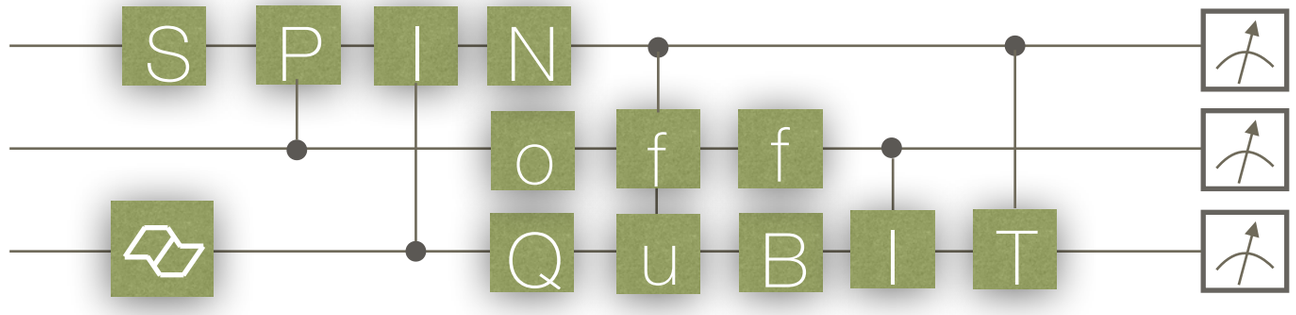

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QUANTUM CORRELATIONS AND THE ARROW OF TIME

Gabriel T. Landi
Instituto de Física da Universidade de São Paulo
www.fmt.if.usp.br/~gtlandi

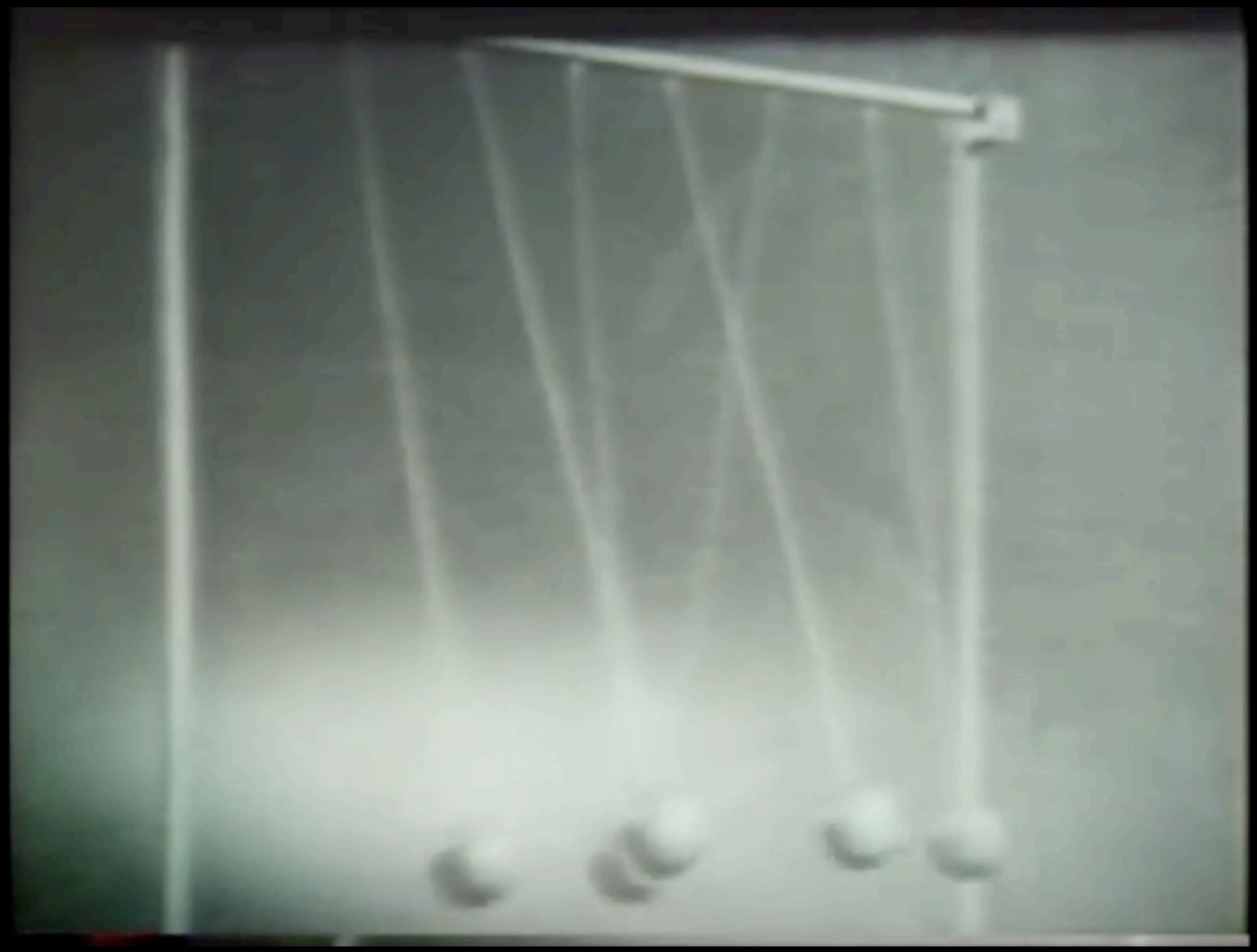
2019 Interdisciplinary Colloquium on Probability Theory:
Philosophy, Physics and Mathematics at Crossroads
October 8th, 2019 @ IEA-USP

Quantum thermodynamics
quantum transport
IFUSP

THE ARROW OF TIME

THE ARROW OF TIME

See video lectures by Prof. George Porter on YouTube



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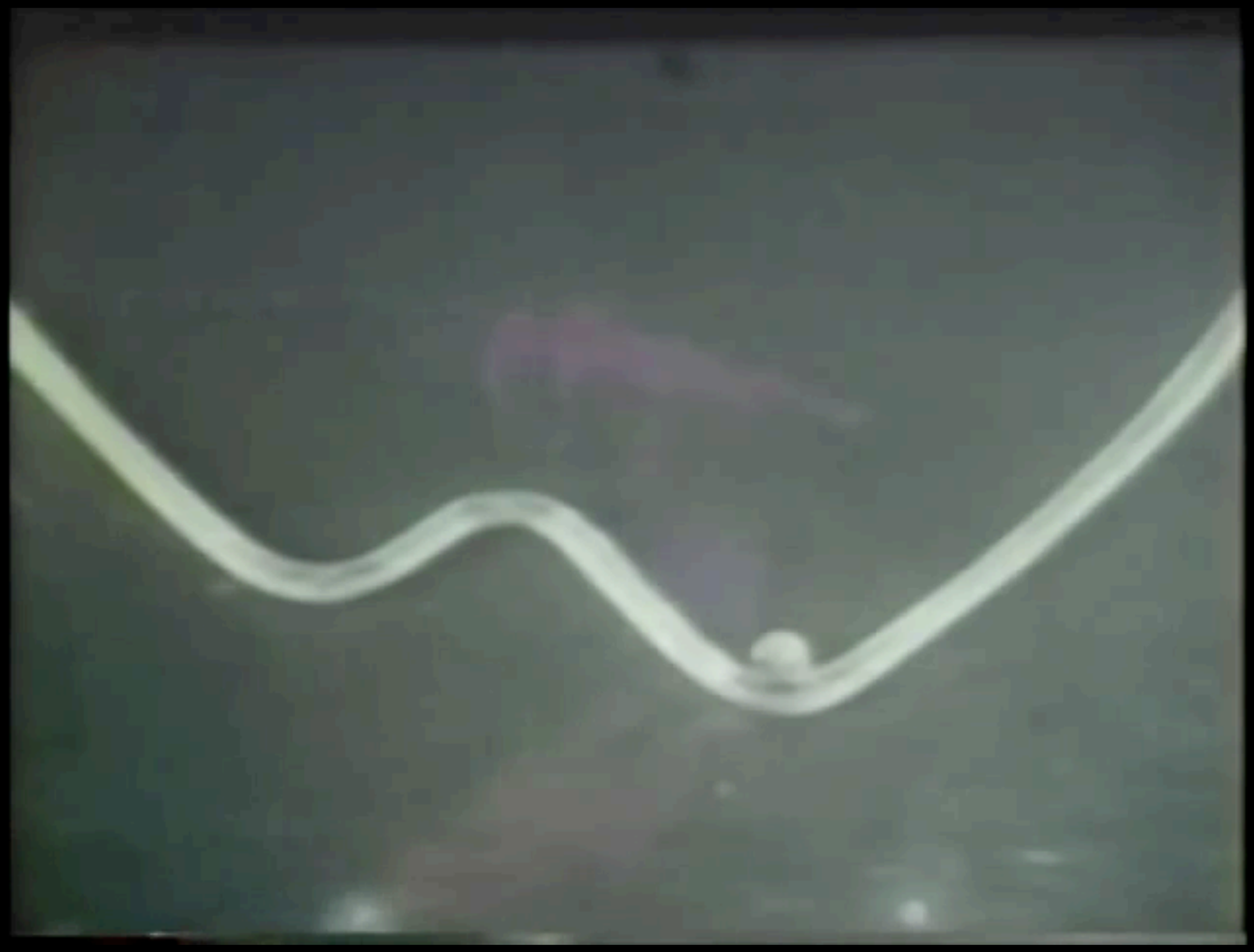

