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QUANTUM CORRELATIONS AND THE ARROW OF TIME

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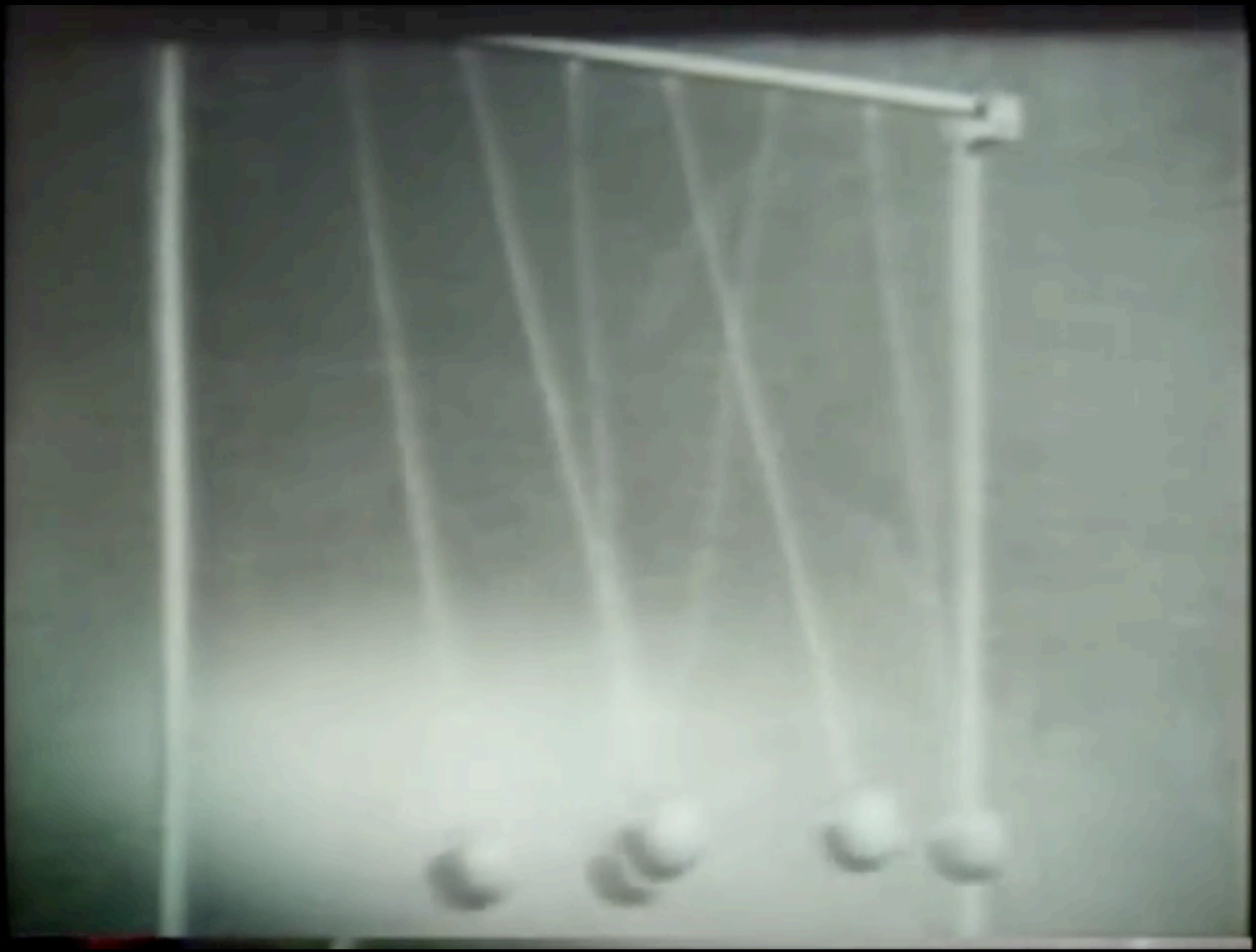
Café com Quantum

April ~~11th~~ 25th @ IFUSP

IFUSP

PART 1: THE ARROW OF TIME

See video lectures by Prof. George Porter on YouTube



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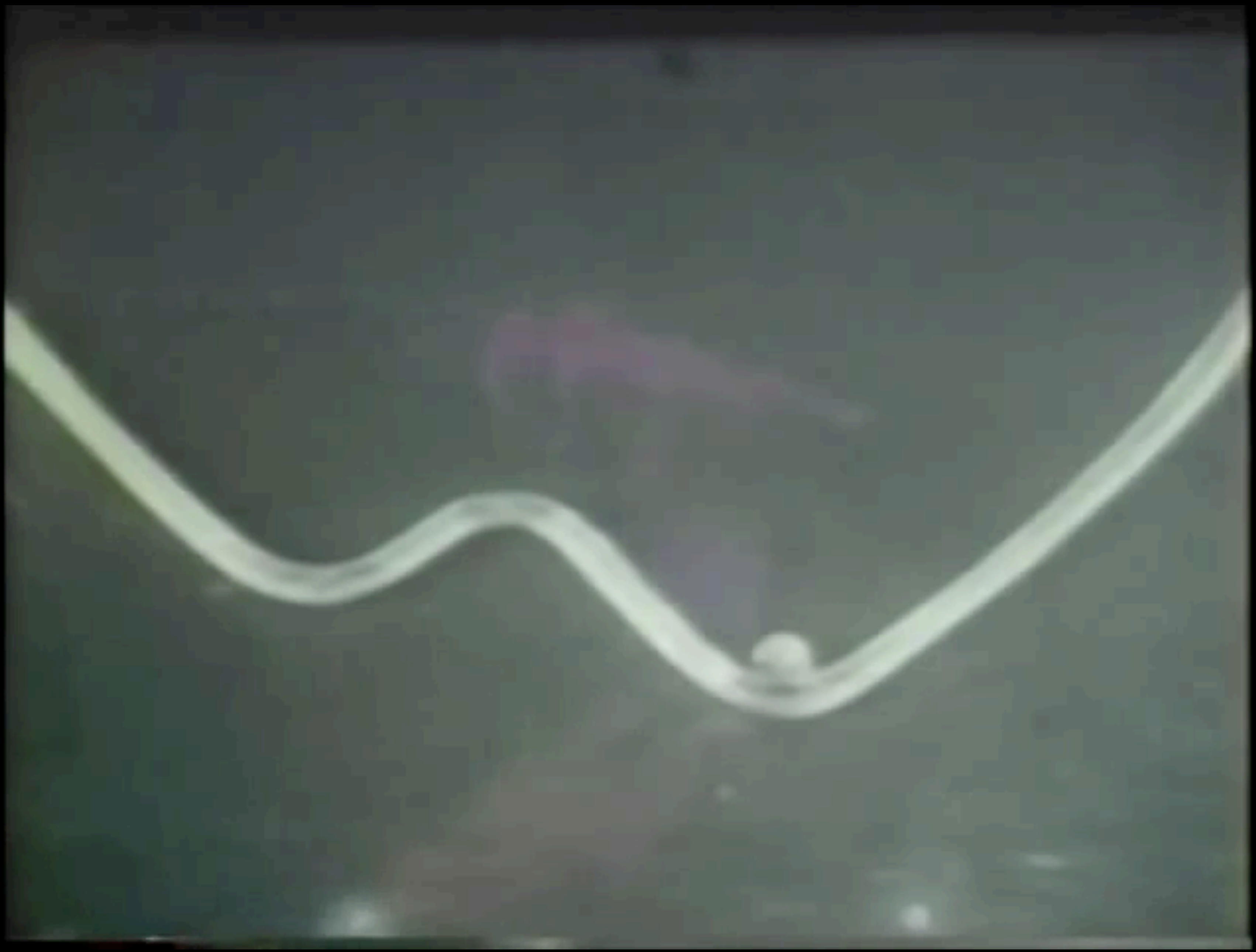

