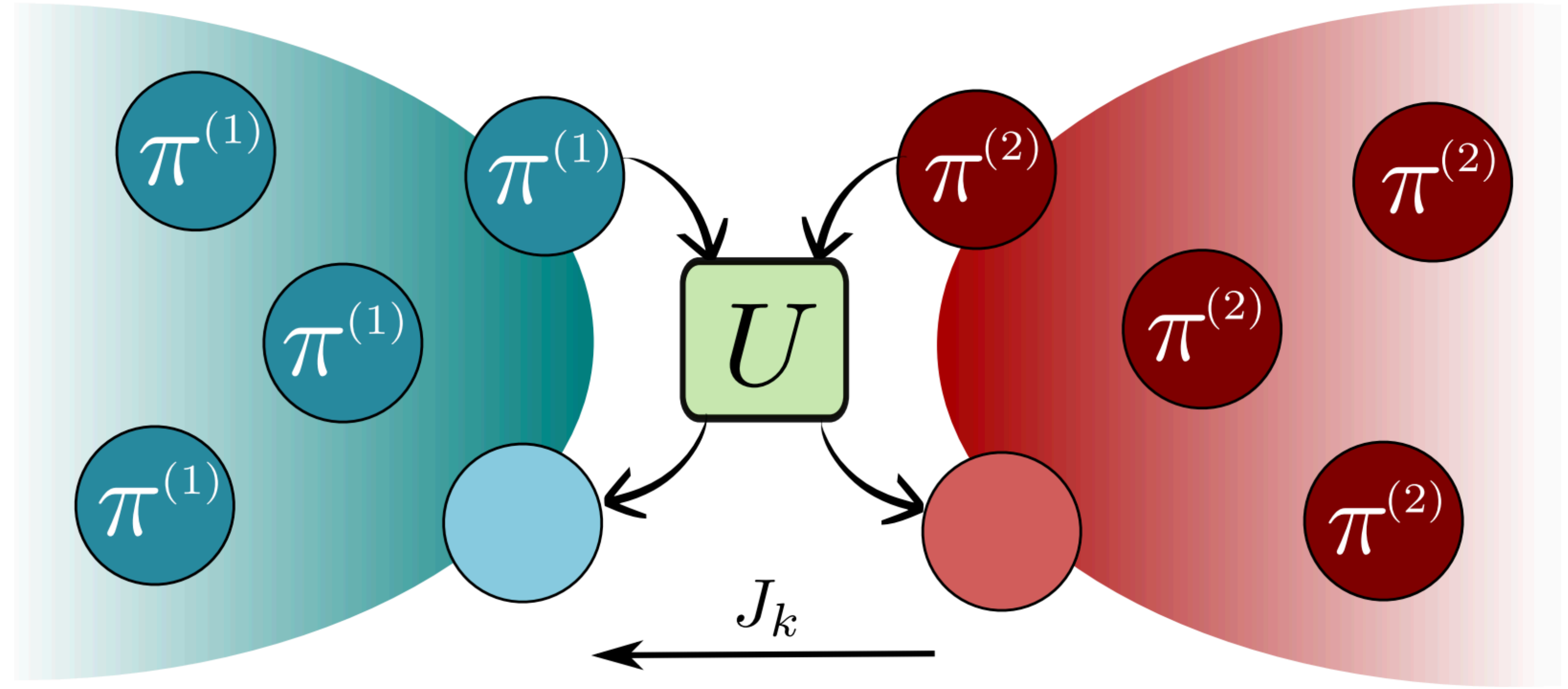




Additional entropy production due to coherence:
Dissipation of information, without dissipation of energy.

J. P. Santos, L. Céleri, GTL, M. Paternostro, npj Quantum Information **5**, 23 (2019)

Transport of non-Abelian charges



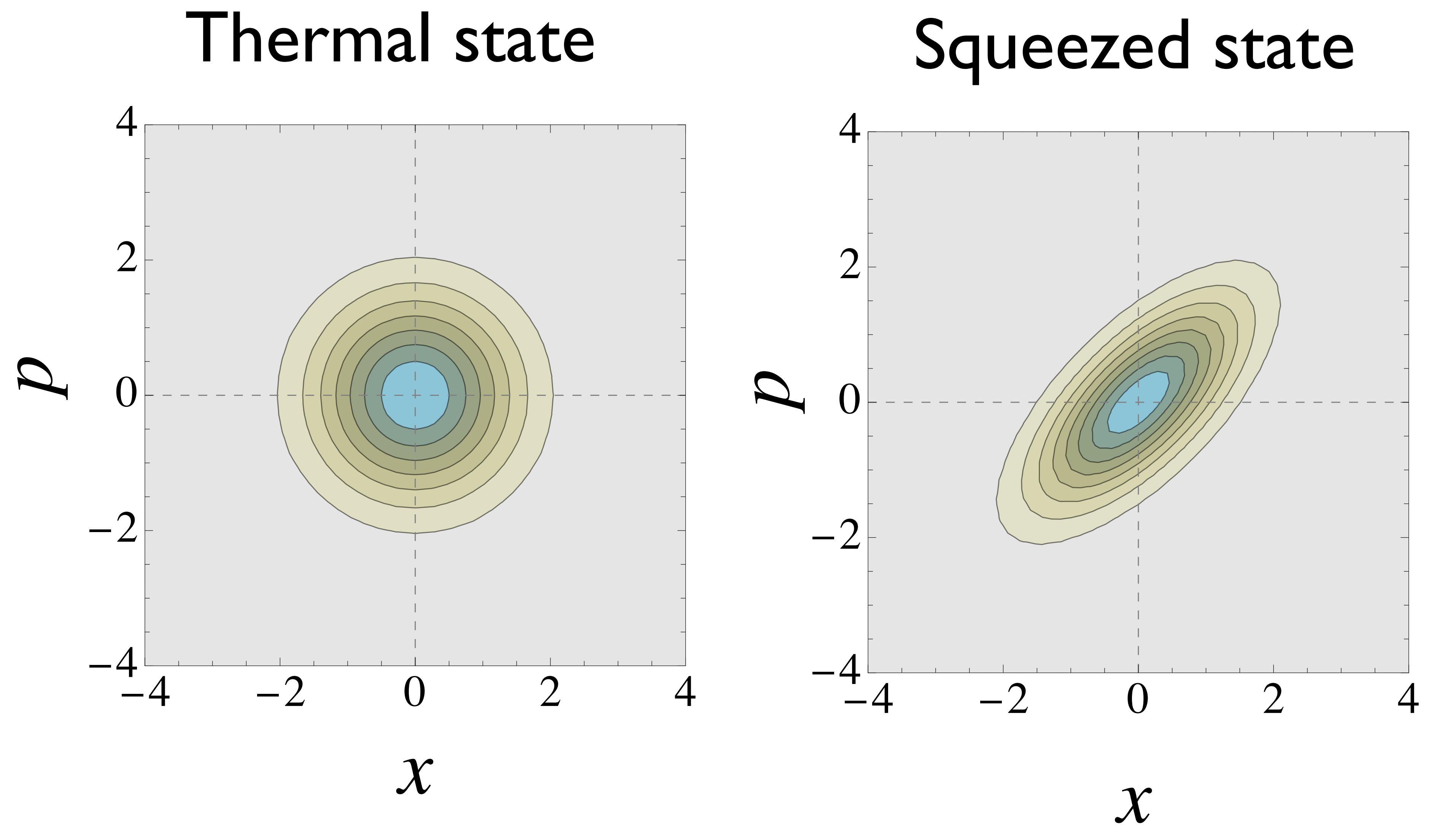
- Classical transport: **energy and particles.**
- Quantum domain: excitations may not commute.
- Single-mode radiation: energy & squeezing