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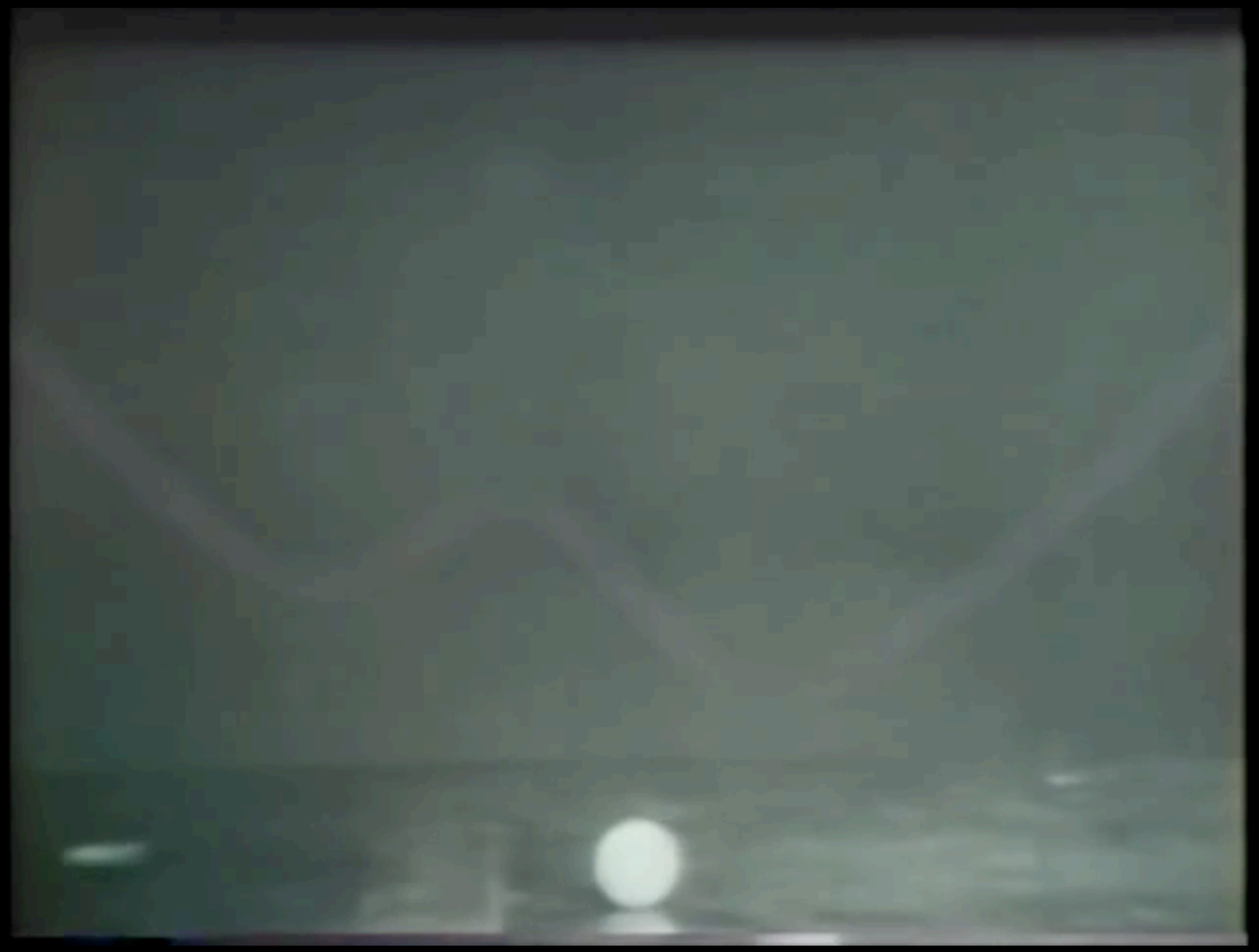

See video lectures by Prof. George Porter on YouTube

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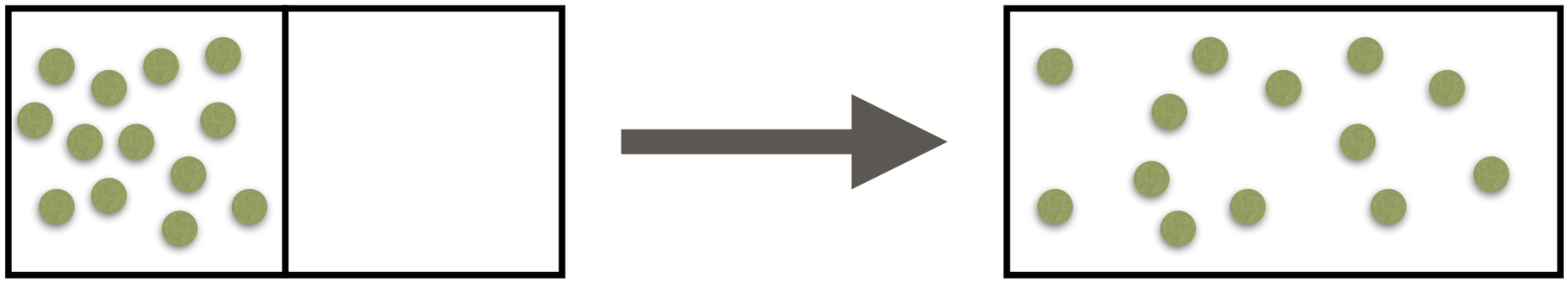
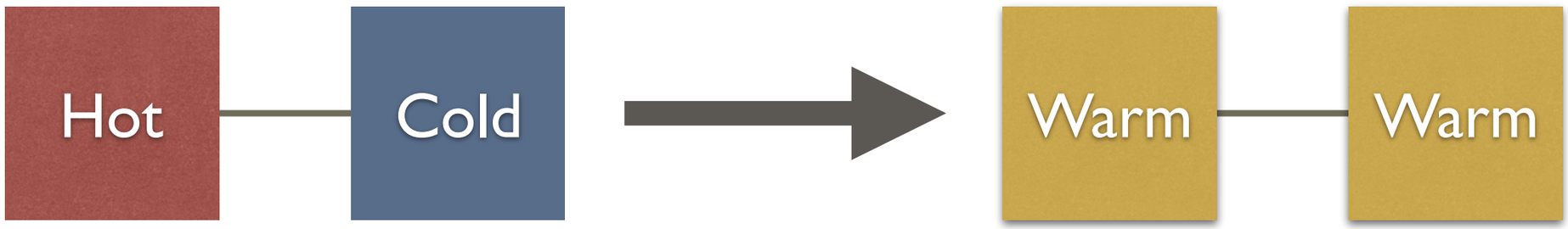
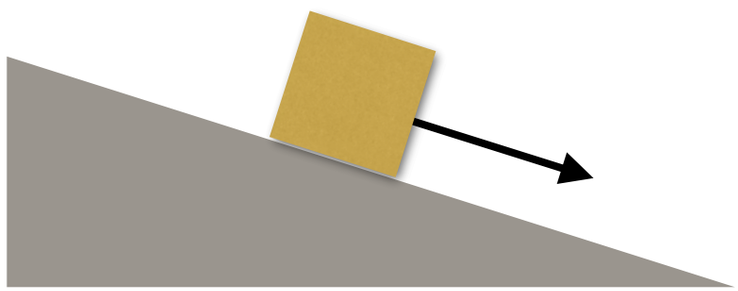
- Free expansion of a gas:



- Flow of heat:

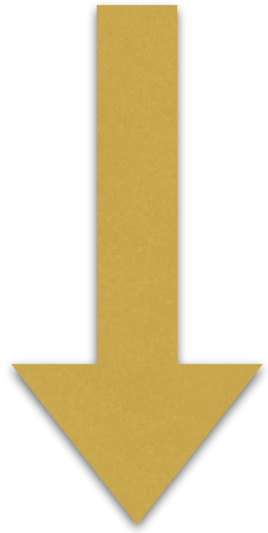


- Friction:



Arrow of time

2nd law of thermodynamics



Imposes restrictions on what processes can happen in nature

4


T- 00:00:01
STAGE 1 TELEMETRY
SPEED
ALTITUDE
00000
km/h
00.0
km
UPCOMING
LIFTOFF
STARTUP
THE FALCON 9 FLIGHT COMPUTERS HAVE TAKEN CONTROL OF THE COUNTDOWN
LAUNCH: CRS-12
STARTUP
LIFTOFF
MAX-Q
STAGE 1 BOOSTBACK
MAIN ENGINE CUTOFF
STAGE 1 ENTRY BURN
STAGE 1 LANDING
SECOND STAGE ENGINE CUTOFF
DRAGON DEPLOY
ARRAY DEPLOY
SPACEX

HOW TO REVERSE THE ARROW OF TIME?

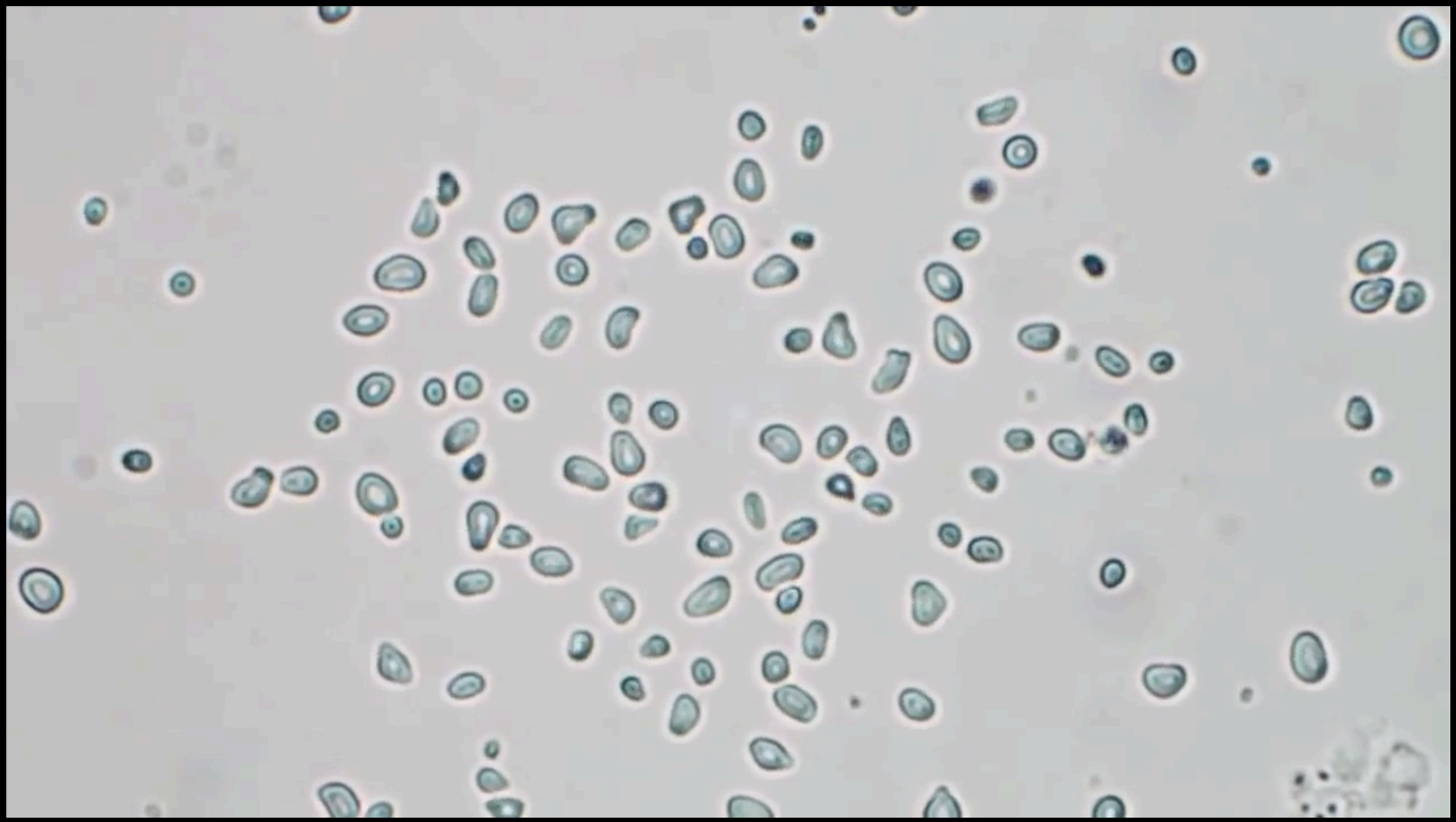
- To reverse the arrow of time, one must consume **resources**.