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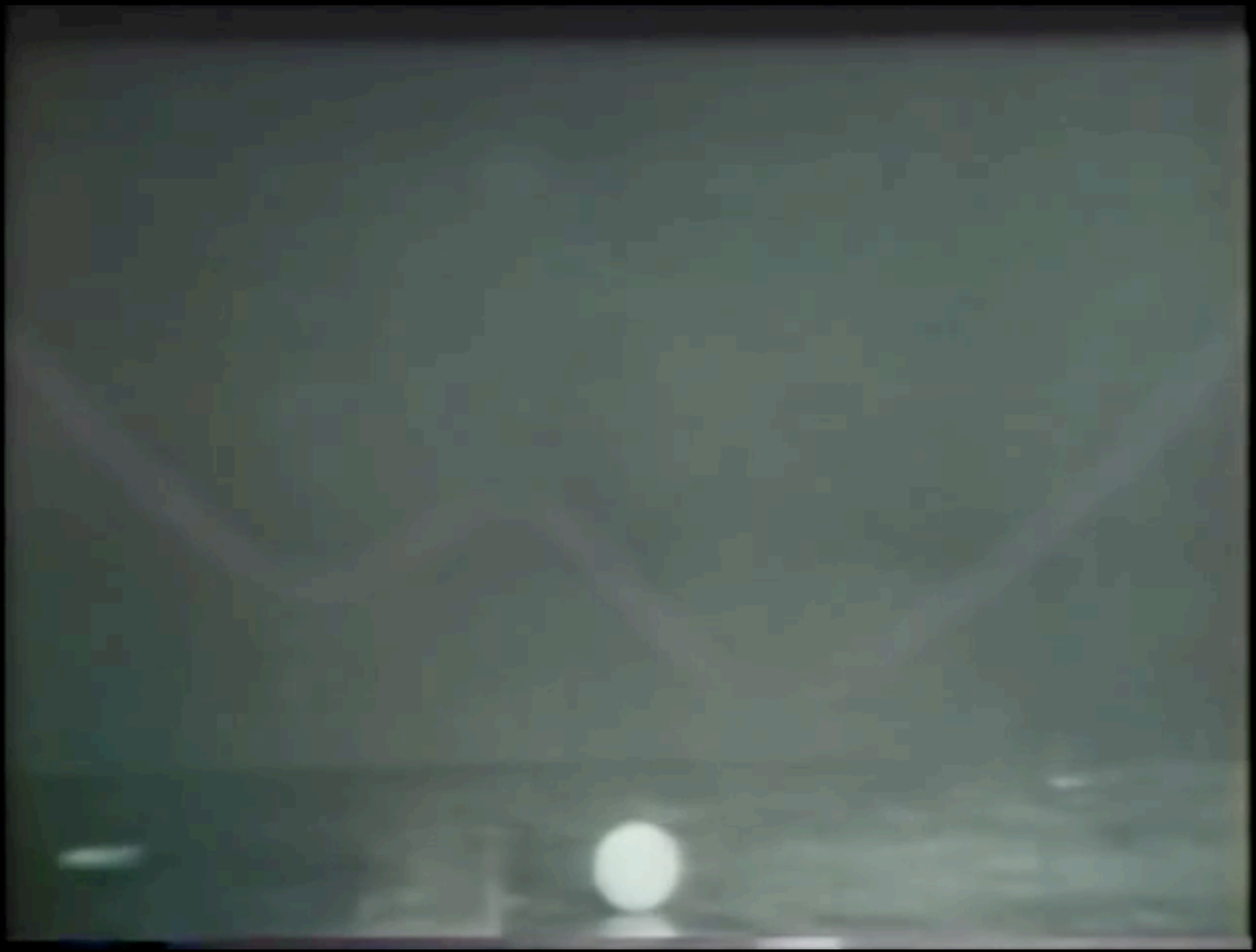

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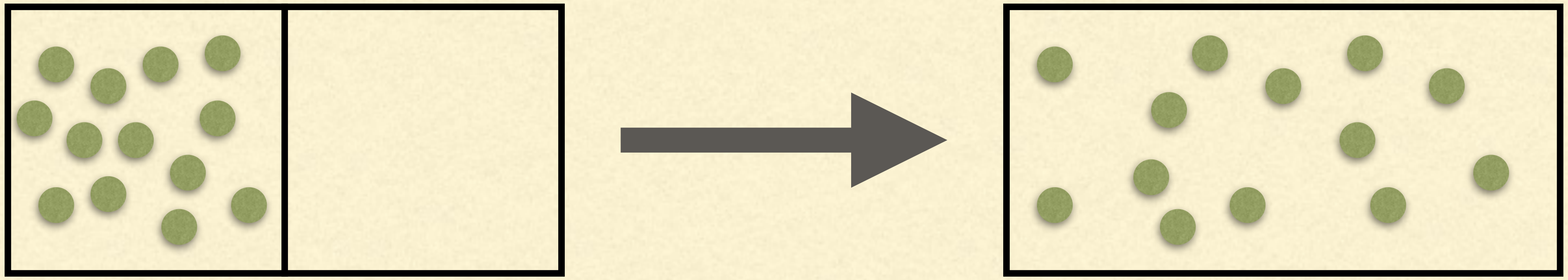
ENTROPY PRODUCTION

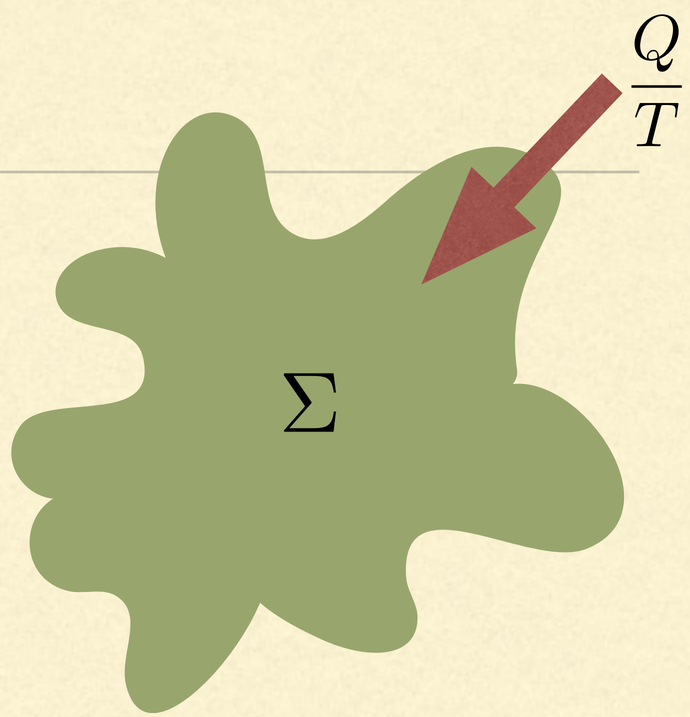
- In certain processes there seem to be a well defined *arrow of time*.
  - *Asymmetry between "forward" and "backward".*
- This asymmetry is quantified by the **entropy production**.