$$H = \frac{\omega}{2}(p^2 + x^2), \qquad A = \frac{\omega}{2}(p^2 - x^2)$$

Entropy production is *reduced* due to non-commutativity

$$\Sigma = \Sigma_{\text{comm}} - I(\rho, D)$$

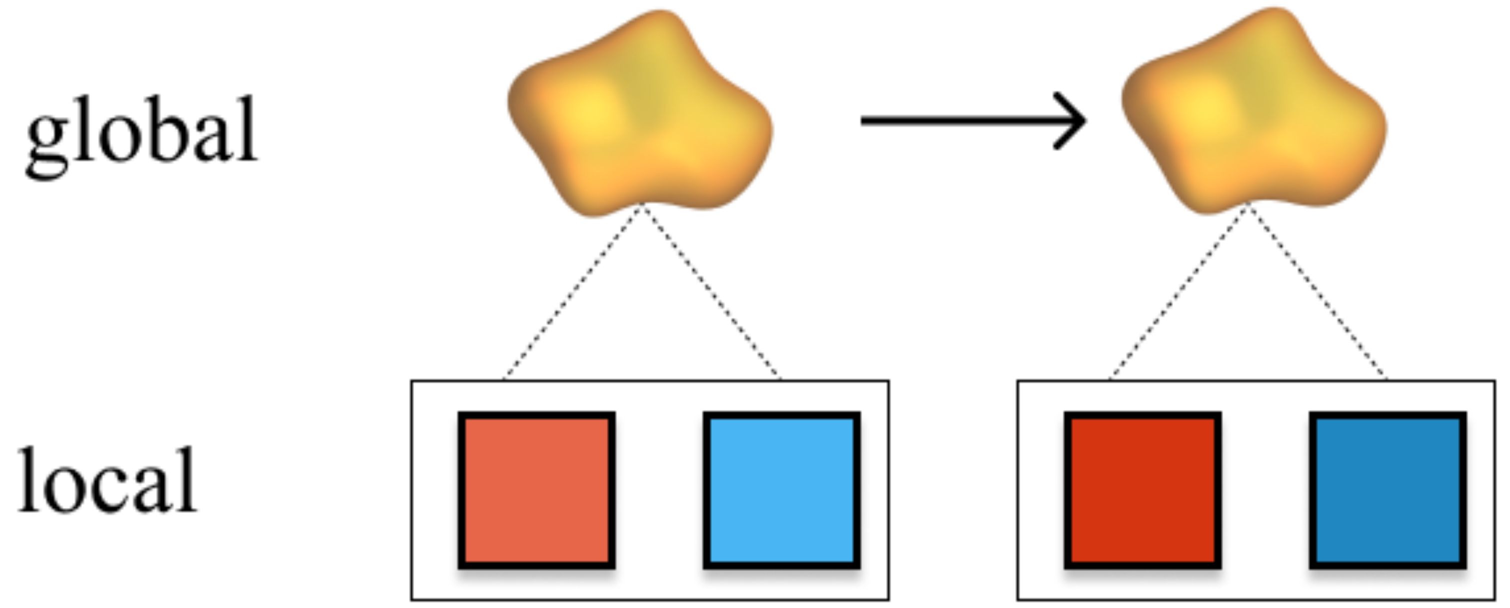
$$D = \sum_k \delta\lambda_k \Delta Q_k$$

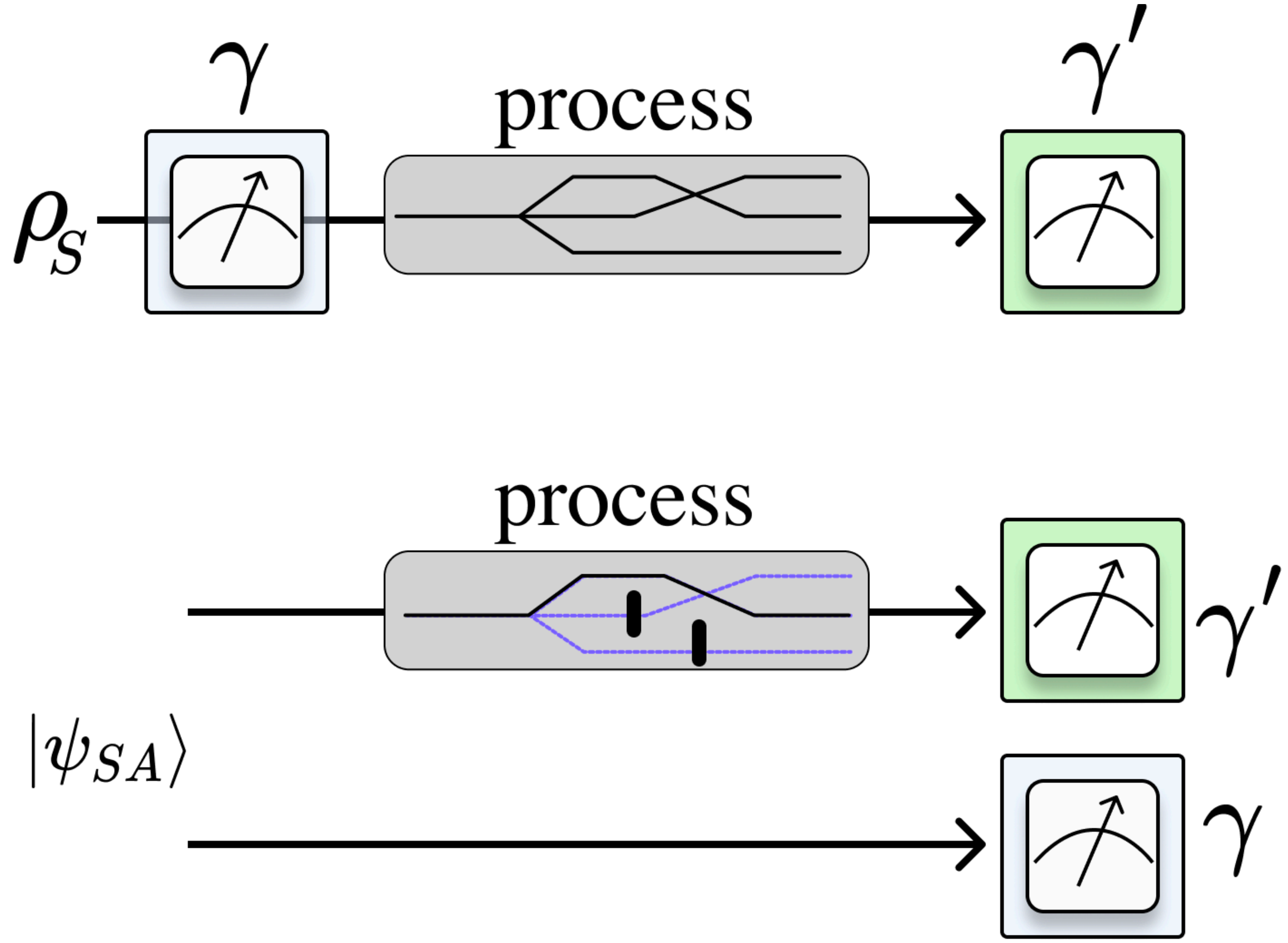


Gonzalo Manzano, Juan M. R. Parrondo, Gabriel T. Landi, *PRX Quantum* **3**, 010304 (2020)

Two-point measurements destroy quantum features

- Measurements in quantum mechanics are invasive.
  - Destroy initial quantum coherences.
- Fundamental limitation of Quantum + Thermodynamics.
- Can be overcome using an ***entangled ancilla***, which is only measured at the end.
- Or if one has access to ***identical copies*** of a quantum system.