There is no such thing as a free lunch.

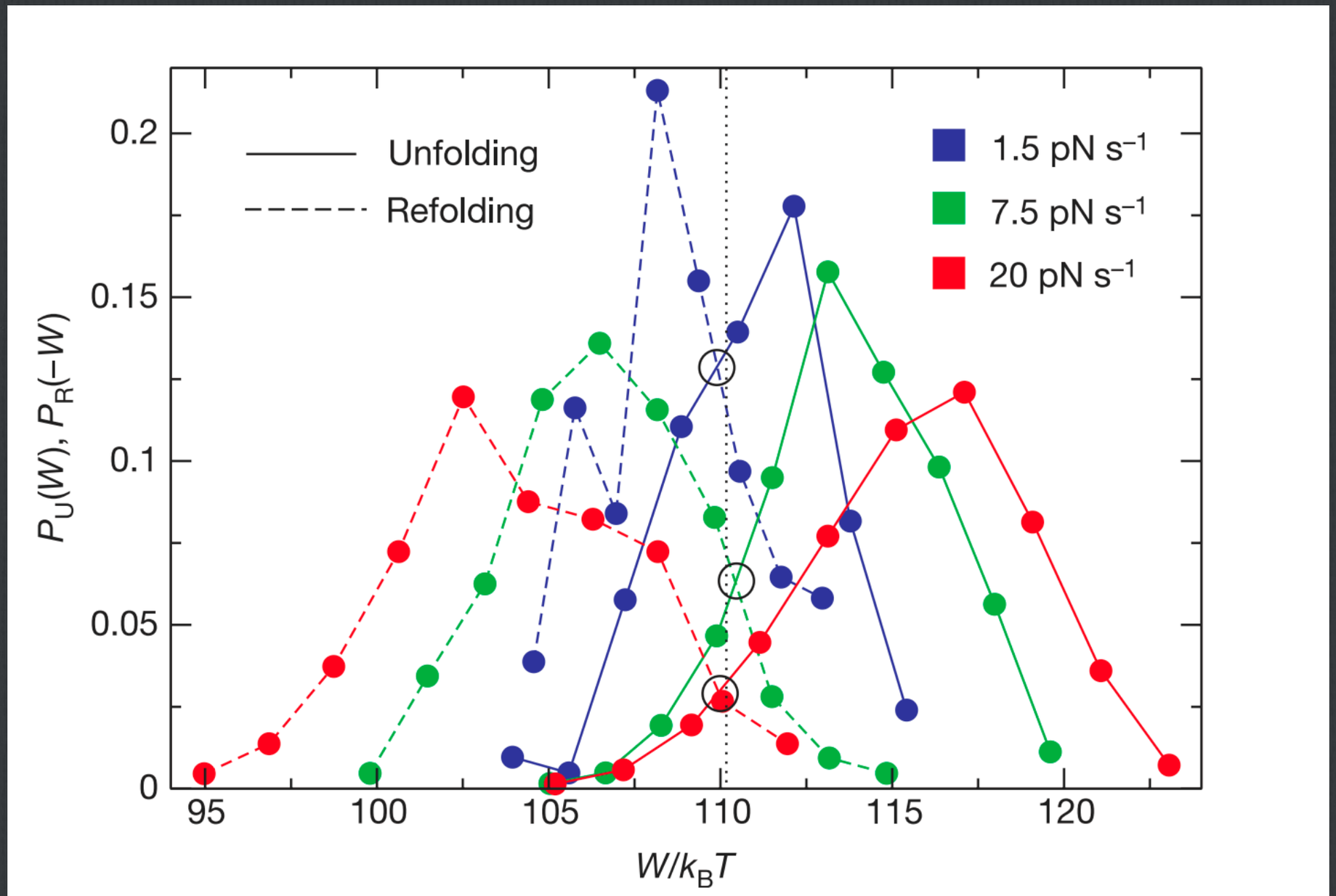
Take home messages

1. We can reverse the arrow of time, but to do so we must consume resources.
2.
3.
4.

FLUCTUATIONS OF HEAT AND WORK

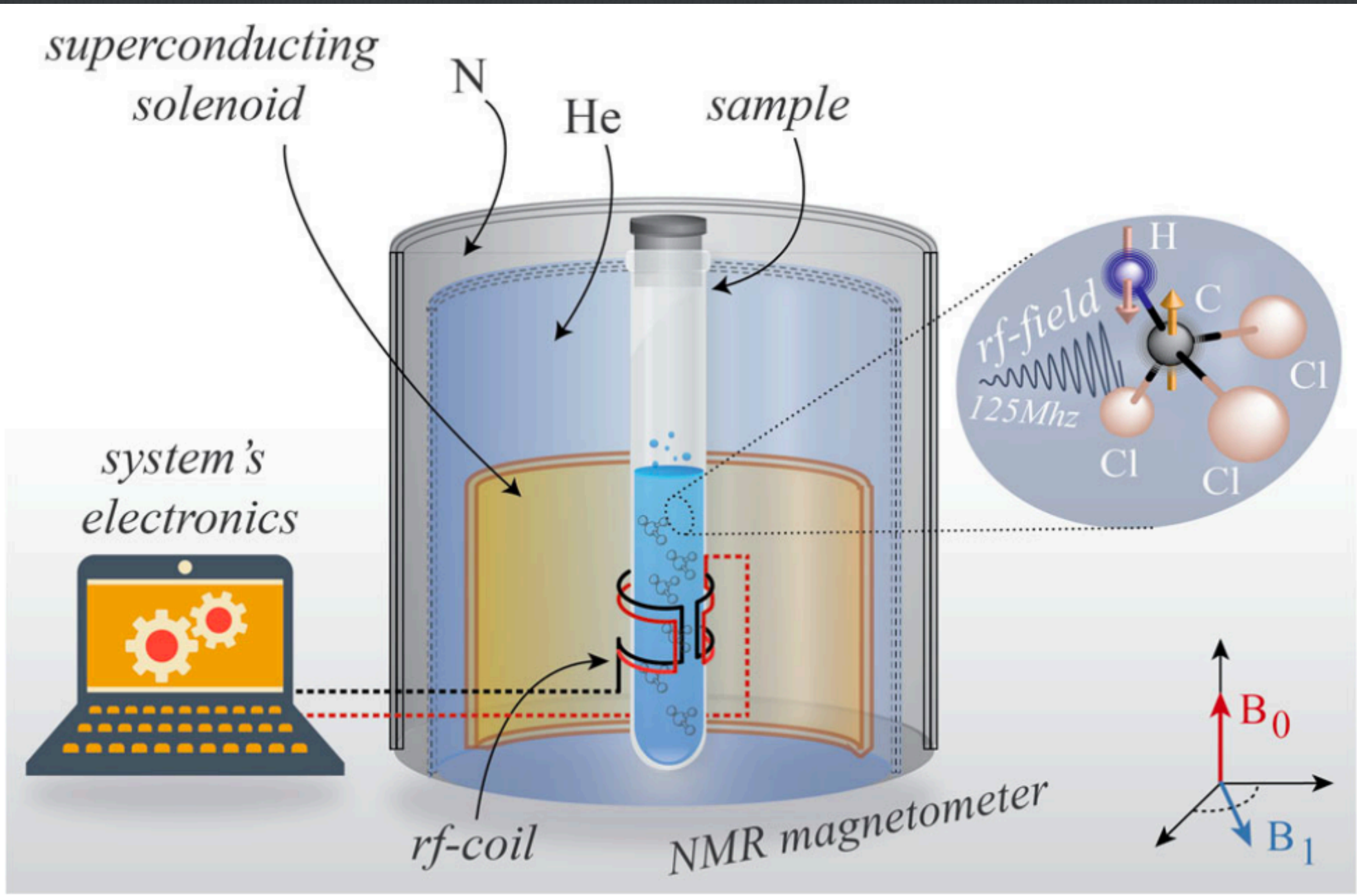


Fluctuations of work in folding an RNA molecule

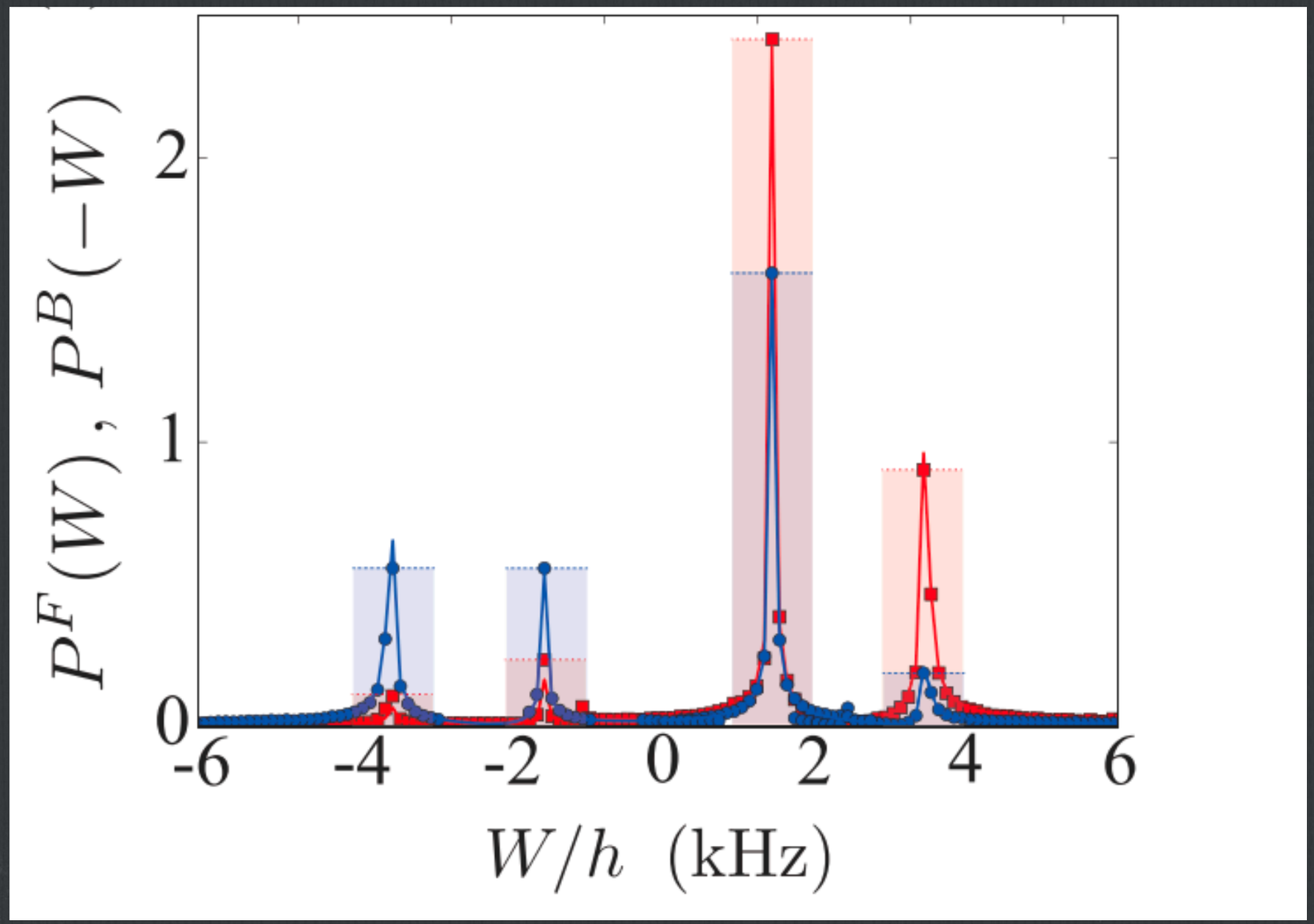