- The 2nd law of thermodynamics can be expressed as:

$$\Sigma \geq 0$$

OPEN SYSTEMS



- For open systems entropy production ≠ entropy.
  - Entropy does not satisfy a continuity equation.
  - There can also be an entropy flux

$$\Delta S = \Sigma + \frac{Q}{T}$$

- The 2nd law then becomes Clausius' inequality:

$$\Delta S \geq \frac{Q}{T}$$

THE MANY FACES OF THE 2ND LAW

EFFICIENCY OF A HEAT ENGINE

- Let us now consider a heat engine.

- I like to write the 1st and 2nd laws side by side:

$$\frac{dU}{dt} = \dot{Q}_h + \dot{Q}_c + \dot{W}$$

$$\frac{dS}{dt} = \dot{\Sigma} + \frac{\dot{Q}_h}{T_h} + \frac{\dot{Q}_c}{T_c}$$

- We are interested in a steady-state operation regime:

$$\frac{dU}{dt} = 0 \quad \Longrightarrow \quad \dot{W} = -\dot{Q}_h - \dot{Q}_c$$

$$\frac{dS}{dt} = 0 \quad \Longrightarrow \quad \dot{\Sigma} = -\frac{\dot{Q}_h}{T_h} - \frac{\dot{Q}_c}{T_c}$$

$$\frac{dU}{dt} = 0 \quad \Longrightarrow \quad \dot{W} = -\dot{Q}_h - \dot{Q}_c$$

$$\frac{dS}{dt} = 0 \quad \Longrightarrow \quad \dot{\Sigma} = -\frac{\dot{Q}_h}{T_h} - \frac{\dot{Q}_c}{T_c}$$

- The efficiency of the engine then becomes:

$$\eta = -\frac{\dot{W}}{\dot{Q}_h} = 1 + \frac{\dot{Q}_c}{\dot{Q}_h} = 1 - \frac{T_c}{T_h} - \frac{T_c}{\dot{Q}_h}\dot{\Sigma}$$

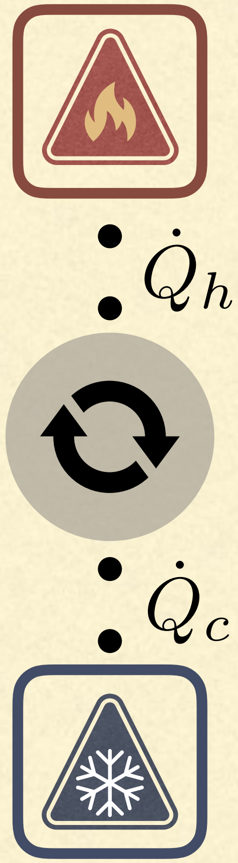
- *Entropy production is therefore the reason the efficiency is smaller than Carnot!*

$$\eta = \eta_C - \frac{T_c}{\dot{Q}_h}\dot{\Sigma}$$

Carnot's statement of the 2nd law

"The efficiency of a quasi-static or reversible Carnot cycle depends only on the temperatures of the two heat reservoirs, and is the same, whatever the working substance. A Carnot engine operated in this way is the most efficient possible heat engine using those two temperatures."

FLOW OF HEAT



- Consider the heat flow between two bodies, one hot one cold.
- This is same as the heat engine, except we do no work.
- We continue to have:

$$\dot{\Sigma} = -\frac{\dot{Q}_h}{T_h} - \frac{\dot{Q}_c}{T_c} \geq 0$$

- But now, since there is no work, $\dot{Q}_c = -\dot{Q}_h$

$$\therefore \qquad \dot{\Sigma} = \left(\frac{1}{T_c} - \frac{1}{T_h}\right)\dot{Q}_h \geq 0$$

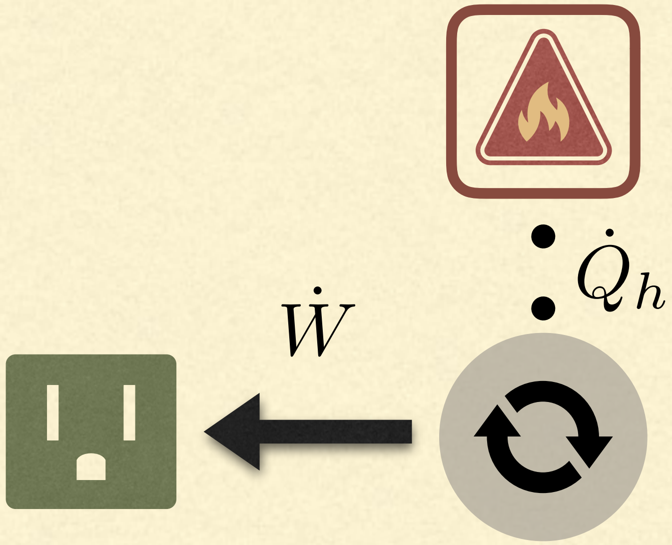
- *Heat flows from hot to cold.*

Clausius' statement of the 2nd law

"Heat can never pass from a colder to a warmer body without some other change, connected therewith, occurring at the same time."

SINGLE BATH

- Finally, suppose we only have 1 bath.



- The 1st and 2nd laws then give:

$$\dot{W} = -\dot{Q}_h$$

$$\dot{\Sigma} = -\frac{\dot{Q}_h}{T_h} = \frac{\dot{W}}{T_h} \geq 0$$

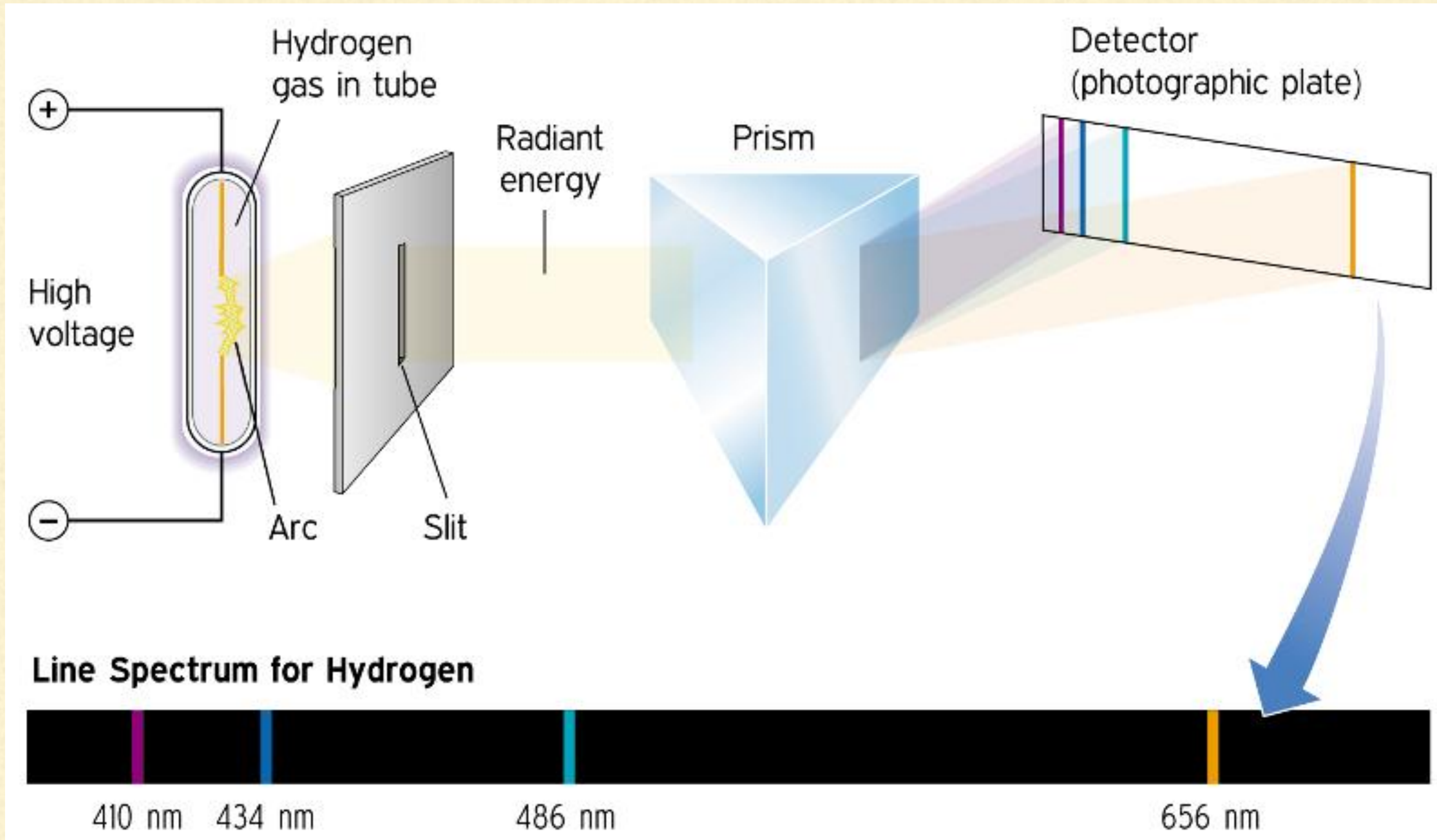
- Positive work (in my definition) means an external agent is *doing* work on the system.

Kelvin-Planck statement of the 2nd law

"It is impossible to devise a cyclically operating device, the sole effect of which is to absorb energy in the form of heat from a single thermal reservoir and to deliver an equivalent amount of work."

PART 2: QUANTUM CORRELATIONS

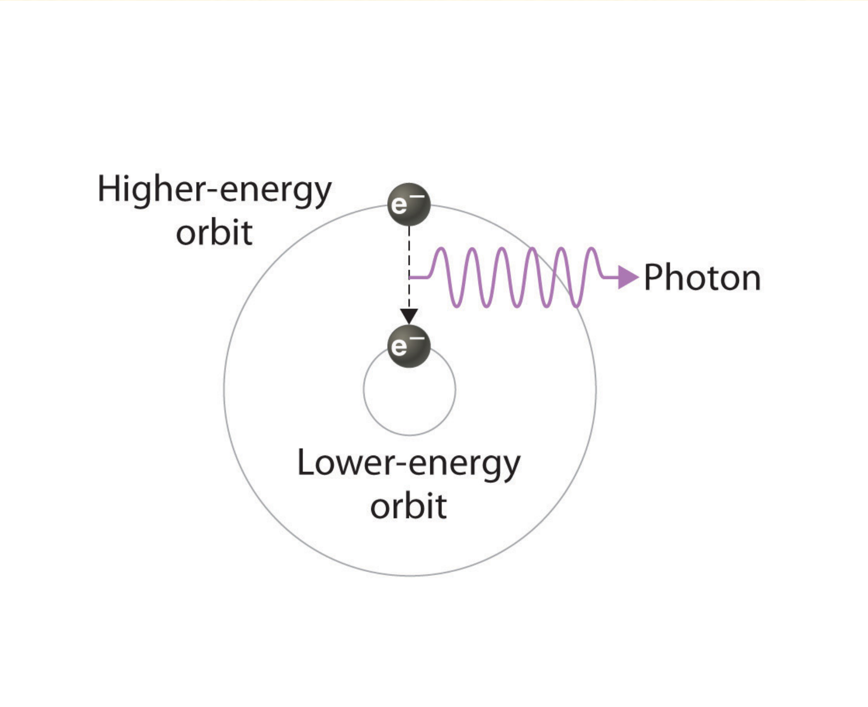
SPECTRAL LINES



Cor	Vermelho	Ciano	Azul	Violeta
λ (nm)	656.3	486.1	434.1	410.2

Signatures of a chemical element. This is how we know the sun is made of hydrogen.

BOHR'S MODEL

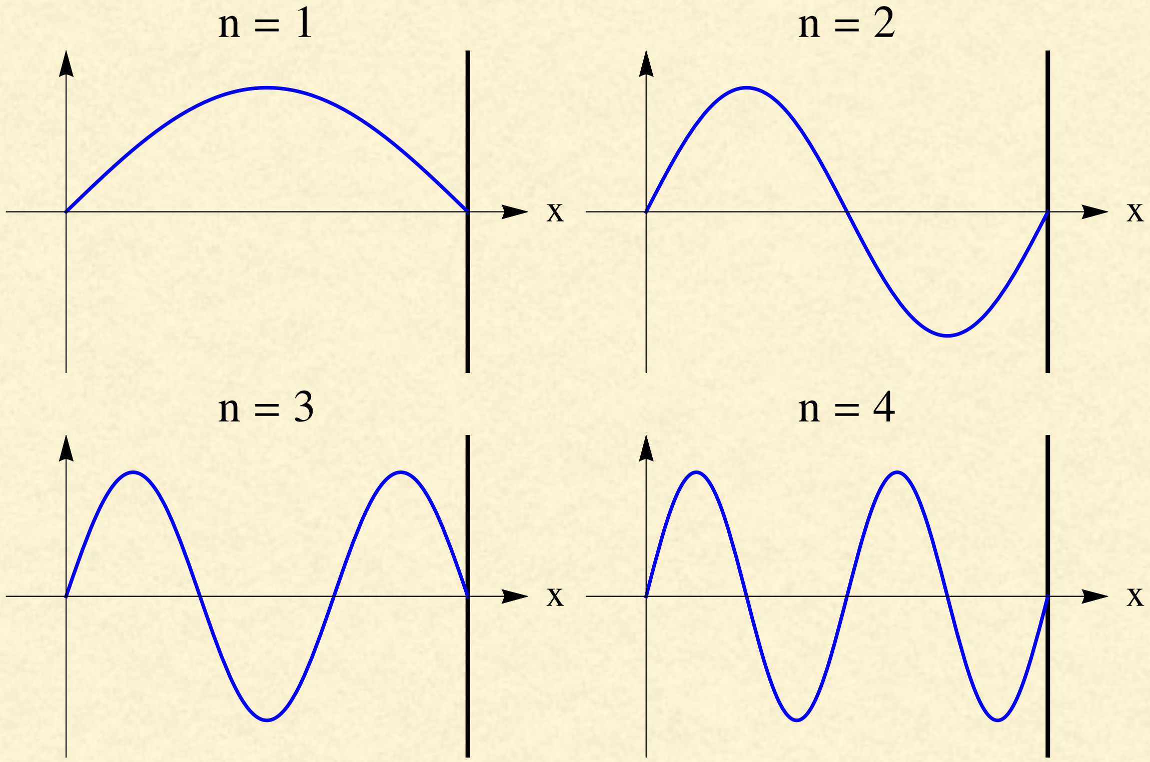


(a) Electronic emission transition

$$\frac{1}{\lambda} = R_H \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right)$$

$$R_H = 0.010974 \text{ nm}^{-1}$$

$$n_{i,f} = 1, 2, 3, \ldots$$



- Discrete stuff are *super weird*!