Gabriel H. Aguilar, Thaís L. Silva, Thiago E. Guimarães, Rodrigo S. Piera, Lucas C. Céleri, Gabriel T. Landi, arXiv:2108.03289 (2021)

Kaonan Micadei, Gabriel T. Landi, Eric Lutz, arXiv:2103.14570

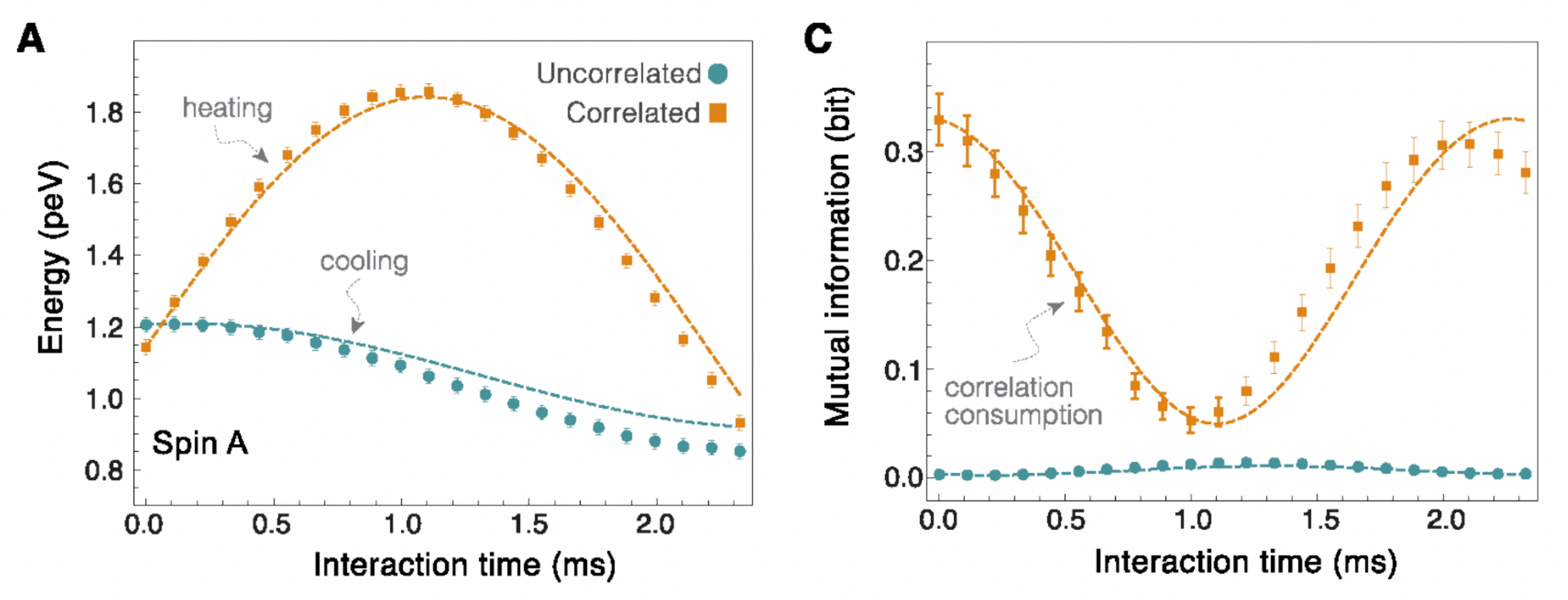
Fully quantum fluctuation theorems

- We put forth a theory encompassing Heat exchange in the presence of general quantum correlations.

$$\frac{P(\Gamma)}{P(\Gamma^*)} = \exp\left\{(\beta_A - \beta_B)Q - \Delta I - S_A - S_B - \gamma\right\}$$

Consequence:

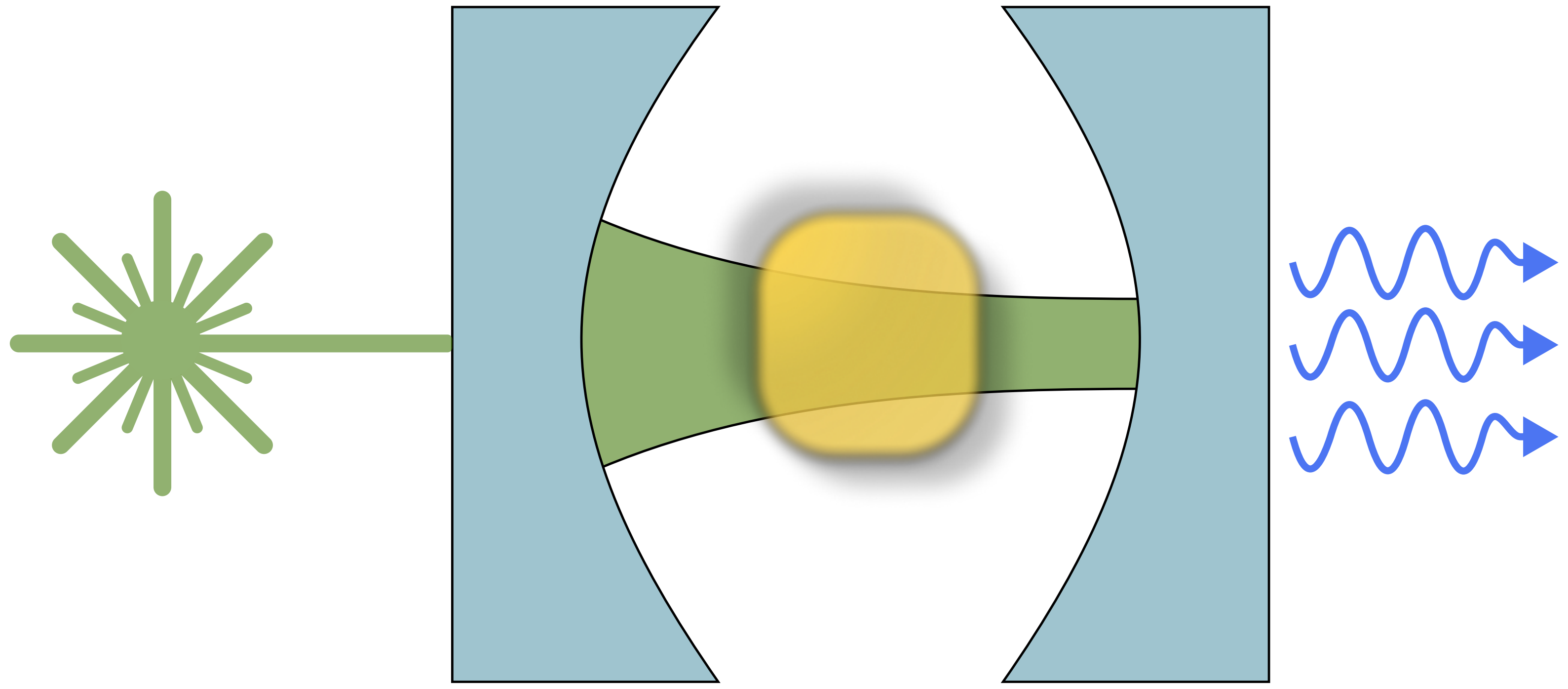
$$(\beta_A - \beta_B)\langle Q\rangle \geqslant \langle \Delta I\rangle$$



K. Micadei, G. T. Landi, E. Lutz, "**Quantum fluctuation theorems beyond two-point measurements**", *Phys. Rev. Lett*. **124**, 090602 (2020)

Kaonan Micadei, John P. S. Peterson, Alexandre M. Souza, Roberto S. Sarthour, Ivan S. Oliveira, Gabriel T. Landi, Roberto M. Serra, Eric Lutz, "**Experimental validation of fully quantum fluctuation theorems**", *Phys. Rev. Lett.,* **127**, 180603 (2021).