Collin, et. al., Nature, 437 (2005)

in quantum systems

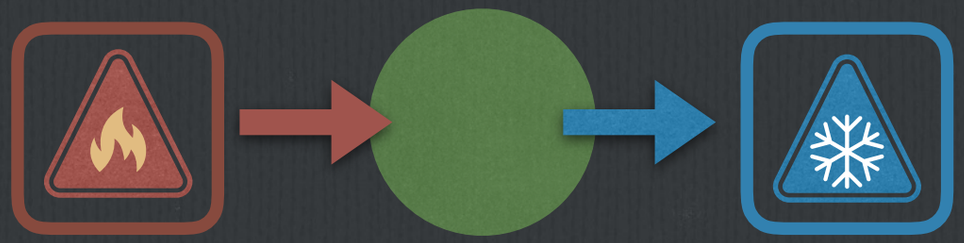


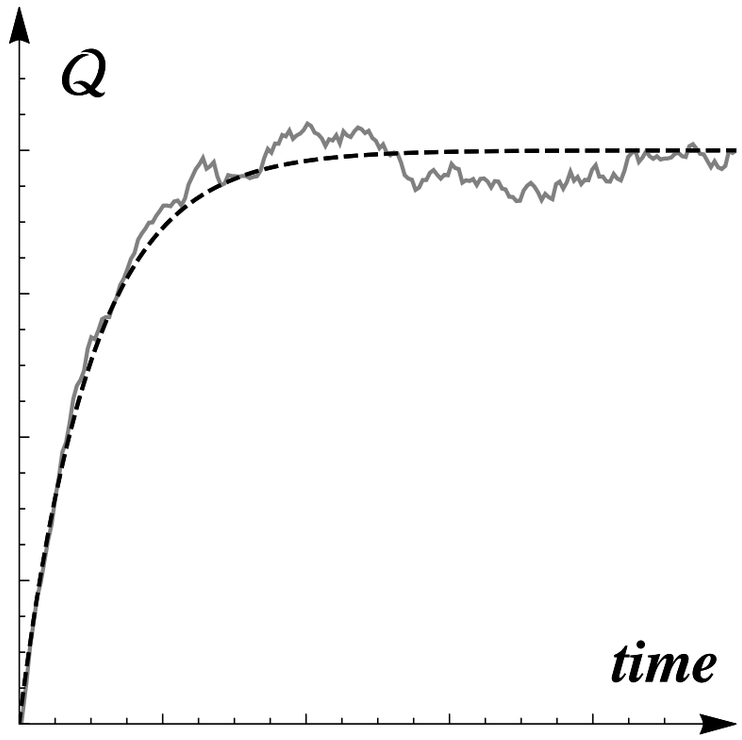
Batalhão, et. al., Phys. Rev. Lett. 113 (2014).

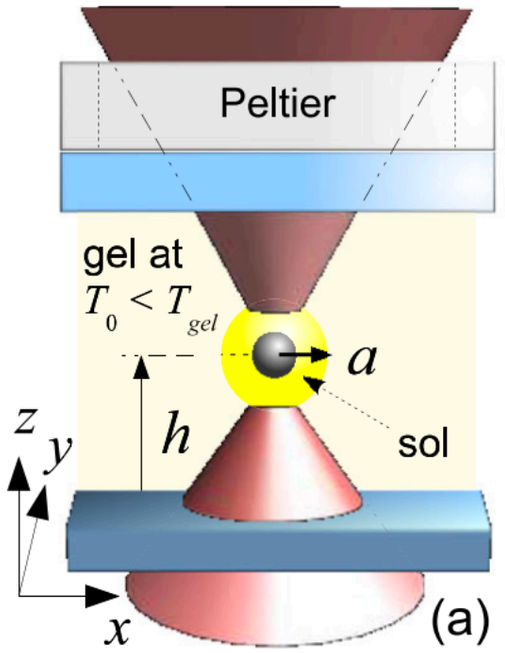


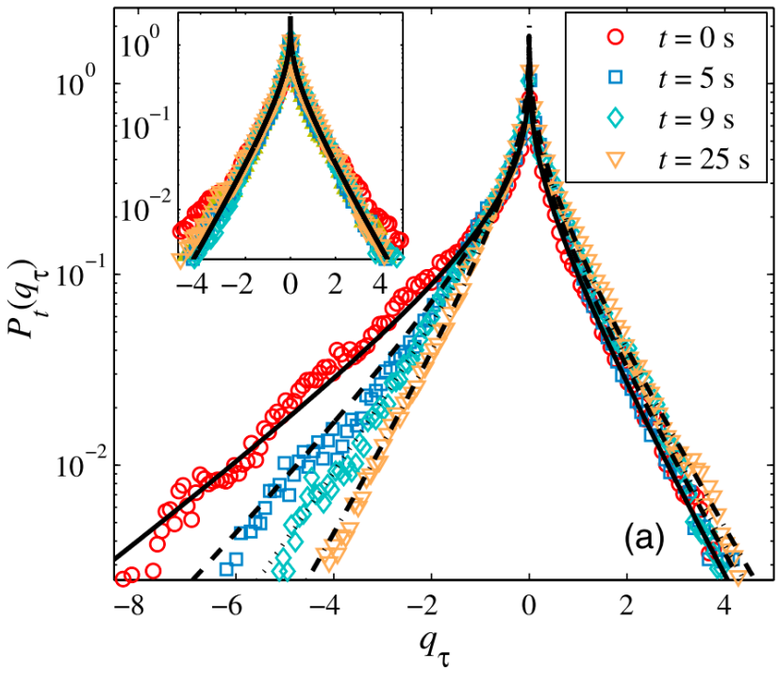
Batalhão, et. al., Phys. Rev. Lett. 113 (2014).