ERWIN SCHRÖDINGER - 1926

Quantisation as a Problem of Proper Values (Part I)

(*Annalen der Physik* (4), vol. 79, 1926)

§ 1. In this paper I wish to consider, first, the simple case of the hydrogen atom (non-relativistic and unperturbed), and show that the customary quantum conditions can be replaced by another postulate, in which the notion of "whole numbers", merely as such, is not introduced. Rather when integralness does appear, it arises in the same natural way as it does in the case of the *node-numbers* of a vibrating string. The new conception is capable of generalisation, and strikes, I believe, very deeply at the true nature of the quantum rules.

INSTANT HIT

- Schrödinger's equation is weeeeeirrrrrd.
  - But it works, so who cares.
- And it became an instant hit: in a matter of a decade, people were already applying quantum mechanics to phenomena ranging from chemistry to nuclear physics.
- *For most of the last century, people have used quantum mechanics to understand many phenomena in nature.*
  - *But little attention was given to understand quantum mechanics itself.*

THE SUPERPOSITION PRINCIPLE

- The simplest example of a quantum system is one with only 2 states (like a coin).
  - We call it a *qubit*.
- A qubit can be in one of two states which we call $|0\rangle, |1\rangle$
- But according to quantum mechanics, the *state* of a qubit can be encoded as a *superposition* of these states:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

- where α and β are complex numbers satisfying:

$$|\alpha|^2 + |\beta|^2 = 1$$

- According to quantum theory, if we measure the system, we will find it in either 0 or 1, with probabilities:

$$p_0 = |\alpha|^2, \qquad\qquad p_1 = |\beta|^2$$

- But if we happen to find the system in 0, then after the measurement, the state of the system is updated to 0 (the state *collapsed to the outcome).*

- These are the rules: *superposition* + *probabilistic outcomes.*

- We need these rules to construct the theory, even though they are super weird.

But what does it mean to be in a superposition?

REALISM

- A probabilistic outcome is usually associated with *ignorance* (lack of information) about what is going on.
  - It could be that we obtain probabilistic outcomes because we lack some kind of information (hidden variables)?
  - Maybe the state of the system (0 or 1) is already established, but we simply don't know what it is.
- This would be a realist theory.

Realism: the idea that objects have properties which exist independent of observation.

EPR PARADOX - SPOOKY

- In 1935 Einstein, Podolsky and Rosen noticed that if nature was not realist, weird stuff would happen.

- Suppose we have two qubits, A and B. According to the principle of superposition we are allowed to prepare them on a state of the form

$$|\psi\rangle = \frac{|0,0\rangle + |1,1\rangle}{\sqrt{2}}$$

- This is what we call an *entangled state.*

- But now we take one of the qubits to another galaxy in a spaceship.

  - In another planet Bob measures qubit B and happen to find it in 1.

  - Then according to the rules of QM, qubit A would *immediately* collapse to 1 as well!

BELL INEQUALITY

- For 3 decades this remained as a philosophical question.
- In 1964 John Bell proposed a *test* to check if a theory is realist or not.
- Bell's idea: create a pair of entangled photons and measure them on different polarization directions. For a realist theory one must *always* have

$$\langle A_0 B_0 \rangle + \langle A_0 B_1 \rangle + \langle A_1 B_0 \rangle - \langle A_1 B_1 \rangle \leq 2$$

- A theory violating this cannot be a realist theory.

VOLUME 49, NUMBER 2 PHYSICAL REVIEW LETTERS 12 JULY 1982

Experimental Realization of Einstein-Podolsky-Rosen-Bohm *Gedankenexperiment*: A New Violation of Bell's Inequalities

Alain Aspect, Philippe Grangier, and Gérard Roger
Institut d'Optique Théorique et Appliquée, Laboratoire associé au Centre National de la Recherche Scientifique, Université Paris-Sud, F-91406 Orsay, France
(Received 30 December 1981)

$$-2 \leq S \leq 2, \tag{2}$$

where

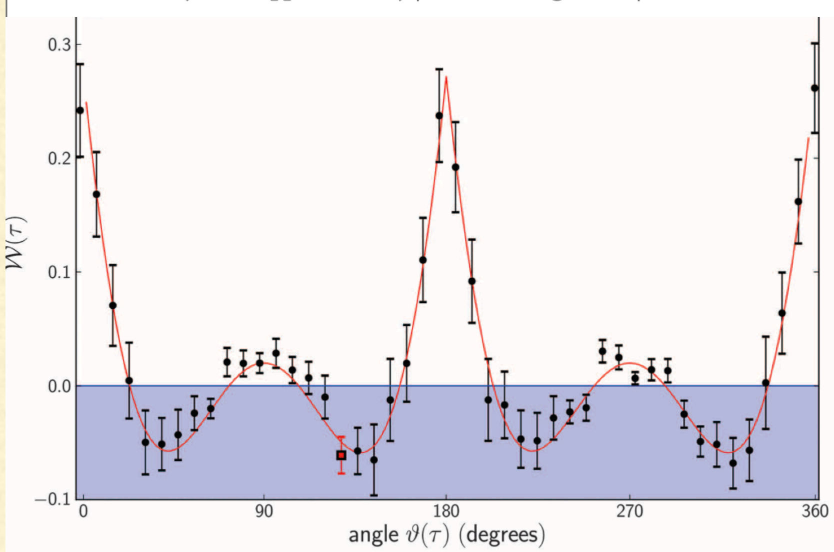
$$S = E(\vec{a},\vec{b}) - E(\vec{a},\vec{b}') + E(\vec{a}',\vec{b}) + E(\vec{a}',\vec{b}')$$

$$S_{\text{expt}} = 2.697 \pm 0.015.$$

QUANTUM OPTICS

Bell correlations in a Bose-Einstein condensate

Roman Schmied,[1*] Jean-Daniel Bancal,[2,4*] Baptiste Allard,[1*] Matteo Fadel,[1] Valerio Scarani,[2,3] Philipp Treutlein,[1†] Nicolas Sangouard[4†]



PHYSICAL REVIEW LETTERS 121, 220404 (2018)
Editors' Suggestion Featured in Physics

Optomechanical Bell Test

Igor Marinković,[1,*] Andreas Wallucks,[1,*] Ralf Riedinger,[2] Sungkun Hong,[2] Markus Aspelmeyer,[2] and Simon Gröblacher[1,†]
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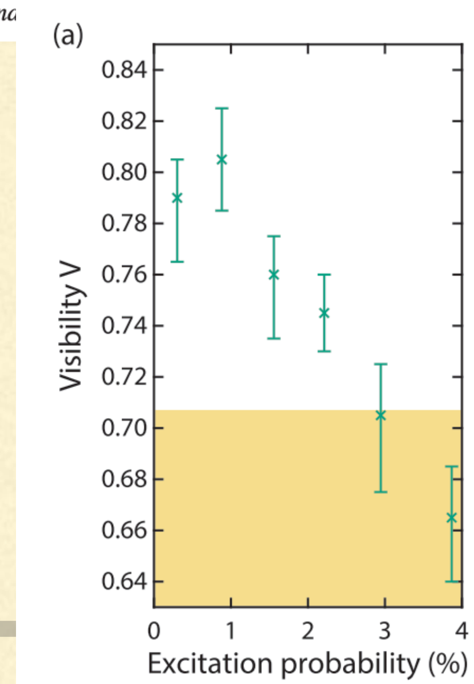
[2]*Vienna Center for Quantum Science and Technology (VCQ), Faculty of Physics, University of Vienna*



QUANTUM CORRELATIONS

- Entanglement is a genuinely quantum effect.
- It is not correlation due to information, but an intrinsic correlation that Nature allows.
- Can we *use* entanglement as a *resource* to do something?
    - Yes! These are the Quantum Technologies 2.0.
    - Quantum communications, quantum computing, quantum sensors, &c.