Quantum phase space



- Many quantum experiments are done using optical cavities with semi-transparent mirrors.
- Photons leaking out $\simeq$ zero temperature bath.
  - Spontaneous emission: excitations can leave, but not return.
- 2nd law is buggy @ $T = 0$: $\Sigma = Q\left(\frac{1}{T_A} - \frac{1}{T_B}\right).$
  - Does not include vacuum fluctuations (*present in every measurement*).
- We reformulated the entropy production problem in terms of quantum phase space & the *Wigner function.*

$$\Sigma = Q\left(\frac{1}{T_A^{\rm eff}} - \frac{1}{T_B^{\rm eff}}\right)$$

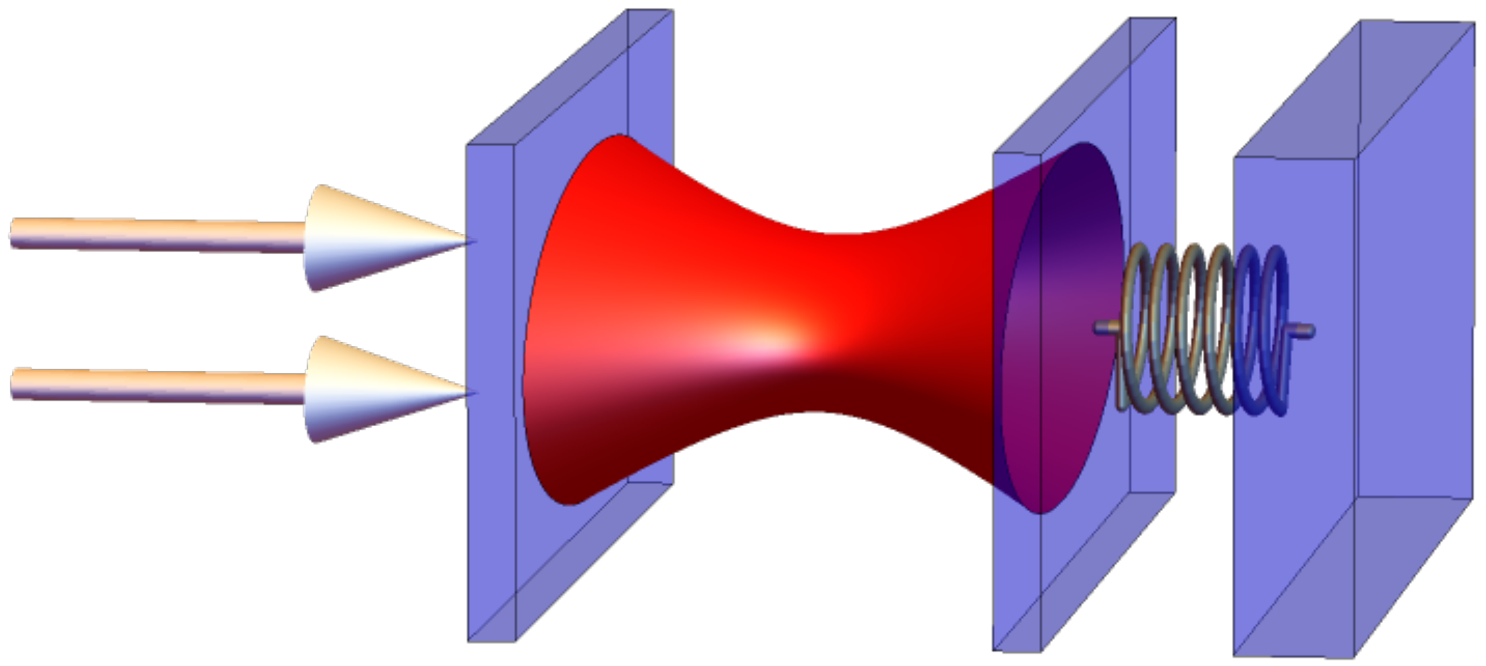
$$T^{\rm eff} = \omega(\bar{n} + 1/2), \qquad \bar{n} = \frac{1}{e^{\beta\omega} - 1}$$

High temperatures: $\omega(\bar{n} + 1/2) \simeq T.$

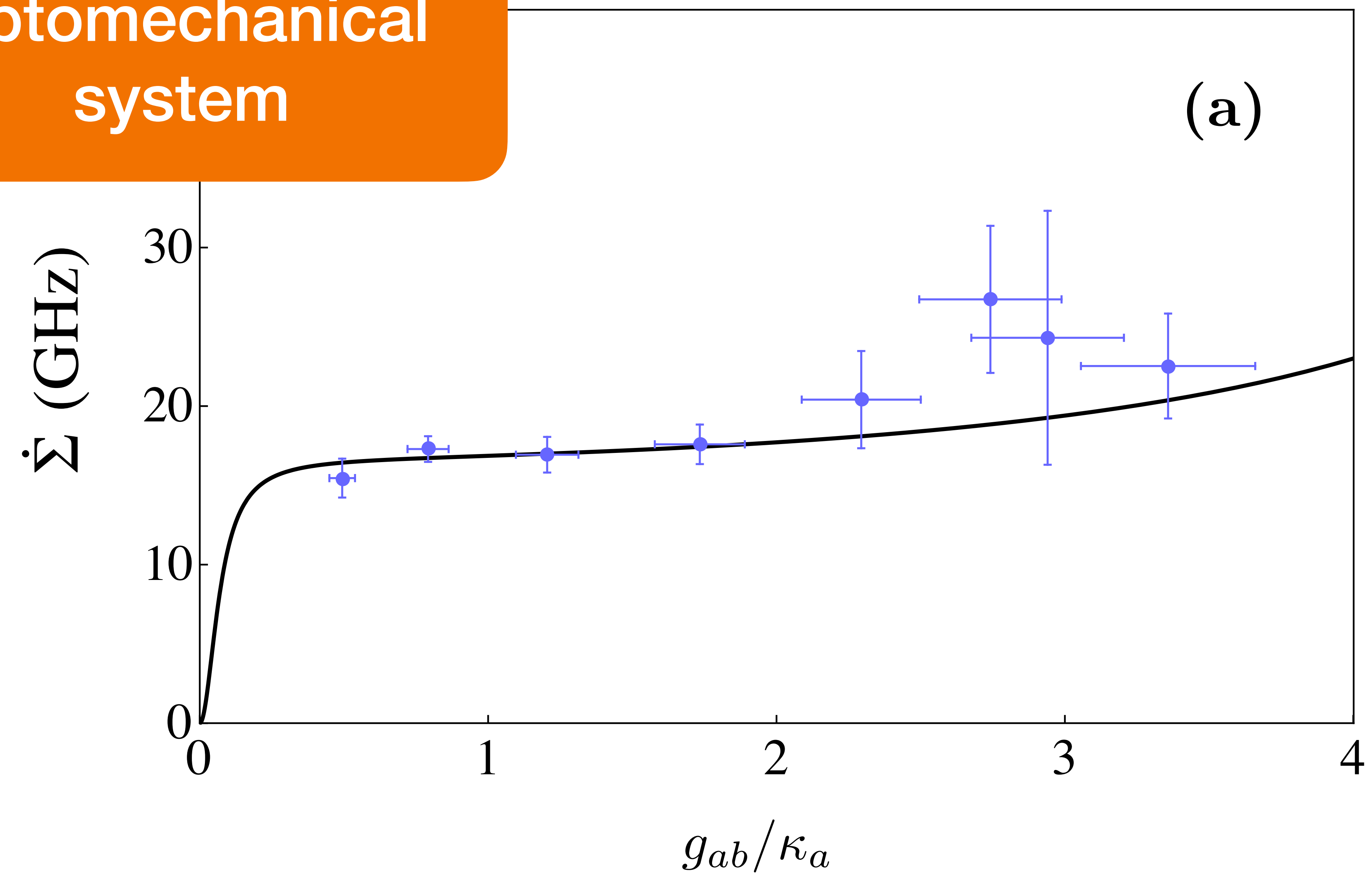
Zero temperature: $\omega(\bar{n} + 1/2) = \omega/2.$