Fluctuations of heat exchange



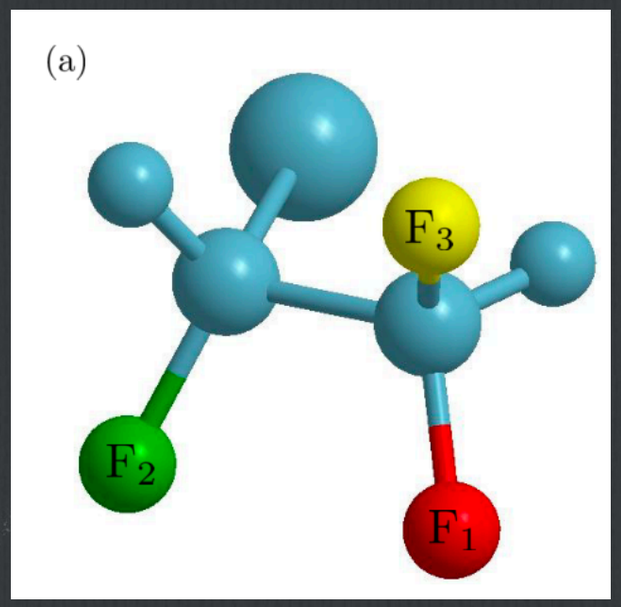


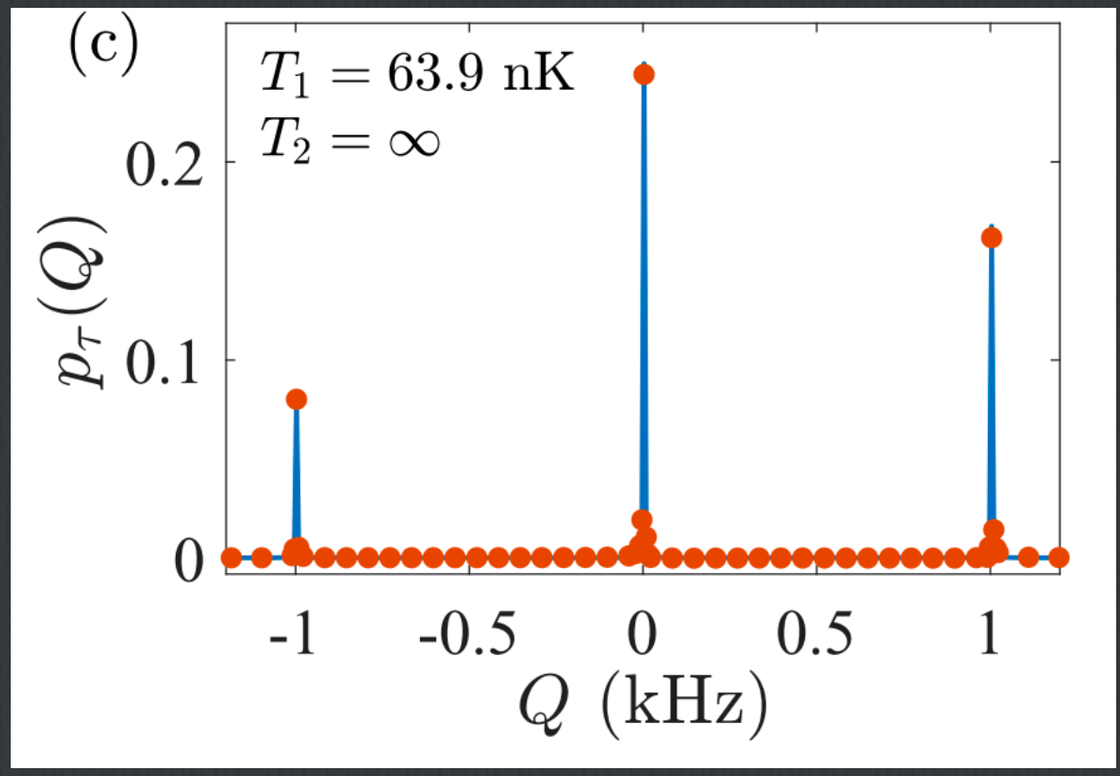




Jarzynski and Wójcik Phys. Rev. Lett. 92, 230602 (2004)

J. R. Gomes-Solano Phys. Rev. Lett. 106, 200602 (2011)

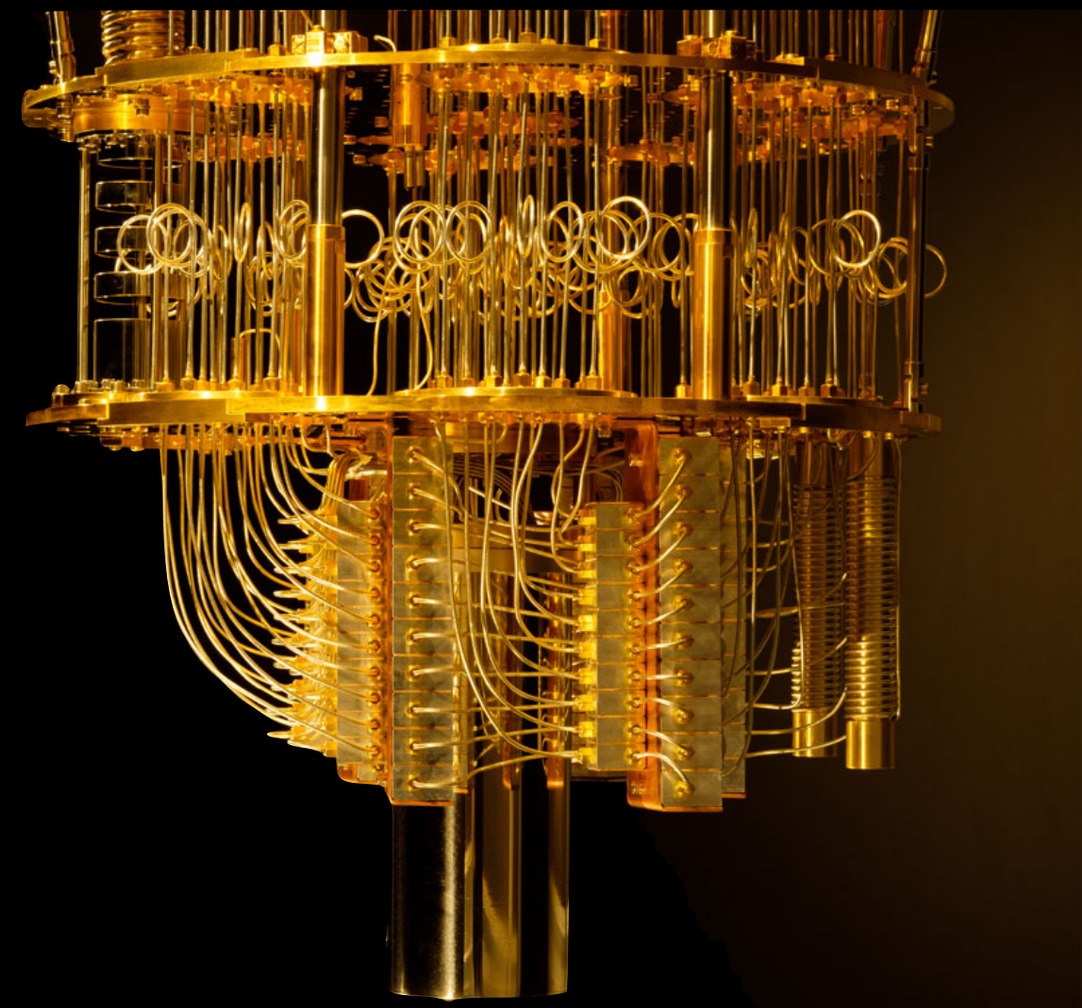




Pal et. al., arXiv 1811.07291

Take home messages

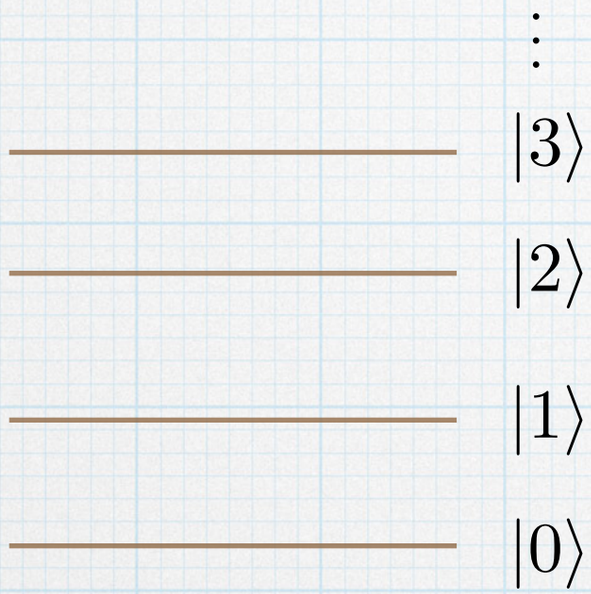
1. We can reverse the arrow of time, but to do so we must consume resources.
2. In microscopic systems, thermodynamic quantities fluctuate and statements must be probabilistic.
3.
4.



THE QUANTUM REALM

REALISM AND QUANTUM CORRELATIONS

* Quantum systems can exist in different states.



* What appears inside $|\rangle$ is just a label for whatever that state means.

* Superposition principle: the system can simultaneously be in multiple quantum states at a time.

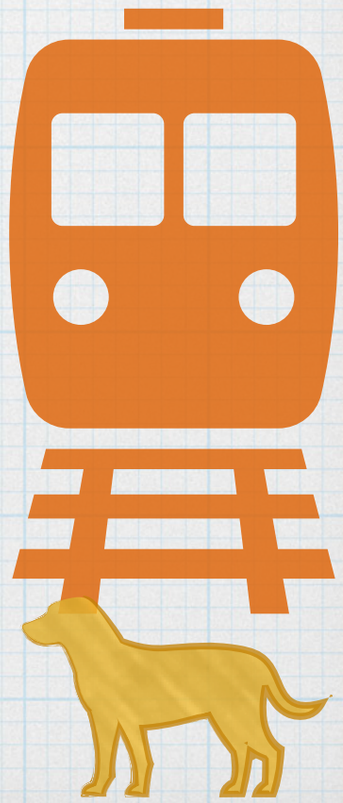
$$|\psi\rangle = \sum_n c_n |n\rangle$$

* But if we measure it, we will find it only in one of the states, with prob.

$$|c_n|^2 = \text{prob. of finding the system in state} |n\rangle$$

Realism

* The idea that the properties of a system exist independent of observation.
    * "The moon is still there even if we don't look at it."
* But then what does a superposition mean?
    * Does it mean we don't know?



* No!
* Probabilistic outcomes are not due to our ignorance.
    * The state of the system is not defined prior to the measurement.
        * Quantum systems do not satisfy realism!
* Quantum measurements are always invasive.

Qubits

* Consider a system with only two levels

$$|0\rangle \qquad e \qquad |1\rangle$$

* Any superposition of these states is also a possible state

$$|\psi\rangle = c_0|0\rangle + c_1|1\rangle \qquad \text{then}$$

$$\text{Prob}(0) = |c_0|^2$$

$$\text{Prob}(1) = |c_1|^2$$

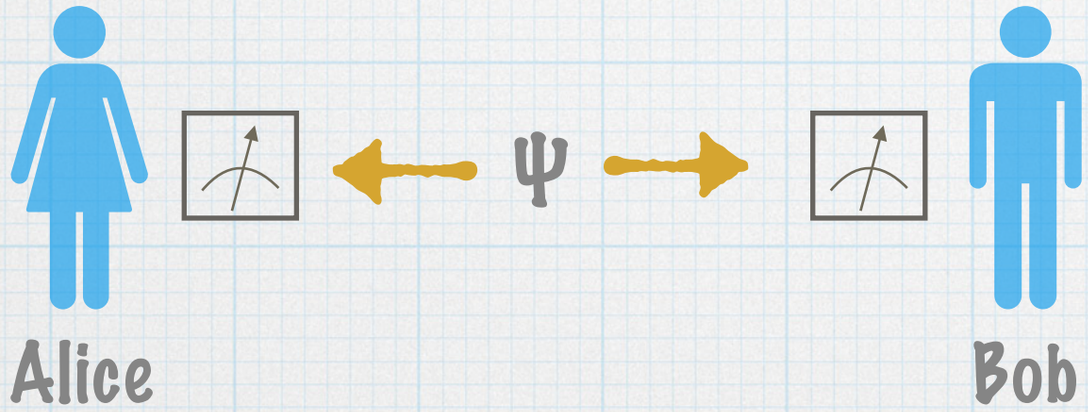
* If we measure and happen to find it in $|0\rangle$ then after the measurement the state of the system will be $|0\rangle$.