REVERSING THE DIRECTION OF HEAT FLOW USING QUANTUM CORRELATIONS

Reversing the direction of heat flow using quantum correlations

Kaonan Micadei,[1,2,*] John P. S. Peterson,[3,*] 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] and Eric Lutz[2]

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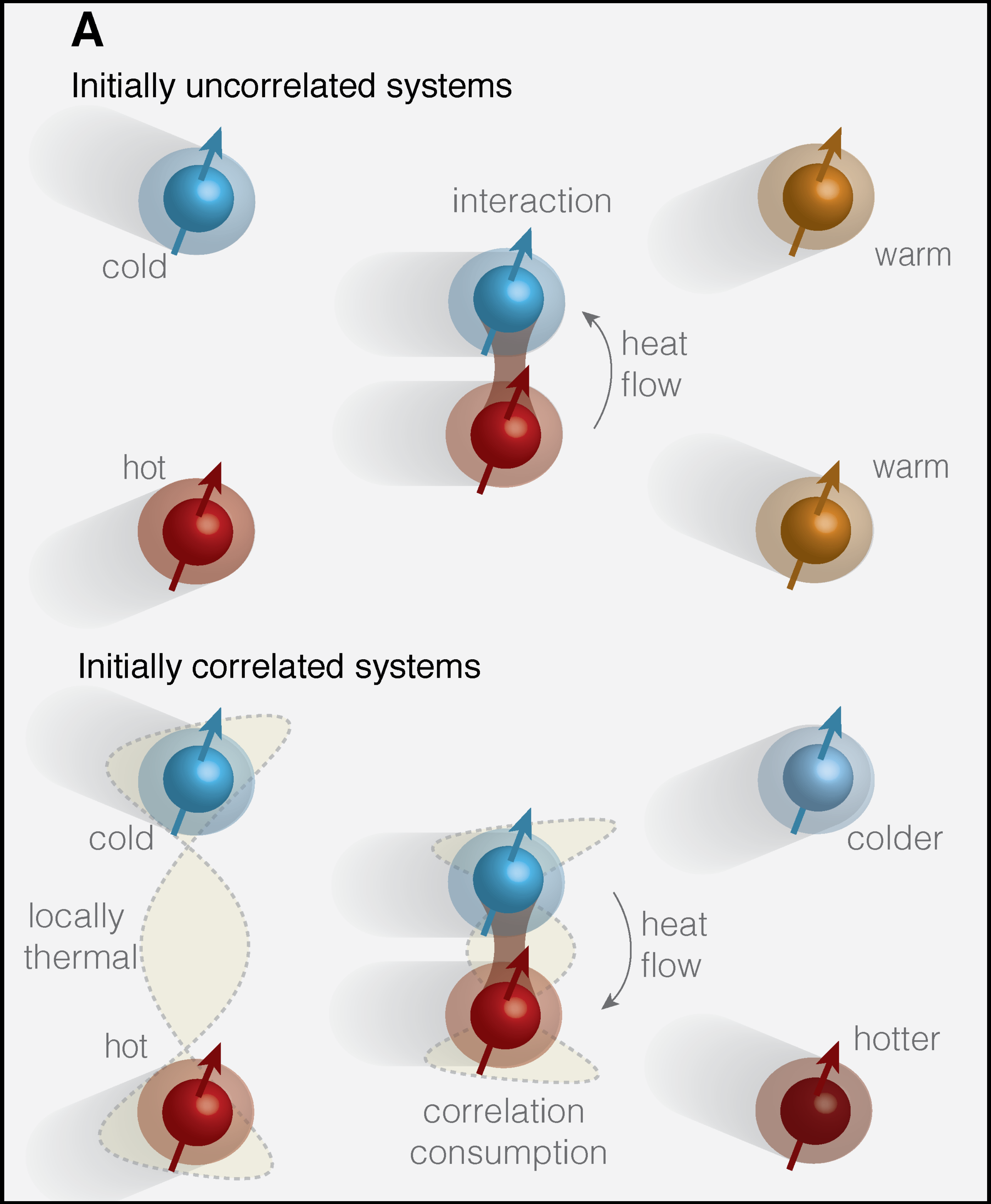
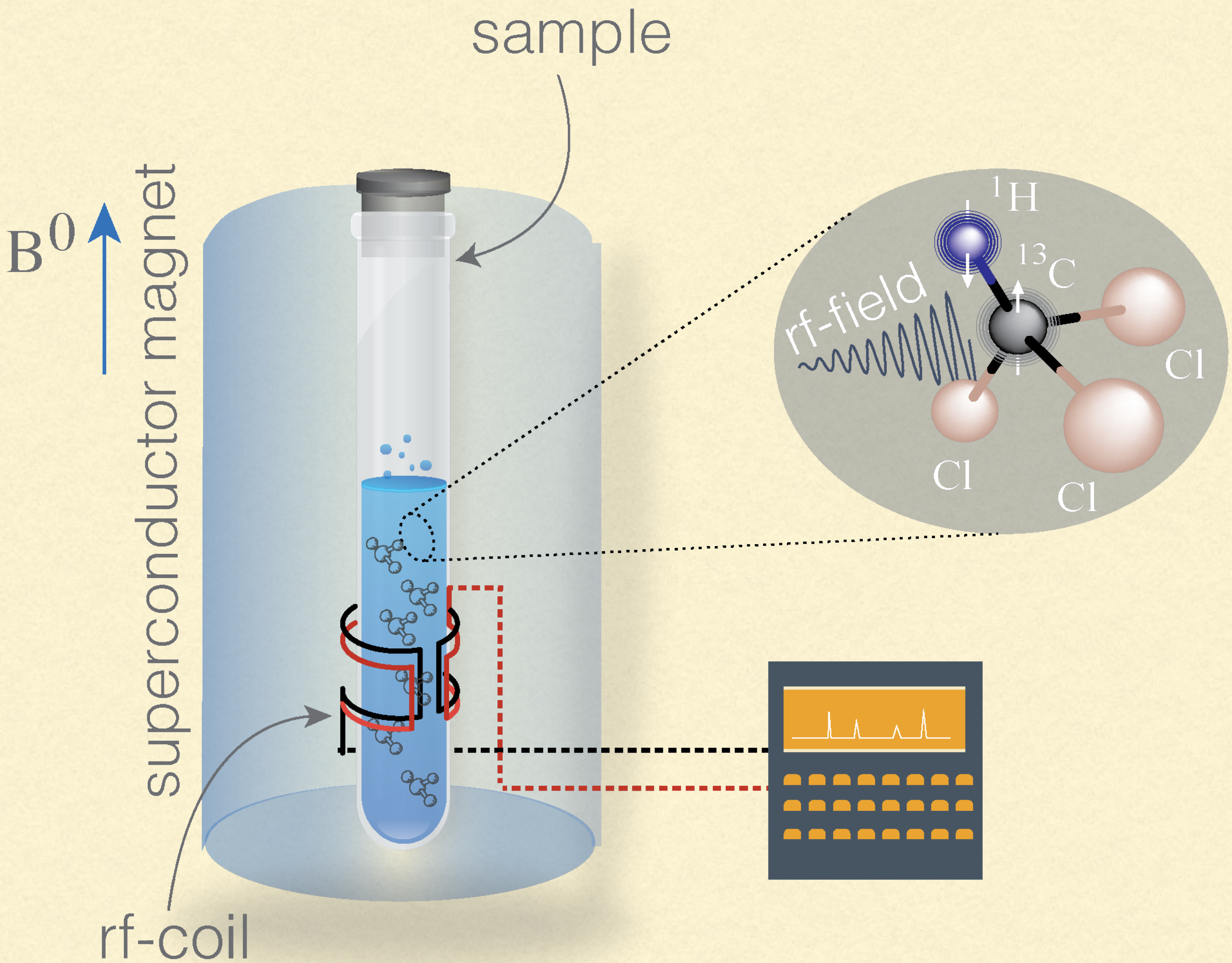
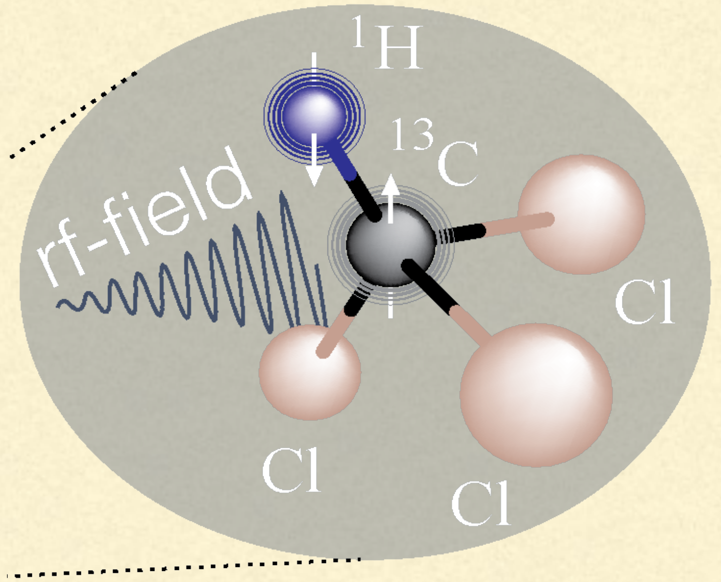
[7]*Department of Physics, University of York, York YO10 5DD, United Kingdom*