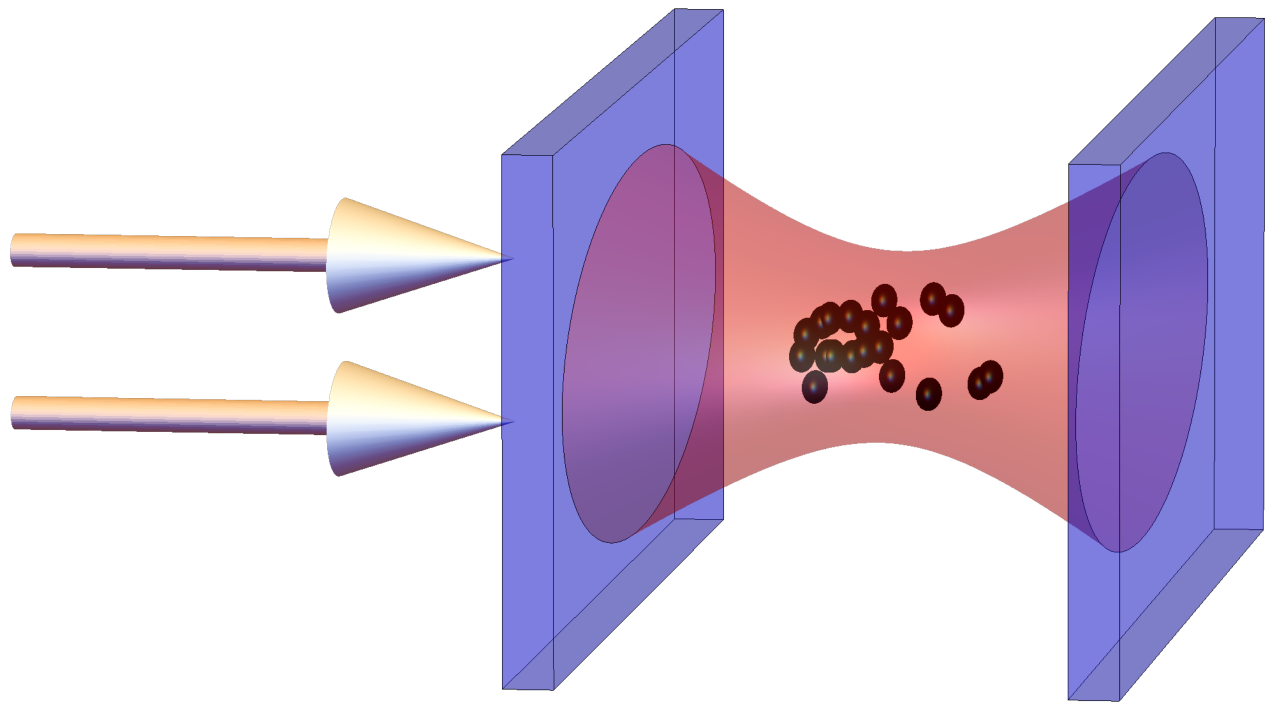
Jader P. Santos, G.T. Landi and Mauro Paternostro, Phys. Rev. Lett, **118**, 220601 (2017),

Experiments



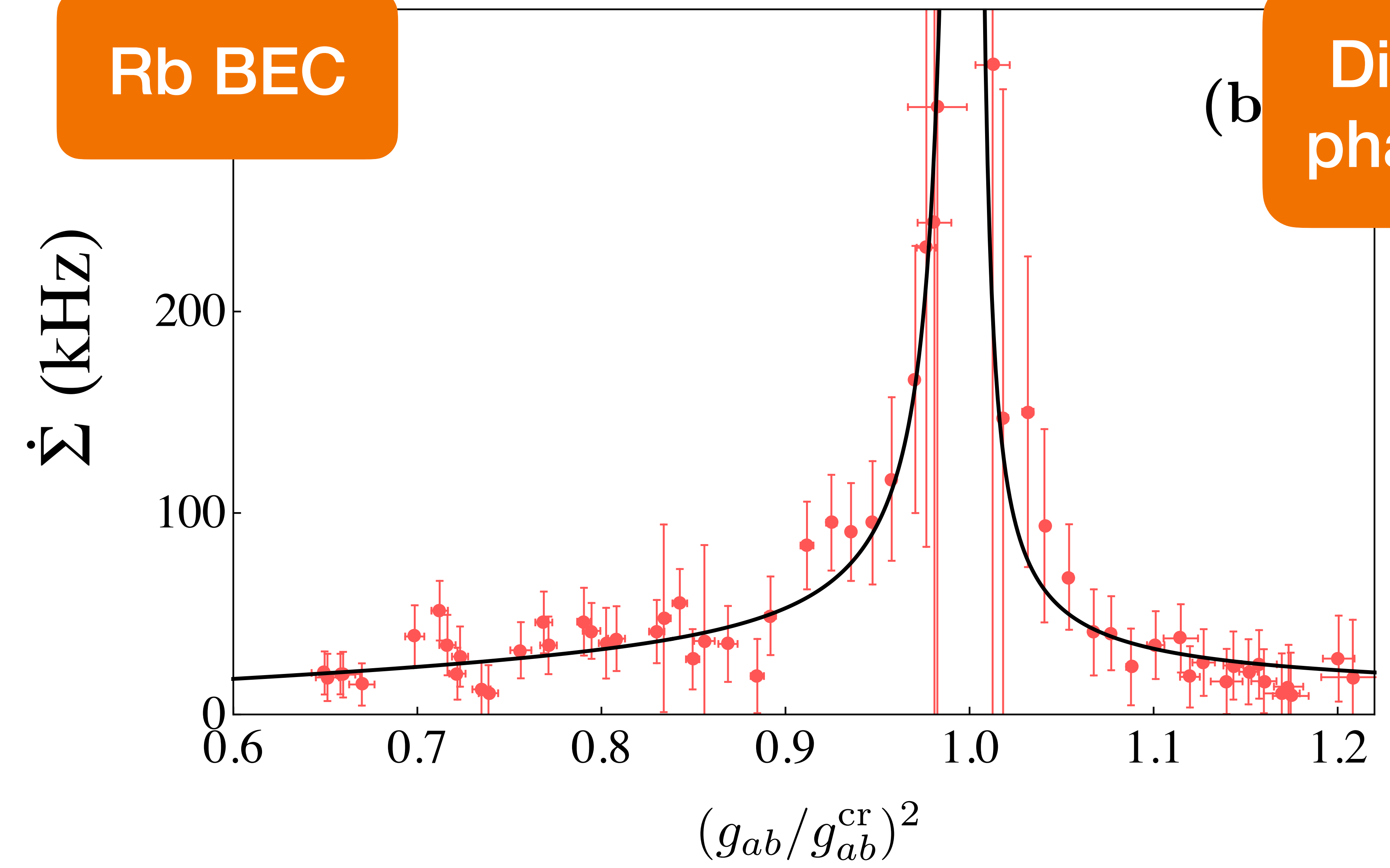
Optomechanical system





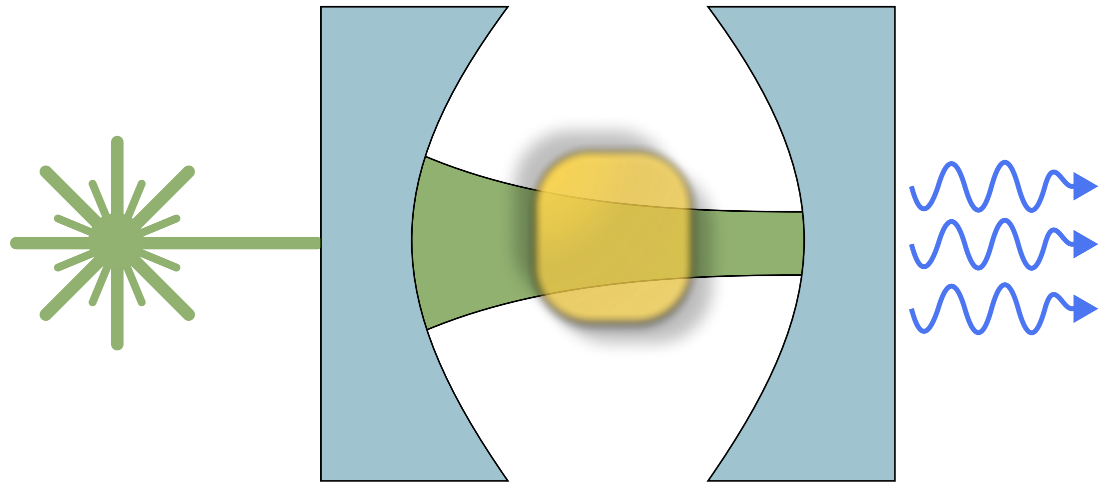
Rb BEC

Dicke quantum phase transition.