Entanglement

* Suppose now we have two qubits. A possible state is

$$|\psi\rangle = c_0|0,0\rangle + c_1|1,1\rangle$$

* We now send the qubits off to two distant labs where Alice and Bob make measurements.

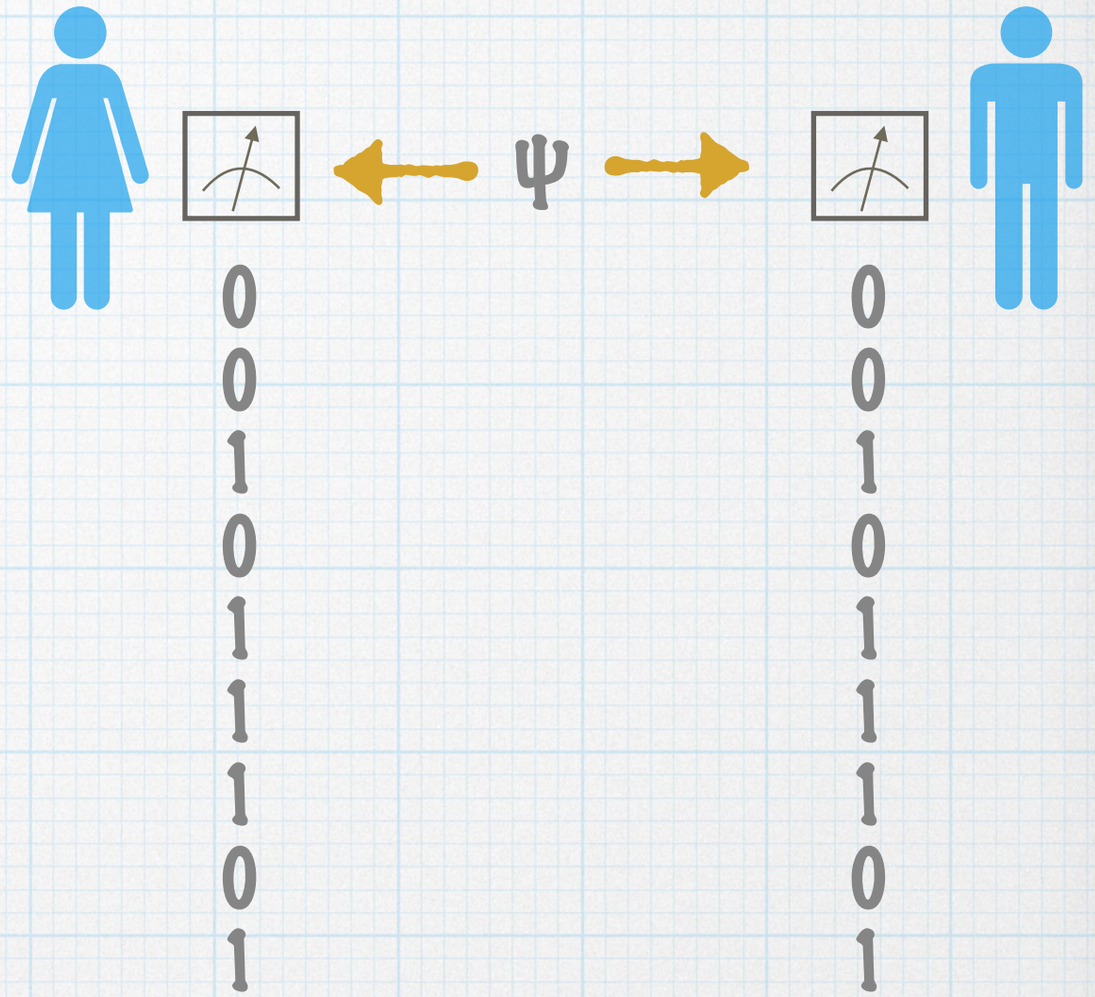


* If Alice measures and finds her qubit in $|0\rangle$ then the state is updated to

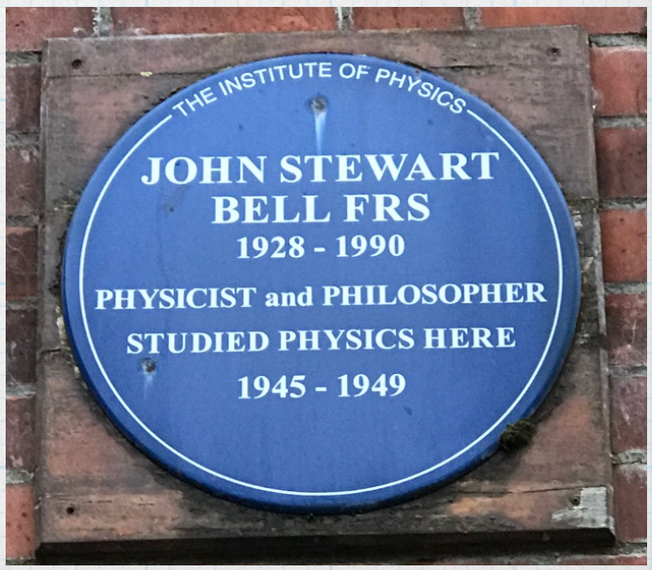
$$|\psi\rangle \to |0,0\rangle$$

* Bob's state is updated.
* Even if he is in another galaxy.

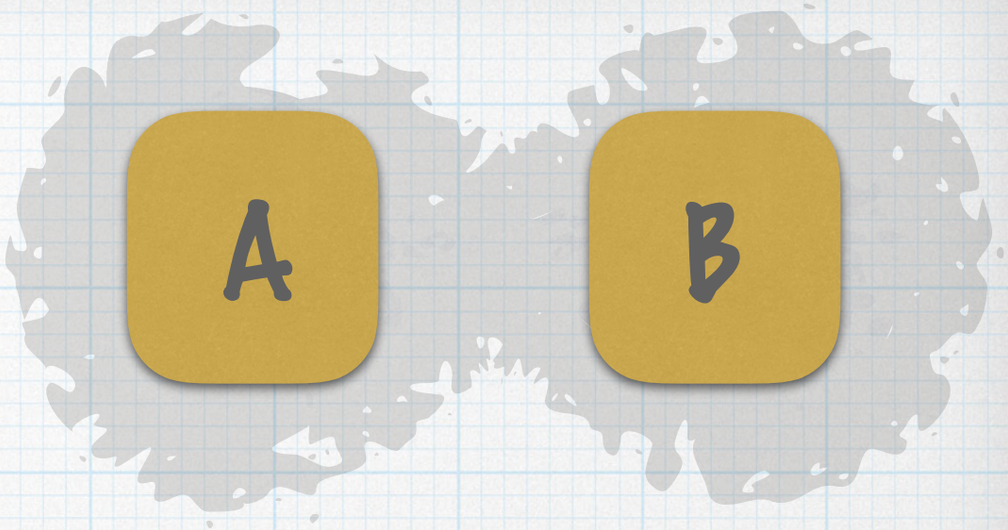
* It is possible to have the same type of perfect correlation without any quantum physics.
  * All you need is a common past factor.
  * Correlation is then purely due our ignorance about this past factor.



* One can show experimentally, however, that this is not the case.
  * Quantum entanglement is not due to our ignorance about past factors.
  * It is a real property of Nature.



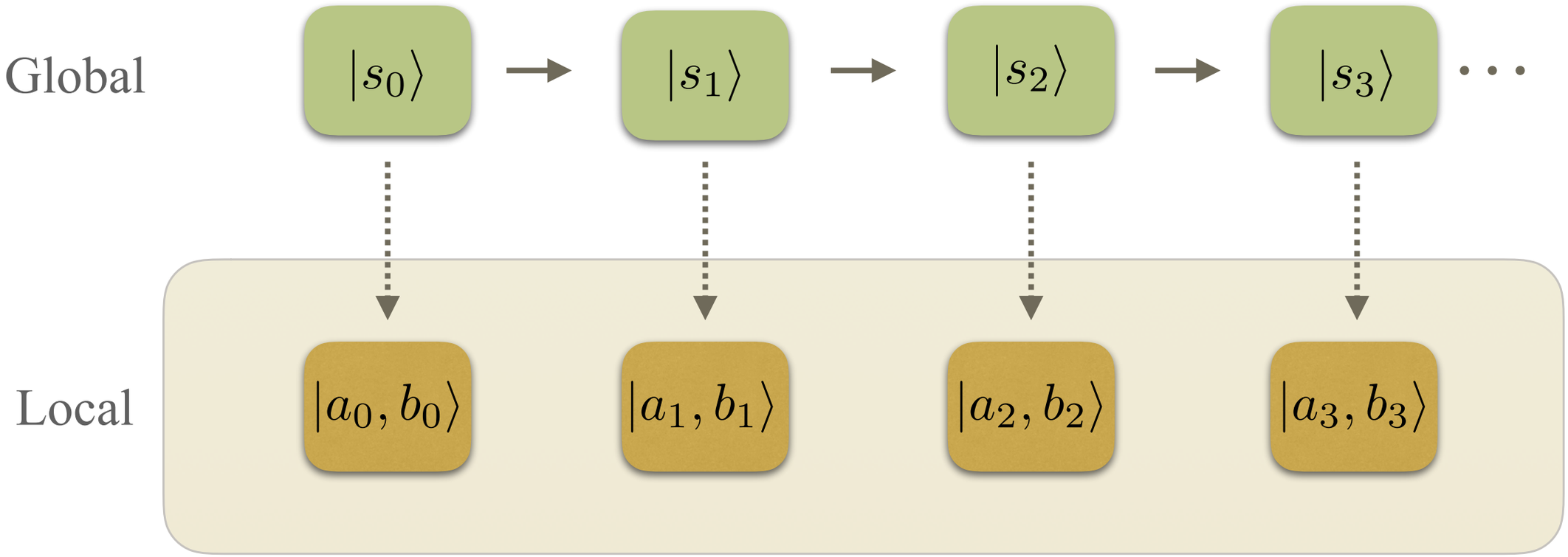
Quantum discord



* Correlations mean if you measure one system, you can learn something about the other.