To appear in Nature Communications.


A
Initially uncorrelated systems
cold
interaction
warm
heat
flow
hot
warm
Initially correlated systems
cold
colder
locally
thermal
heat
flow
hot
hotter
correlation
consumption

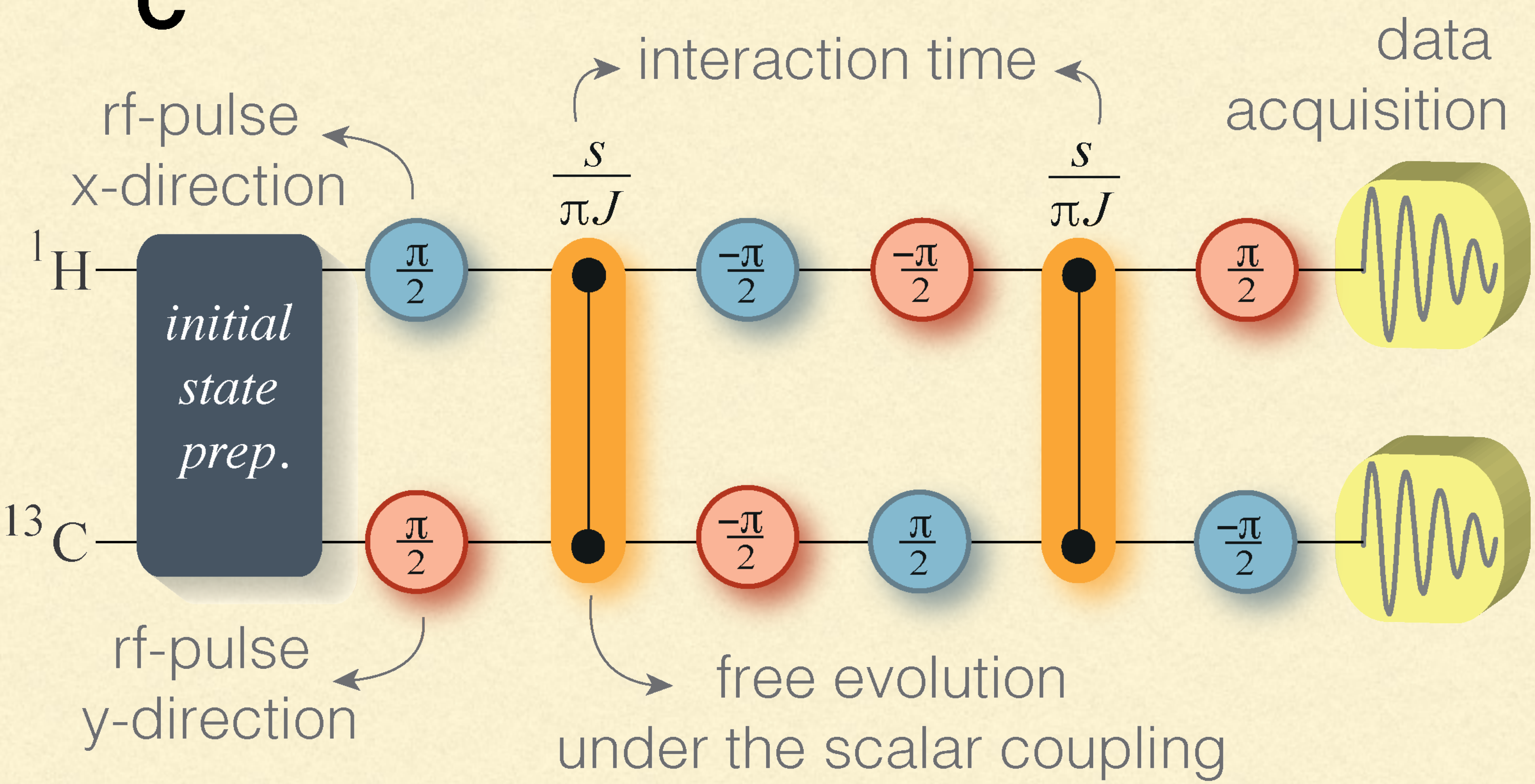
B


sample
B0
superconductor magnet
rf-coil
rf-field
1H
13C
Cl
Cl
Cl
Cl



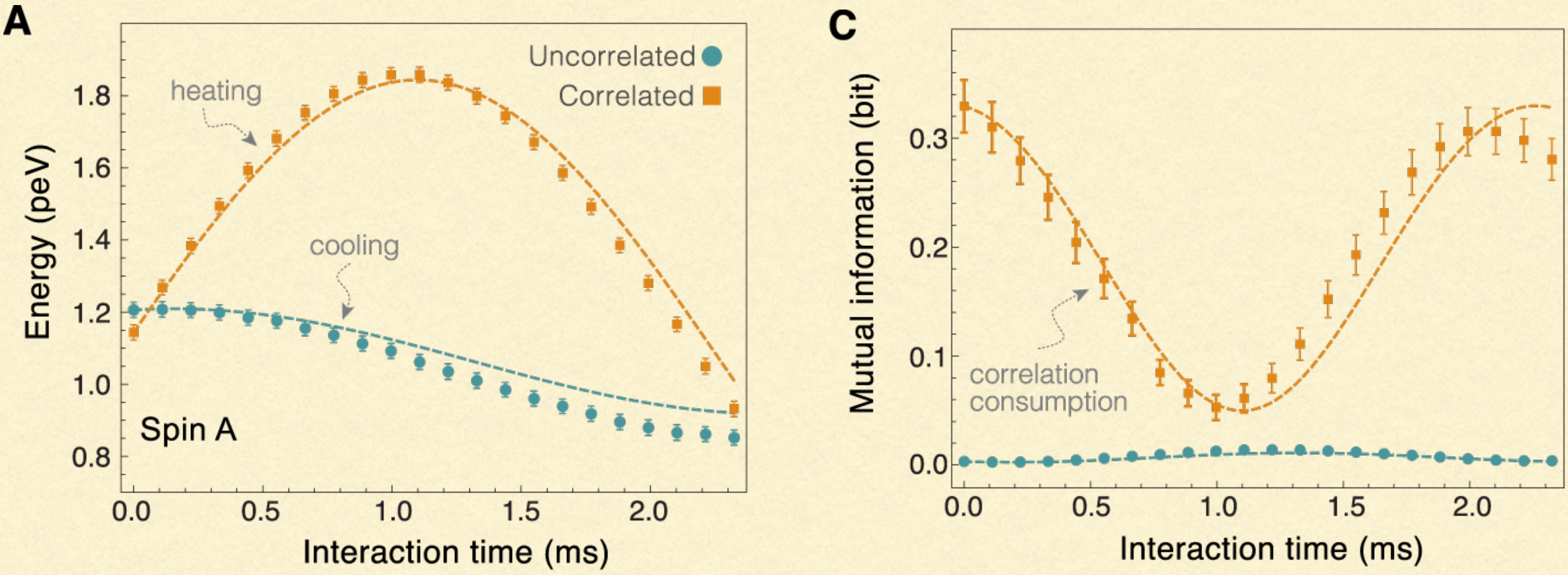
^{1}H
^{13}C
rf-field
Cl
Cl
Cl

C



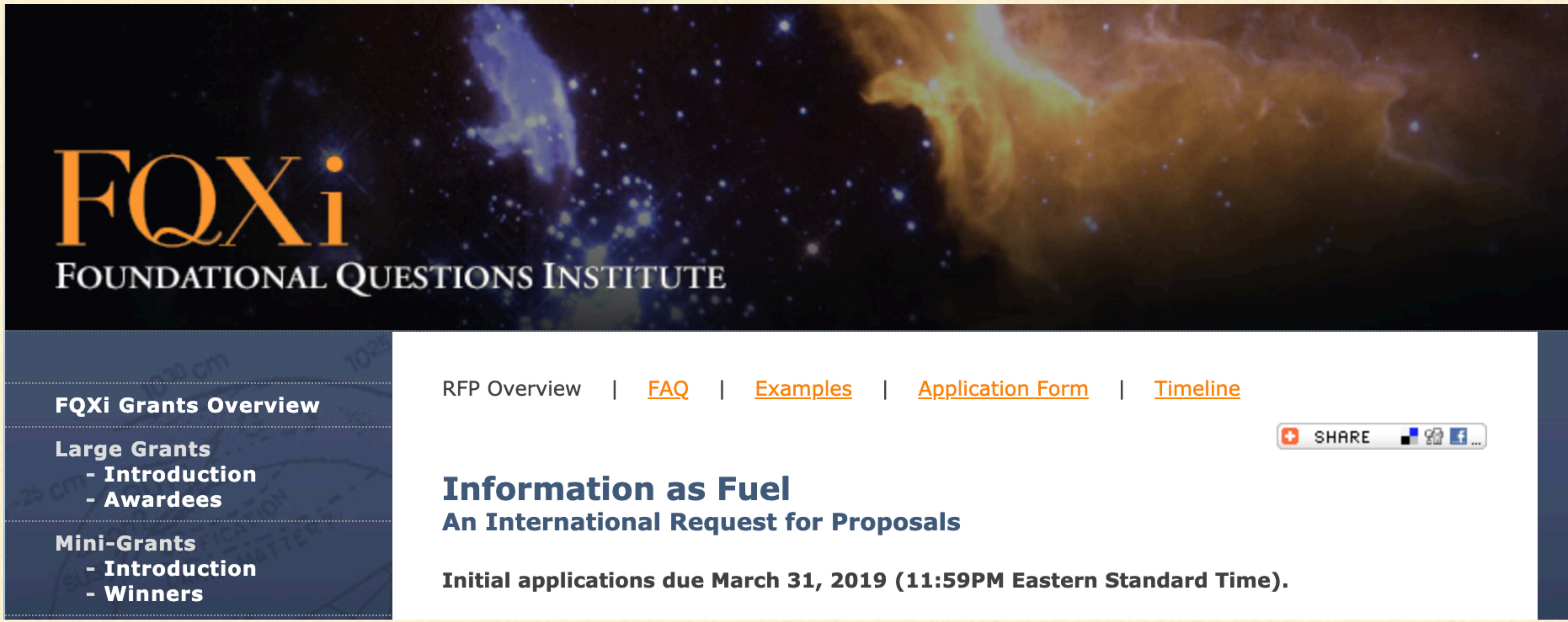
interaction time
data
acquisition
rf-pulse
x-direction
$\frac{s}{\pi J}$
$\frac{s}{\pi J}$
^{1}H
$\frac{\pi}{2}$
$\frac{-\pi}{2}$
$\frac{-\pi}{2}$
$\frac{\pi}{2}$
initial
state
prep.
^{13}C
$\frac{\pi}{2}$
$\frac{-\pi}{2}$
$\frac{\pi}{2}$
$\frac{-\pi}{2}$
rf-pulse
y-direction
free evolution
under the scalar coupling

EXPERIMENTAL RESULTS



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).
  - *Here we showed that entanglement is also a resource.*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An International Request for Proposals
Initial applications due March 31, 2019 (11:59PM Eastern Standard Time).

PSEUDO FILMES

CONCLUSIONS

- Entropy production is *the* central concept in all of thermodynamics.
    - (undergraduate courses usually don't reflect that).
- Correlations can be informational or intrinsic. Quantum correlations (entanglement) are intrinsic.
    - Entanglement is an *informational resource:* can be consumed to perform tasks that are not possible with classical resources.

Quantum thermodynamics
QT²
quantum transport
IFUSP

Thank you!

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