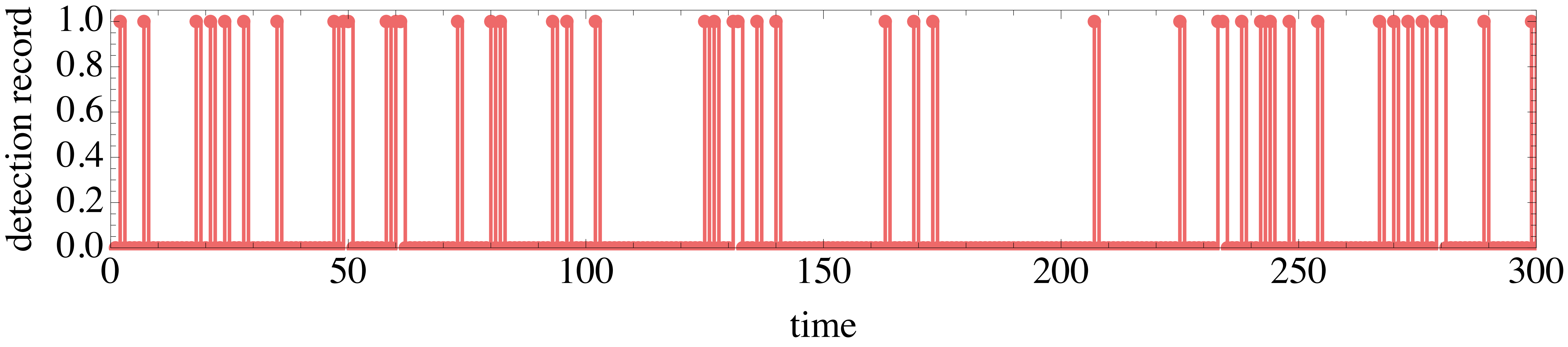


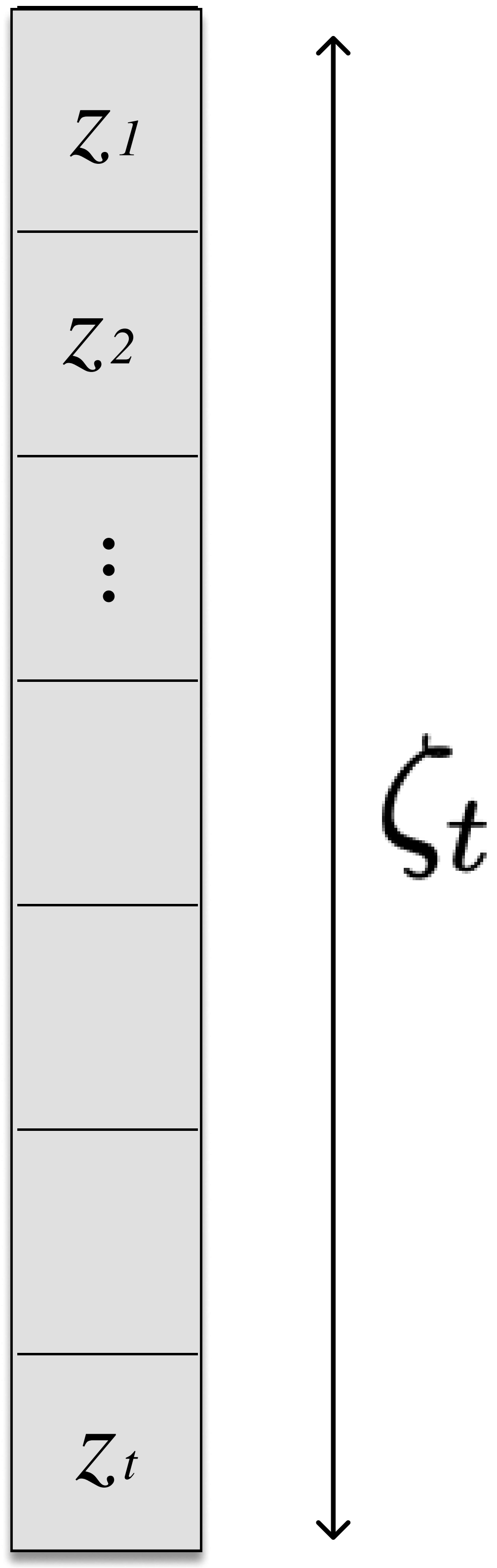
M. Brunelli, L. Fusco, R. Landig, W. Wieczorek, J. Hoelscher-Obermaier, GTL, F Semião, A. Ferraro, N. Kiesel, T. Donner, G. De Chiara, and M. Paternostro. *Phys. Rev. Lett.*, **121**, 160604 (2018)

Continuously monitored quantum systems



- Continuous monitoring of photons that leak out of the cavity.
  - Individual clicks in the detector.
- Fundamental questions: what is entropy production *given* a detection record.
  - Operation: define thermodynamics in terms of what we can actually measure.
  - Includes *information* directly in the formulation.





Holevo information

- **Unconditional:** If we do not know the individual clicks: ρ_t
- **Conditional on the detection record:** $\rho_{t|\zeta_t}$
- **Holevo information:** accumulated information we learned from the detection.

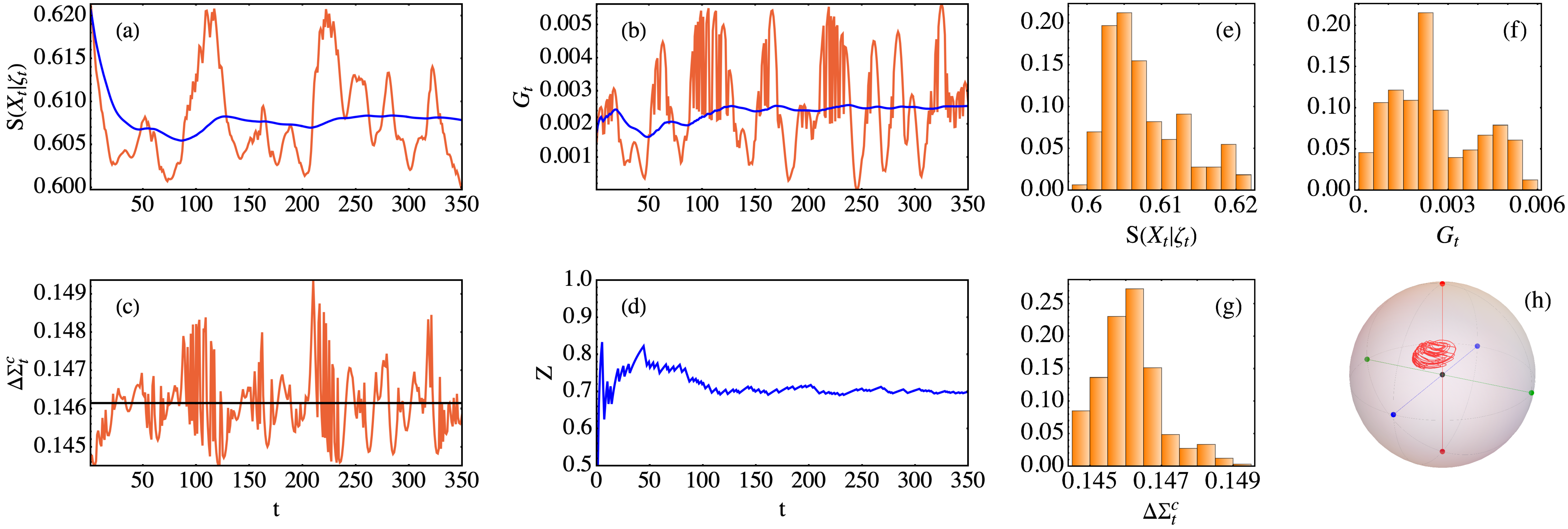
$$I(S_t : \zeta_t) = \sum_{\zeta_t} P(\zeta_t) D\left(\rho_{t|\zeta_t} || \rho_t\right)$$