* In quantum systems the information you extract depends on what kind of measurement you do.

  * And, in general, by measuring one system we can only extract part of the information about the other.



Dynamic Bayesian Network
(Hidden Markov model)

Take home messages

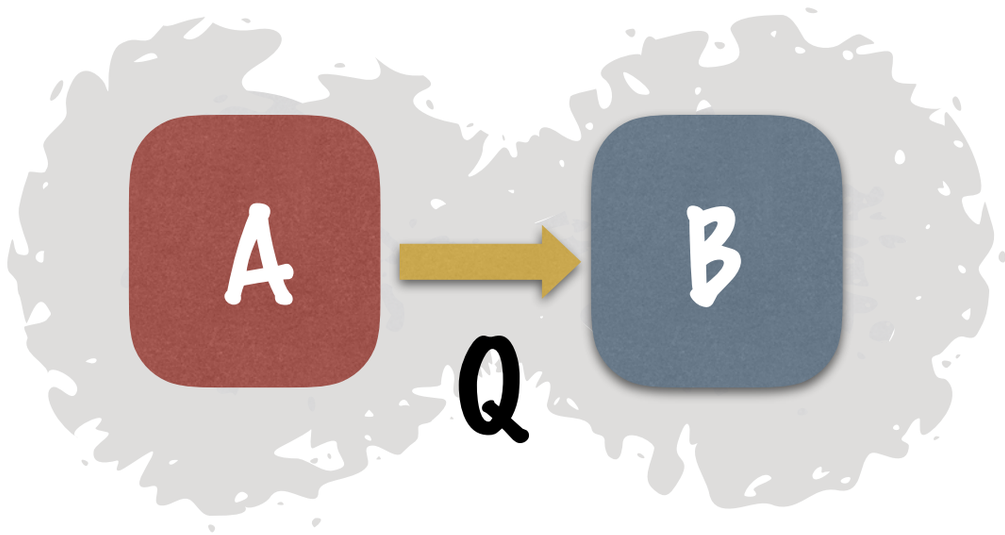
1. We can reverse the arrow of time, but to do so we must consume resources.
2. In microscopic systems, thermodynamic quantities fluctuate and statements must be probabilistic.
3. Quantum correlations (entanglement and discord) are fundamental properties of Nature and have experimentally observable consequences.
4.

ARTICLE

https://doi.org/10.1038/s41467-019-10333-7 OPEN

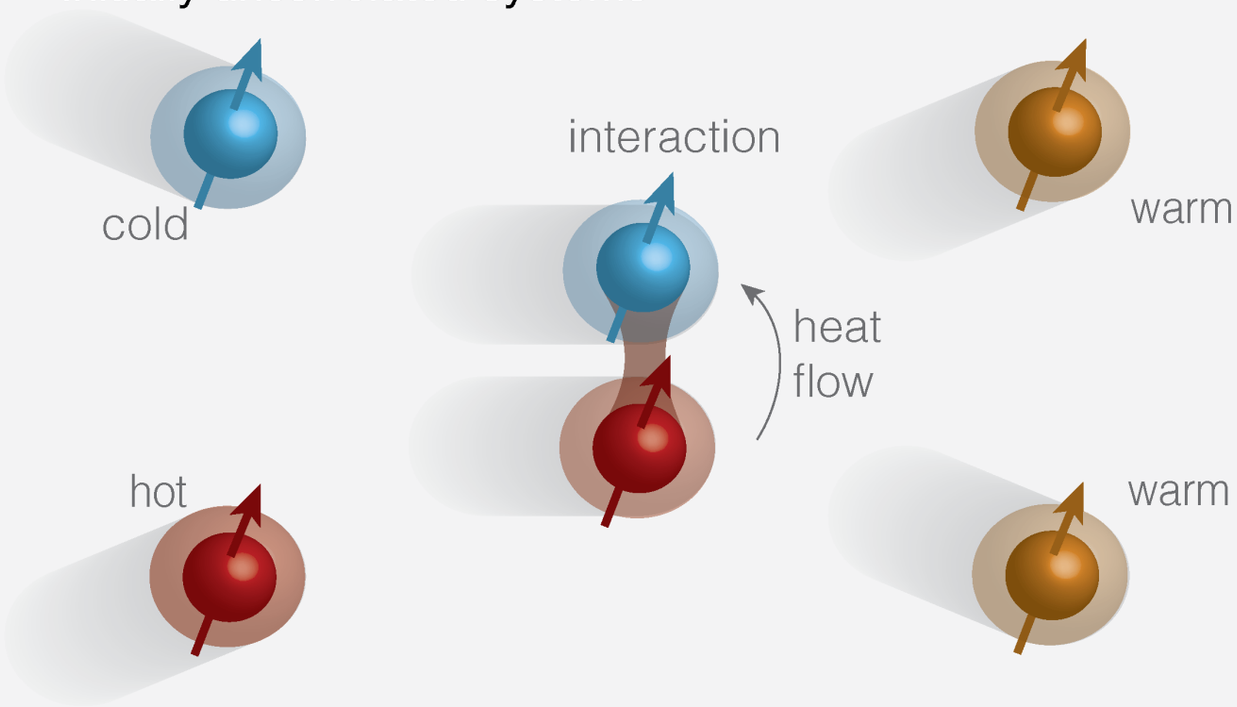
Reversing the direction of heat flow using quantum correlations

Kaonan Micadei[1,2,8], John P.S. Peterson[3,8], Alexandre M. Souza[3], Roberto S. Sarthour[3], Ivan S. Oliveira[3], Gabriel T. Landi[4], Tiago B. Batalhão[5,6], Roberto M. Serra[1,7] & Eric Lutz[2]