- With each new detection

$$\Delta I_t = G_t - L_t = \text{gain} - \text{loss}$$

- Conditional entropy production

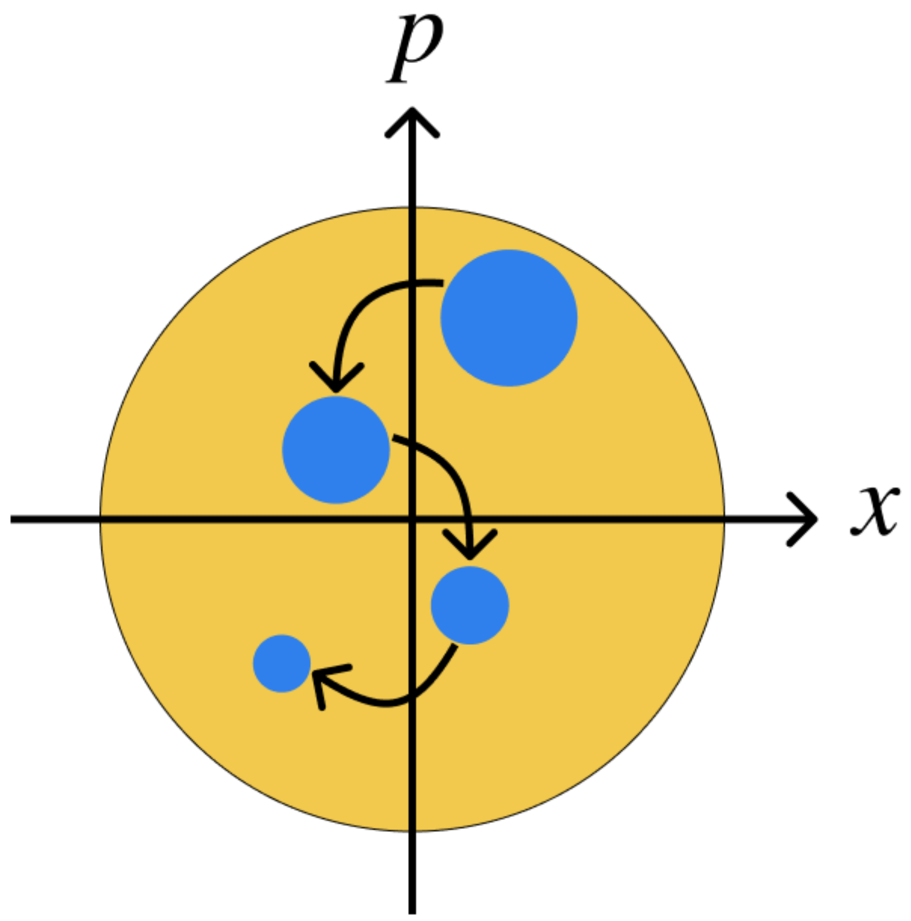
$$\Delta \Sigma^c = \Delta \Sigma^u - \Delta I$$

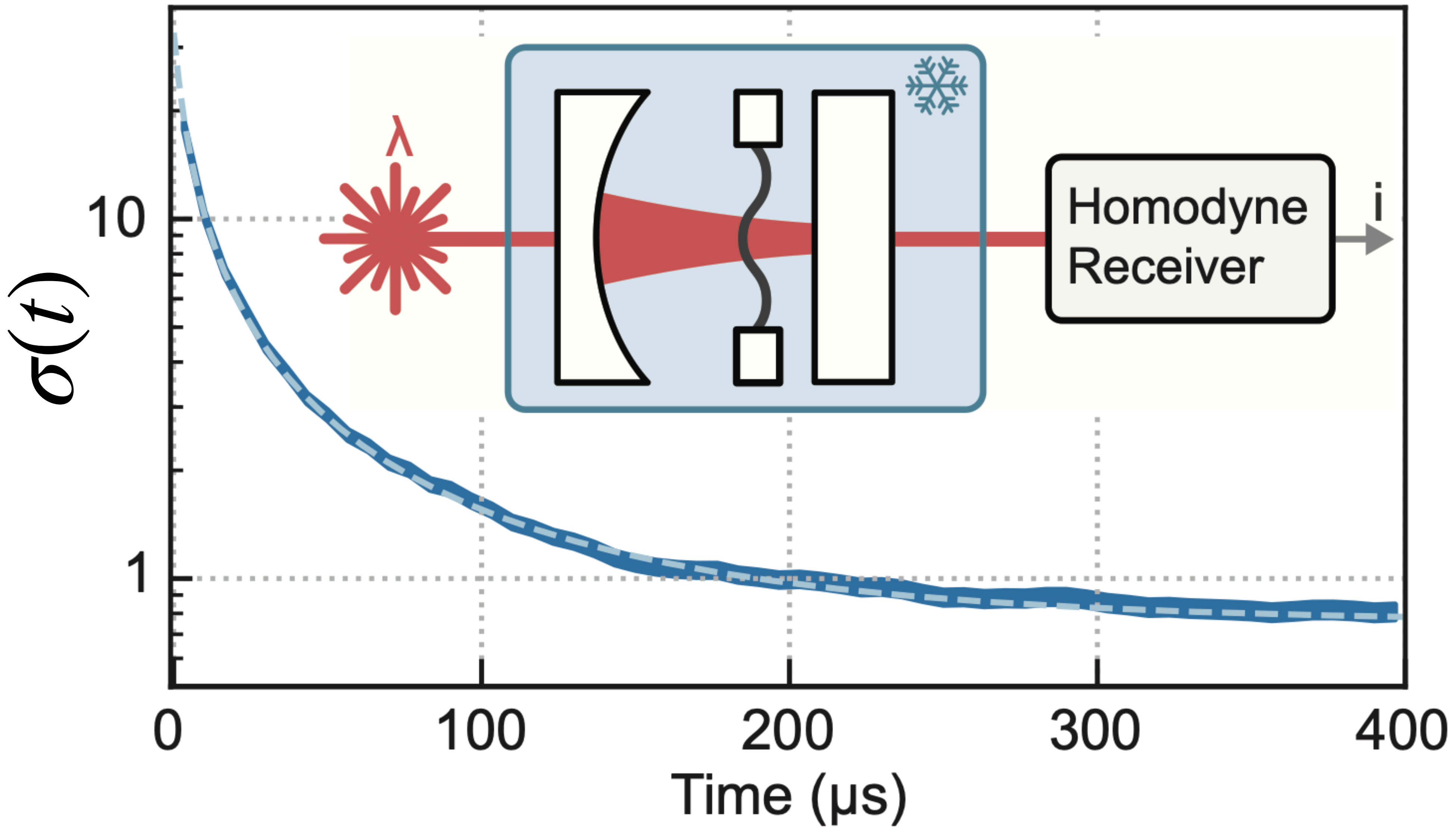


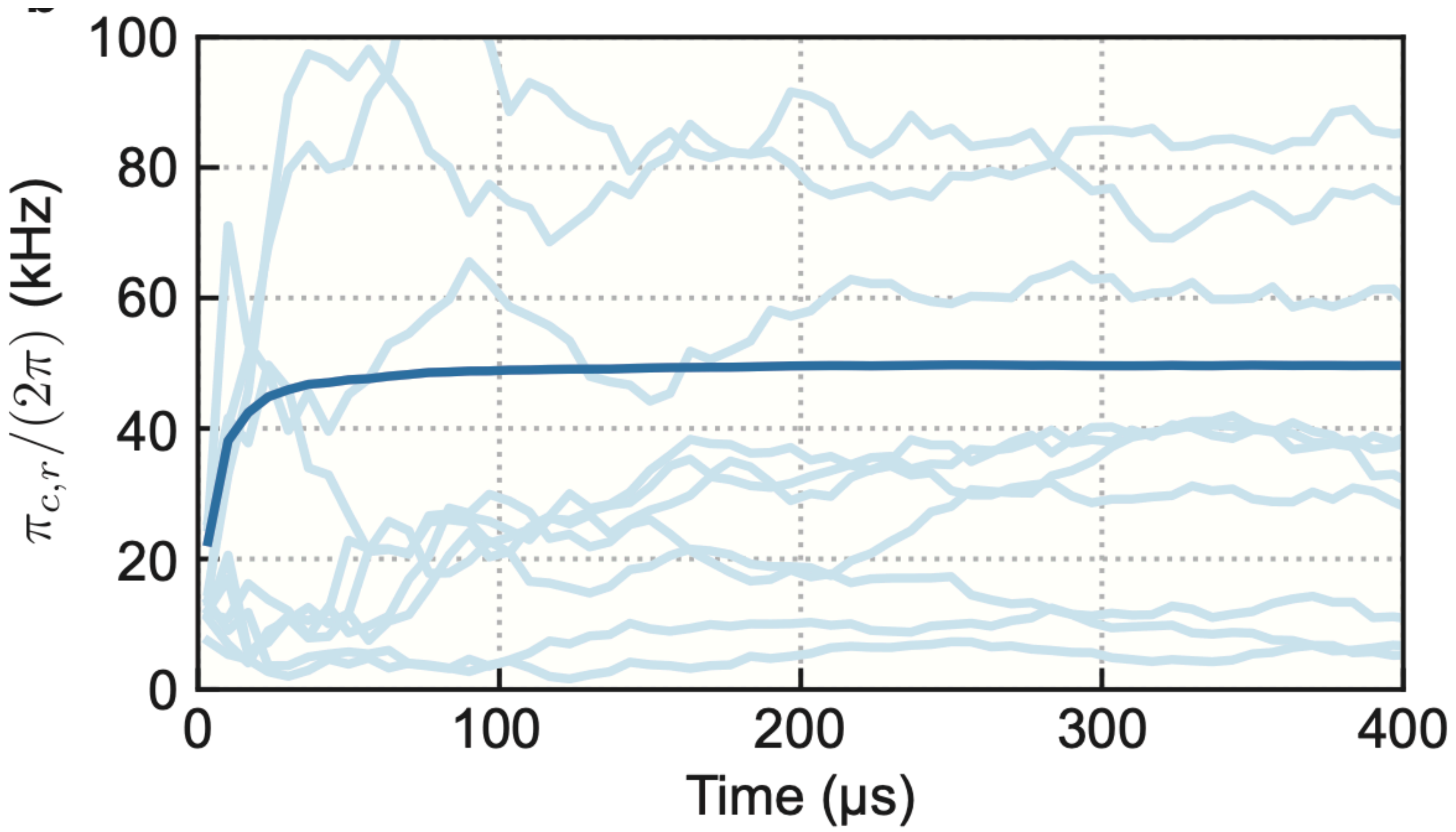
Alessio Belenchia, Luca Mancino, Gabriel T. Landi and Mauro Paternostro, "**Entropy production in continuously measured quantum systems**", npj Quantum Information, **6**, 97 (2020).

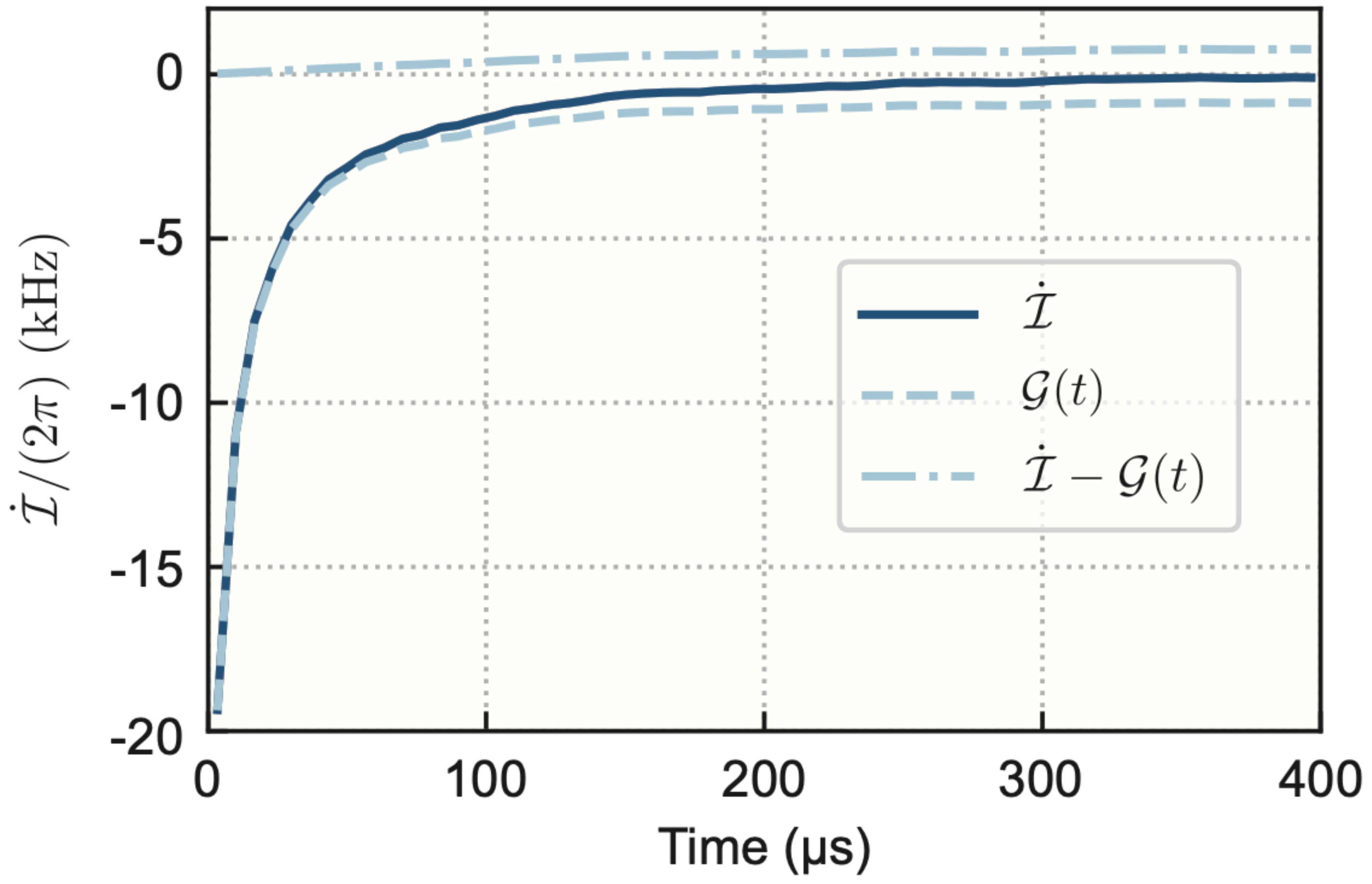
Gabriel T. Landi, Mauro Paternostro and Alessio Belenchia, "**Informational steady-states and conditional entropy production in continuously monitored systems**", PRX Quantum **3**, 010303, (2020).

Optomechanical setup









Informational steady-state:

Conditional dynamics relaxes to a colder state, which can only be maintained by continuously monitoring S.

Massimiliano Rossi, Luca Mancino, Gabriel T. Landi, Mauro Paternostro, Albert Schliesser, Alessio Belenchia, "**Experimental assessment of entropy production in a continuously measured mechanical resonator**", Phys. Rev. Lett. **125**, 080601 (2020)

Conclusions

- **Information is a thermodynamic resource.**
- How to incorporate information in the laws of thermodynamics is still an open question.
- I have focused on some recent developments, concerning the 2nd law (entropy production)
    - Quantum correlations.
    - Quantum coherence.
    - Non-Abelian charges.
    - Quantum phase space.
    - Continuous measurements.

Thank you!

www.fmt.if.usp.br/~gtlandi

Thermosqueezing operations

- Single-mode radiation:

$$\rho = \frac{1}{Z}\exp\left\{-\beta H - \beta\mu A\right\}, \qquad H = \frac{\omega}{2}(p^2 + x^2), \qquad A = \frac{\omega}{2}(p^2 - x^2)$$

- Two charges, H (energy) and A (squeezing). Satisfy SU(1,1) algebra.