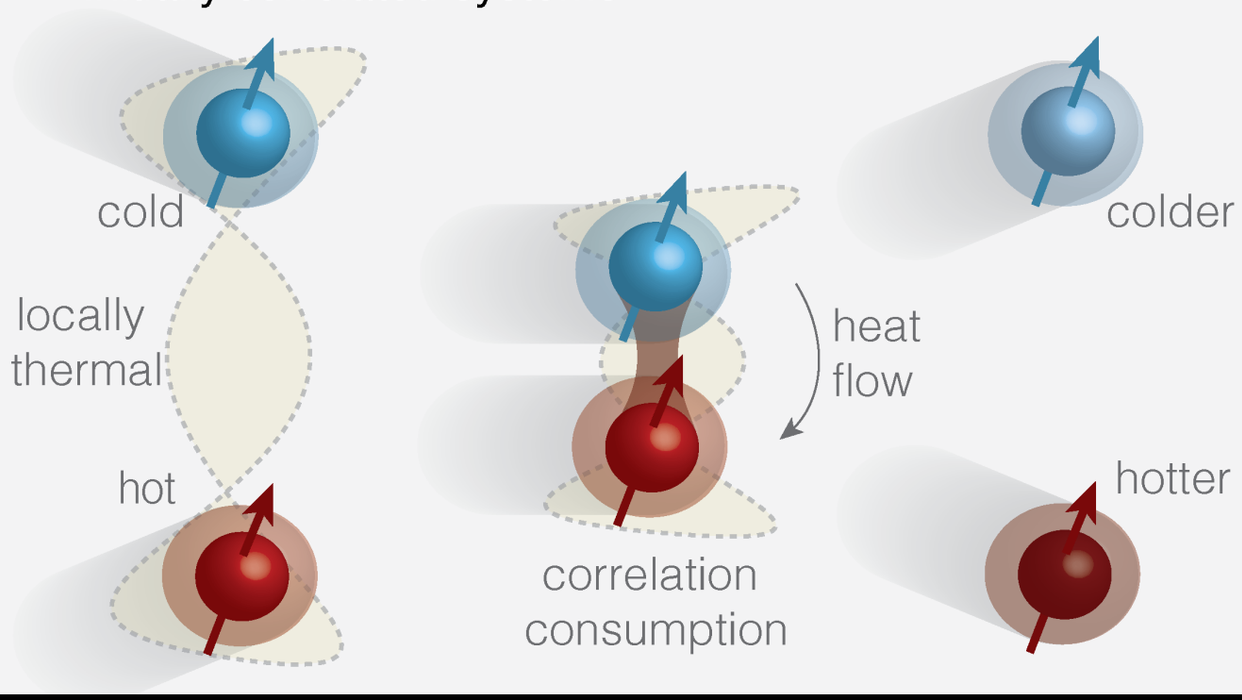


A

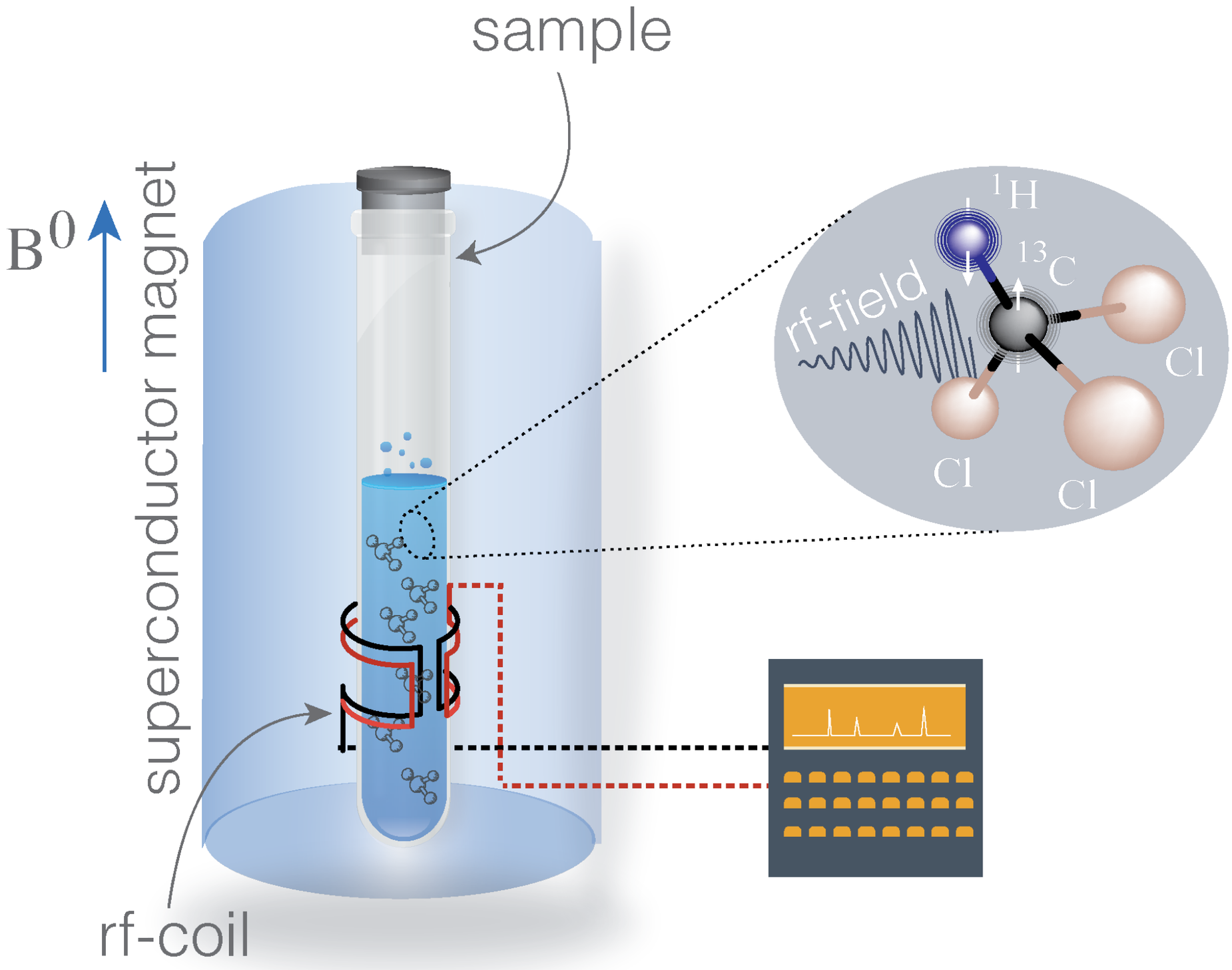
Initially uncorrelated systems



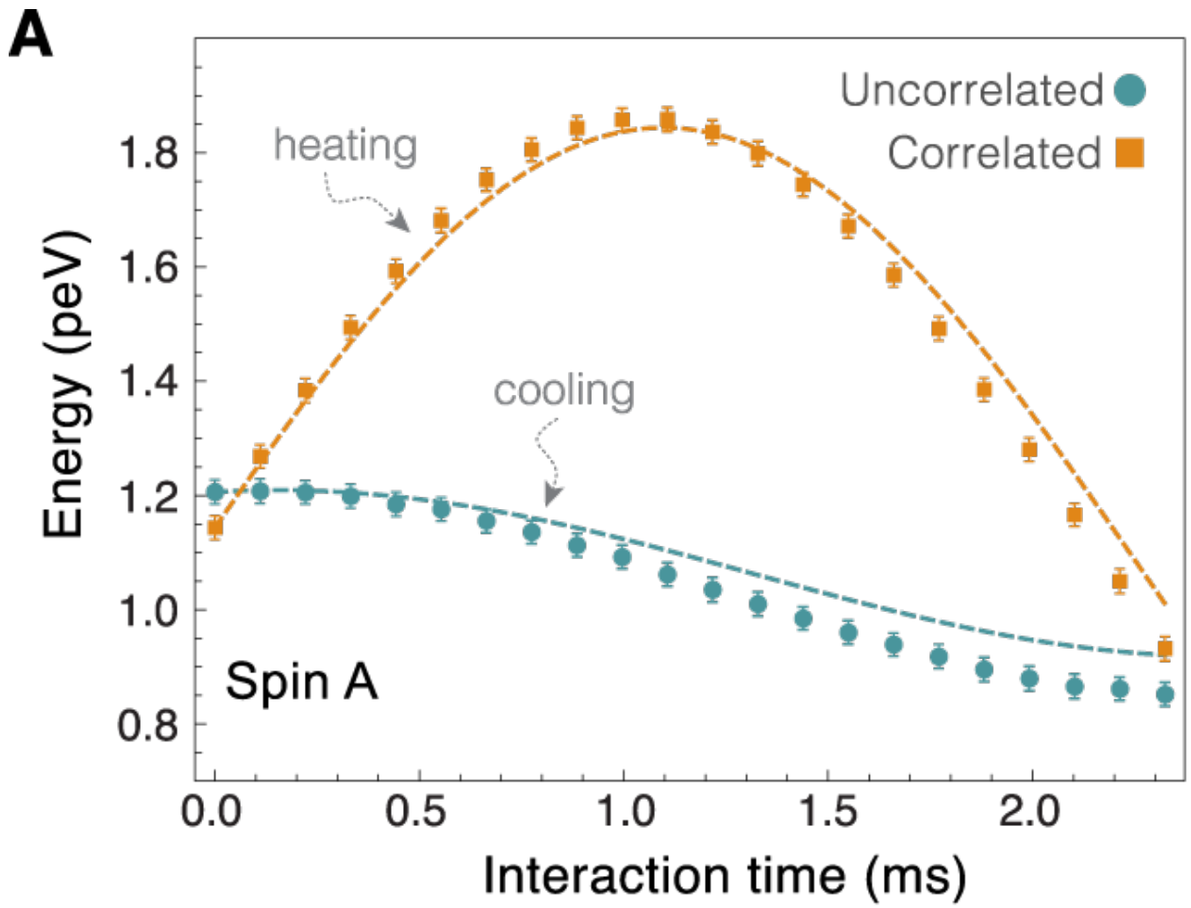
Initially correlated systems

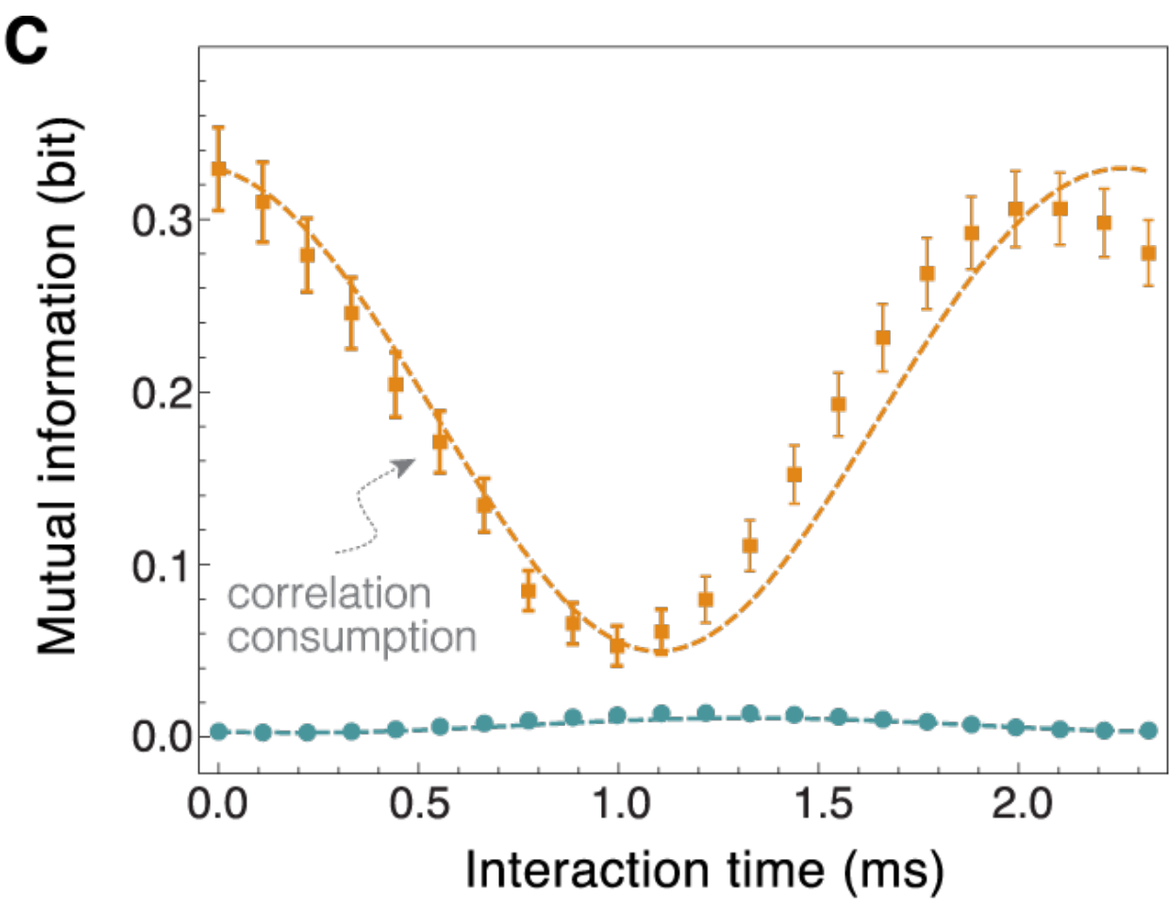


B


sample
B^0
superconductor magnet
rf-coil
rf-field
^1H
^{13}C
Cl
Cl
Cl

EXPERIMENTAL RESULTS





$$\left(\frac{1}{T_A}-\frac{1}{T_B}\right)Q \geq \Delta\mathcal{I}(A:B)$$

WHAT DOES THIS MEAN?

- The arrow of time and the 2nd law determine what kinds of thermodynamic processes are allowed.

- According to the 2nd law, *resources* have to be consumed to make heat flow from cold to hot (refrigerate).

  - *Quantum correlations are also a resource in thermodynamics!*

Take home messages

1. We can reverse the arrow of time, but to do so we must consume resources.

2. In microscopic systems, thermodynamic quantities fluctuate and statements must be probabilistic.

3. Quantum correlations (entanglement and discord) are fundamental properties of Nature and have experimentally observable consequences.

4. Quantum correlations are a resource that can be used to perform thermodynamic tasks.

PSEUDO FILMES

Thank you!

Quantum thermodynamics
quantum transport
IFUSP

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